EVOLUTION OF TRANSPORT SYSTEMS: PAST AND FUTURE

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RR-91-8
June 1991

INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
Laxenburg, Austria

Foreword

The environmental compatibility of human activities depends to a large extent on the efficiency in the use of energy, basic materials, capital, and other factor inputs in both production and consumption. Improved efficiency may thus alleviate many adverse impacts and enhance the environmental compatibility of human actions. However, another important factor is efficiency in the use of time. In 1987 global CO_2 emissions from fossil energy use were about 5.7 Gt carbon. The transport sector accounts currently for some 1.2 Gt carbon emissions annually, or for slightly less than 25 percent of global energy-related CO_2 emissions. Perhaps more important than the absolute magnitude of the emissions is the vigorous growth of transportation demand in both developed and developing countries even in periods of rising energy prices.

In this report Arnulf Grübler and Nebojša Nakićenović develop a scenario for future developments in the transport sector and their implications for energy demand. In developing a comprehensive mode-space-time coverage of the evolution of transport systems, the analysis indicates that present transport systems are approaching a number of limits: market saturation in leading countries and an increasing awareness of the social and environmental disbenefits associated with a further intensification in the use of present-day oil-based transport systems. The report describes an innovative scenario from a historical perspective, taking into account a number of institutional and physical constraints to significant future increases in the car population and air travel demand at the global level. The scenario challenges the more conventional approaches in projecting future developments in the transport sector, often based on econometric analysis or income and price elasticities. These approaches usually result in very high growth rates of future transport systems perhaps indicating the inappropriateness of these methods for long-term projections.

The saturation scenario outlined in conjunction with further efficiency improvements in the transport sector holds important implications for future energy demand profiles and the resulting environmental impacts at the local, regional, and global level. Energy demand for transportation in OECD countries may even decline, while it continues to rise in centrally planned (or now, reforming) and developing economies. The overall increase in the energy demand for transportation in the scenario is, however, significantly lower than in most other energy studies. As such the scenario illustrates a possible future in which a worldwide homogenization of life styles and resource consumption levels along past energy and resource-intensive development trajectories of industrialized countries would not take place. Given that appropriate policies are implemented, a transition toward a more sustainable development path in the transport sector may thus not only be feasible, but also be consistent with historical experience.

However, the scenario does not indicate a permanent stagnation in the demand for transportation fuel in the long term, but rather a transition from the forthcoming saturation of current transport technologies to the introduction of a new generation of more productive systems. Their productivity will have to be defined not only in terms of more efficient use of economic resources and time, but also with respect to their environmental impacts. With current concerns about global environmental change the report is of interest in that it provides a contrast to conventional wisdom and illustrates alternative scenarios developed within the Environmentally Compatible Energy Strategies (ECS) Project at IIASA.

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Acknowledgments

We gratefully acknowledge the continuous support of Group Planning, SHELL International, London, for part of the research reported here. In particular, we would like to thank Didier Borderon and Ged Davis for their intellectual encouragement and helpful suggestions which led to this study.

Abstract

Technological change in all areas of economic and social activities has been a major determinant of development. With advances in technology it is possible to provide entirely new services and to achieve more with less input. This implies that in addition to productivity increases, the efficiency in the use of energy, basic materials, capital, and other inputs will improve, alleviating many adverse impacts and improving environmental compatibility. Efficient use of time is another important factor, especially in the context of the long-term development of transport systems. Great leaps in the advancement of transport systems have allowed ever greater distances to be covered in a unit of time, from the traditional villages and preindustrial cities connected by walking, to almost the whole world being connected in one day by aircraft.

Technological improvements are achieved both through the introduction of fundamentally new solutions (basic innovations), and through incremental improvements in existing techniques and systems (product and process innovations). Although an overlap exists, it is important to distinguish between the two because it is the basic innovations as originally formulated by Schumpeter that will lead to the creation of entirely new industries and growth sectors. Innovations provide for economic growth only by their widespread application throughout the economy, i.e., via their diffusion.

During the diffusion process, there is a gradual transition from basic innovations that initially leads to the creation of new industries, to incremental improvements, and product innovations as the diffusion process matures. During the early development phases the new industry is fluid with a high degree of diversity and experimentation. The major emphasis is on improving technical performance without much regard for price. In the Schumpeterian sense there are often monopoly opportunities arising for the innovative entrepreneur.

As competition begins, one particular technological variant becomes dominant and standardization emerges in the new industry. This is usually a disruptive phase of development with a characteristic "shake-out": only a few competitors survive this phase as prices decrease with the increasing cost reductions resulting from standardization and learning curve effects. Emphasis then shifts to incremental improvements and small cumulative innovations. Economies of scale and further reductions of costs along the learning curve lead to advantages for only a few competitors who can internalize the benefits and realize higher profits. Successful basic innovations diffuse in many sectors, from manufacturing, to transport services, and end use or consumption. Computers, internal combustion motors, and jet engines (gas turbines) are good examples.

Eventually the diffusion of pervasive systems can fundamentally change many commercial activities and even everyday life. Nonetheless, as the technology and its applications mature, the awareness of many disbenefits can begin. Cumulative and incremental improvements cover an increasingly smaller domain of technical and managerial possibilities. Saturation starts and the problems associated with widespread and large scale applications become important. The social and institutional response is rather nonlinear and disruptive. The awareness of social disbenefits and risks often increase rapidly making further diffusion unacceptable.

During these periods new techno-economic paradigms emerge, and the old development trajectory associated with the previous generation of pervasive technologies and institutional forms is not only challenged, but in time also replaced with new solutions. This illustrates that there are strong links between social development, economic growth, innovation processes, and the subsequent diffusion of new technologies. Technological change, or the lack of it, is thus a fundamental force in shaping the pattern of social and economic development. As regards the former, it is both disruptive during the transition period (marked by fluctuations, frictions, and sometimes crises) and is a source of order for the direction of change and the dynamic adjustment processes, as new technologies diffuse through national and international economies.

Some of the most important changes in socio-institutional frameworks and economic structure are indeed related to the pervasive adoption of new systems. For example, the diffusion of motor vehicles was contingent on the development of numerous other systems, such as paved roads, the internal combustion engine, oil refining and motor fuels, new sheet metals and high quality steels, electrical equipment, and a whole host of other new technologies, products, and institutions.

In this report we use the following approach to outline the likely future development of transport systems and their energy requirements. We first analyze the development of pervasive transport systems in the past, starting with canals, railroads and horse-driven road vehicles, through to automobiles and air transport. One of the results of this analysis is that these transport systems and their infrastructures evolved according to the technological evolutionary scheme we have described; an early development phase marked by a high degree of experimentation, followed by a rapid growth phase characterized by standardization and finally the saturation phase when the technical and economic potentials appear to be exhausted, leading to structural change and transition to the next generation of transport systems. This replacement process proceeds according to a schedule that apparently defines the opportunity windows for the development of particular systems. In the leading countries, subsequent diffusion leads to a long, sustained period of development with all the diffusion characteristics of pervasive systems. In other countries the diffusion is either blocked or occurs later. Our findings show that in these cases the diffusion process can be faster and can be completed at the same time as in the leading countries. However, the development time is shorter and the extent of the diffusion is much lower. Consequently, railroad networks are smaller in countries where they are introduced later; similarly, automobile ownership is also lower compared with the leading countries. Thus, by the time saturation sets-in the diffusion level is lower in those countries where the innovation was introduced later.

This is basically the nature of our scenario for the further diffusion of automobiles and air transport. Automobile ownership and car fleets appear to be rather close to saturation in most countries. Until complete saturation, the global automobile fleet is expected to grow by another 20 to 40 percent. We find an analogous situation with the further development of air transport. The volume of all operations is expected to grow by another 60 to 80 percent. Both development trajectories will be completed during the next 20 to 30 years. Furthermore, we expect this process to lead to frictions and misadjustments, so that the saturation phase will most likely be characterized by oscillations. This is the reason for the rather wide range in the still expected expansion of these two transportation modes. To evaluate the actual energy requirements associated with the projected future automobile fleet and volume of air transport, we have made two scenarios; both assume efficiency improvements in the future. One is based on long-term historical efficiency improvements of about one percent per year, and the second on more vigorous improvements of about 2.5 percent per year. Based on these scenarios, transportation fuel demands will at best stagnate during the next two to three decades.

This projection, however, does not indicate permanent stagnation of fuel demand, but rather a transition period from the saturation of current transport technologies to the introduction of a new generation of more productive transport systems. Thereafter, energy demand could be expected to increase again with further increases in mobility, exchange of tangible goods, and advancement of transport systems in general. There are already a number of candidate technologies that might lead to the development of pervasive transport systems in the next century. Maglevs and hypersonic aircraft are two 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. However, our analysis indicates eventual saturation as the technical and economic potentials of these systems slowly become exhausted to make way for entirely new forms of travel and goods transport.

Depending on whether and how our societies adopt these systems, we may witness new diffusion clusters in the future, which would have fundamental impacts both on employment and competitiveness, the structure of the economy, and consequently also on the patterns of energy use. Since their adoption and mediation by society will not be homogeneous and will affect countries and regions differentially, the process can be expected to be disruptive.

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"Add as many mail-coaches as you please, you will never get a railroad by so doing."

Joseph A. Schumpeter (1935)

1. Introduction

The history of transport systems is a history of revolutions. Processes of *technological mutation* from the mail-coach to the airplane have transformed and extended the spatio-temporal range of commercial and private activities, leading to unprecedented levels of performance in terms of speed, quality of service, spatial division of activities, and integration of economic spaces. In this report we provide a quantitative history of the transport system. Intriguing 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, ordered, development trajectories that can be formalized mathematically by simple, biological growth and interspecies 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 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.

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 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 early 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 and is, in addition, time dependent. Based on historical analysis, we conclude that there was a time to build canals and railways, as there is a time to build highways and to 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*, in which the expansion of a particular technological system reaches its 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 consequences for energy demand, in particular for oil. The scenario postulates the forthcoming saturation of automobile diffusion in industrialized countries with no comparable (in terms of intensity levels) development in the developing countries. At the same time, we consider the possibility of further growth in air transportation, as well as the emergence of new high-speed and productivity transport modes, such as super- or hypersonic aircraft fueled by methane or hydrogen, or maglevs (magnetic levitation trains) based on superconductivity.

The report begins by giving a long-term account of the evolution of transport infrastructures and of the changing structure of the system using physical (length) as well as financial (capital stock) measures for a number of countries. We then proceed to demonstrate that the evolutionary envelope that emerges is consistent with the evolution of the intensity of use (i.e., passenger- and ton-km transported) of different infrastructures both for passenger and goods transportation, including a short discussion of the main driving forces behind the historical development pattern.

We continue with a more detailed analysis of the growth of railway systems in different countries, a process completed in all industrialized countries by the 1930s. We analyze *ex post* the very divergent densities in different countries in the development of this particular transport system. This then serves as an illustrative case to investigate whether a similar observation can be made in the diffusion of the automobile (and as we will see it *can*), and to derive a global scenario for automobile diffusion.

Based on our conclusions with respect to the future evolution of the structure of the transport system and our scenario of forthcoming global saturation in automobile diffusion, we then discuss the long-term winner in the competitive game of medium- and long-range transport systems: air transportation. Using currently available technology, however, even air transport with jet-engine propulsion is not capable of meshing the world's major gravity centers into a functional entity. As a next logical, long-term technological development, we therefore consider the emergence of aircraft with super- or even hypersonic flight regimes. Finally based on a historical example, we illustrate the likely market response once such advanced long-distance transport becomes available.

Following the scenario on the future of the world's transport system, we conclude the report with a short discussion on the possible consequences for energy demand in general, and particularly for various oil products, under two different sets of assumptions: (1) a continuation of historical trends in the evolution of energy efficiency in the transport sector, and (2) a vigorous improvement in efficiency. As a comparison, the resulting energy demand based on current efficiency levels is also presented.

2. Evolution of Transport Infrastructures

One clear trend emerges from historical analysis – transport systems have become ever faster, more productive and, at the same time, were greatly expanded. The first major improvement occurred with the age of canals. Canals represented a fundamental construction effort toward reducing natural barriers in order to connect coastal and inland waterways in an *interconnected* transportation infrastructure *grid*. At the same time, canals were the first powerful motor of the industrial age. Waterways facilitated new flows of goods, unprecedented exchanges between regions, specialization of labor, and access to more distant energy and raw material resources. Local fuelwood shortages were resolved by substituting with coal, a higher energy-density fuel, the transport of which was made possible by canals. The age of canals started about two centuries ago and lasted almost one hundred years. By the end of the 19th century most national canal systems were in place and many links were already decommissioned. Eventually the canals had to yield to the vicious competition from railroads, including hostile takeovers.

The first railways were constructed in the 1830s and they were able to extend the range, speed, and productivity levels previously achieved with canals. In time, North America and Europe were covered with elaborate networks of railway systems. Together with railways, a new era of coal, steam, steel, and the telegraph began. The great railway era lasted until the 1930s. Despite some further construction of railway lines in developing countries, the global railway network has (because of the decommissioning of lines in industrialized countries) remained constant, at a level of 1.3 million km, ever since the 1930s. Railways have consequently lost their dominant position (around 80 to 90 percent of all passenger- and ton-km transported in the 1920s and 1930s) in the transport sector throughout the world.

Around the turn of the century the automobile was born and became the symbol of modern industrial development along with oil, petrochemicals, electricity, the telephone, and (Fordist) manufacturing. Following the development of road infrastructure, the automobile again facilitated an increase in the speed and performance of the transport system.[1] The flexibility of an individual mode of transportation became affordable for a wider social strata, and it was not until about two or three decades ago that the disadvantages of the automobile became socially transparent.

The last in the sequence of infrastructure developments is air transportation. Once more, it also promoted an increase in the productivity level of the transport system in terms of speed, range, and comfort. However, its associated infrastructure is "dematerialized" to right-of-way air corridors, with only control and communication and the connecting nodes to other transport modes (airports and hubs) relying on physical structures.

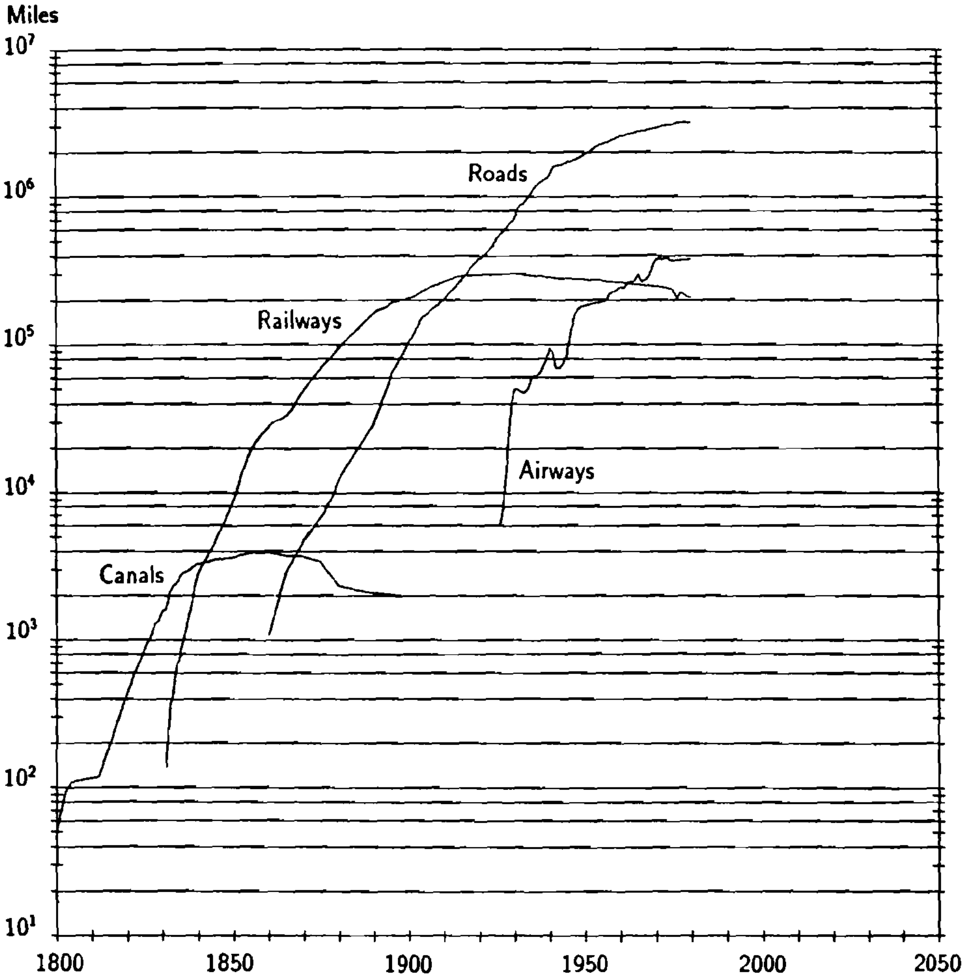


Figure 1. Length of canals, railroads, surfaced roads, and federal airways in the USA, in 1,000 miles. Source: Nakićenović (1988); Grübler (1990).

Figure 1 illustrates the development of the four major transport systems for the USA, represented by the growth in length of their respective infrastructures. The length of all four increased by more than four orders of magnitude over the last two centuries. Each successive mode of transport expanded into an infrastructure ten times larger than the previous one. It is also interesting to note that new infrastructures overtook existing ones only when the latter started saturating, e.g., canals and railways in the 1840s, and railways and surfaced roads in the 1920s.

The first canals were built in the 1780s and reached a total length of 4,000 miles (6,400 km) by 1870 before saturating and then declining; thus the expansion of canals lasted about 90 years. The first railroads were built in the 1830s and saturation started in the 1920s; again about 90 years later. By 1929 the total length of railroads was more than 300,000 miles (480,000 km). Thus, railways saturated at almost ten times the level of canals. Since then rail infrastructure has undergone a phase of rationalization, and railways have experienced losses in market shares and volume, both for freight and passenger transport. In fact, railways have virtually disappeared from the US market in intercity passenger travel, and consequently the size of the railway network in the USA has decreased by about one-third, to some 200,000 miles (320,000 km).

The first high quality roads of significant length were introduced a century ago. Today, surfaced roads are approaching saturation with about 3.4 million miles (5.5 million km) in the USA, again larger by more than a factor of ten than the maximum length of railways. Each successive transport infrastructure was thus not only an order of magnitude larger than the one it replaced, but it also provided a service that was almost ten times faster.

Figure 2 shows the expansion of the three physical infrastructures in the USA, normalized with respect to their respective saturation levels (by plotting the relative length as a percentage of the saturation level). The succession of individual infrastructure development can be described in terms of three S-shaped growth pulses that are given together with the estimated logistic curves. The development of canals, relative to the achieved saturation level, was much quicker than the expansion of railways and roads. The time constant of growth, Δt, is about 30 years for canals, 55 years for railroads, and 64 years for surfaced roads.[2] The midpoint of the individual infrastructure growth pulses (i.e., the time period of their maximum growth rate) are spaced at 55-year intervals, as are their periods of saturation of expansion.

It is remarkable that the saturation and onset of decline of all three infrastructures coincides with the beginning of prolonged economic recessions (i.e., in the 1870s, 1930s, and 1980s). At the same time these periods of structural discontinuity see the emergence of new transport systems: surfaced roads around 1870 and air transport in the 1930s. If we agree with Plutarch that history repeat itself, then one could expect the emergence of a new transport infrastructure (maglevs?) around the turn of the millennium.

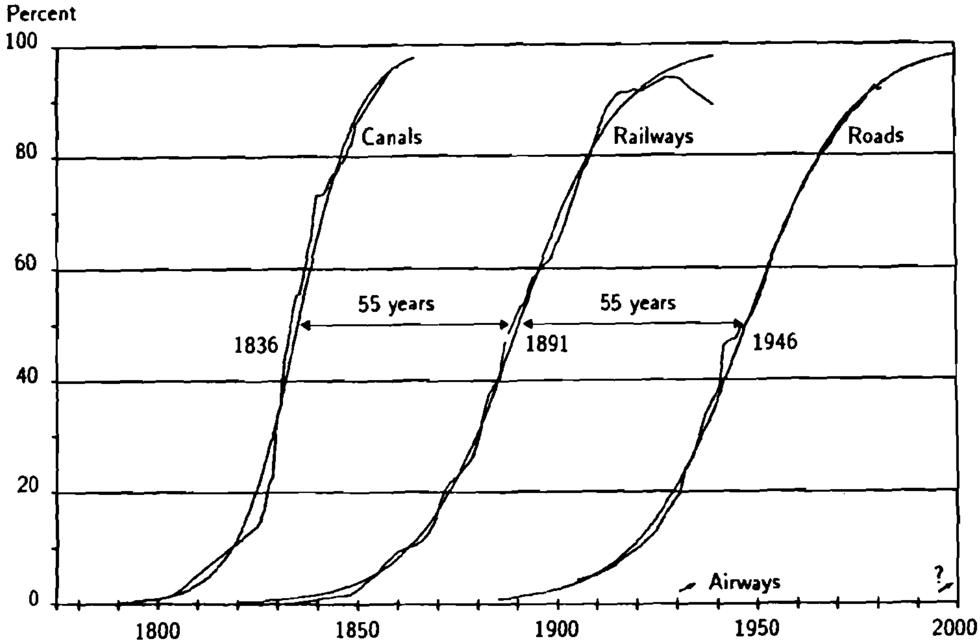


Figure 2. Growth to limits of canals, railroads, and roads in the USA. Source: Adapted from Nakićenović (1988).

In periods of structural discontinuity, where old mature systems saturate and new ones are born, "gales of creative destruction" (Schumpeter, 1942) prevail, to give a powerful image of the innovation triggering effects of recessions/depressions. The successive dichotomy of "boom" periods of economic growth, followed by recessionary, even depression periods is known as "long waves" in economic development.[3]

The life cycles between birth, growth, and saturation and the start of senescence (decline) of infrastructures are indeed very long, often spanning periods in the order of a century. The duration of senescence can be even longer. The most vital of the structures, however, are here to stay. Their immortality is marked by providing different services than originally envisaged. More than a century after the canal age, the remaining inland waterways are used for leisure activities, transport of low-value goods, and irrigation. There are also more sails today than in the heyday of ocean clippers, but they have entered a different market niche serving as pleasure boats and do not carry any commercial goods.

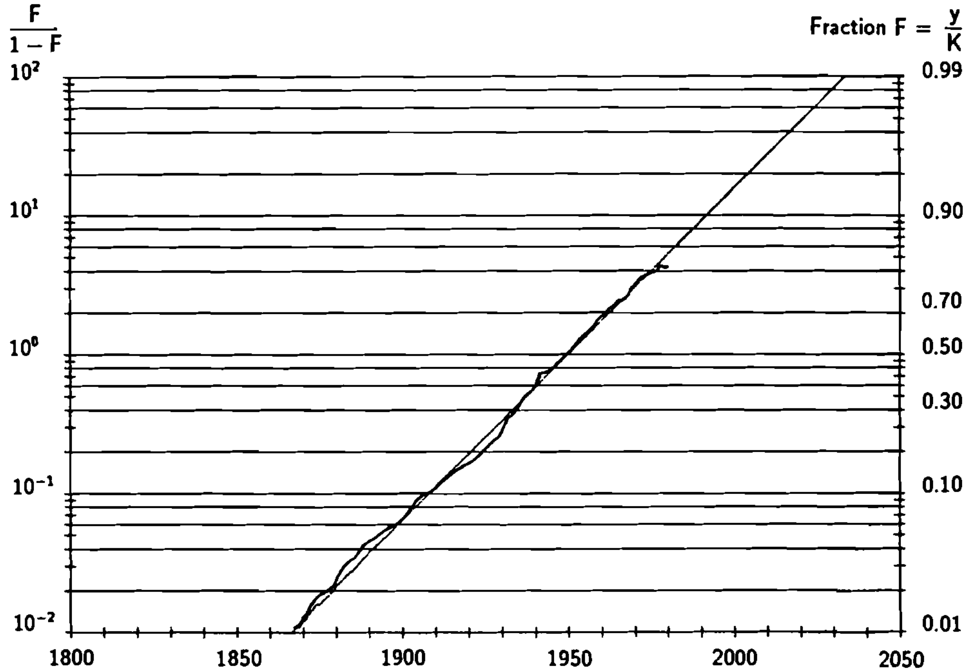


Figure 3. Growth in length of all transport infrastructures in the USA, in fractional share of ultimate saturation level (4.7 million miles or 7.6 million km), logit transformation. Source: Grübler (1990).

Despite the complex picture that emerges when analyzing the evolution of individual infrastructures which overlap in their growth, saturation, and decline phases, it is interesting to note that the length of the total transport infrastructure again proceeds along an ordered evolutionary growth envelope, as shown in *Figure 3*.

Here we analyze the growth in the length of all transport infrastructures by using an S-shaped growth model, in our case a logit model with a 3-parameter logistic function.[4] In this and in the following figures we present a linear transformation of the S-shaped growth or substitution process in the form of $f/(1-f)$ on a logarithmic scale, where f is the fractional growth (market share) achieved at any particular point in time. The ratio of growth (market share) achieved over the growth (market share) remaining to be achieved, when plotted on a logarithmic scale, reveals the logistic growth or substitution process as a secular linear trend with small annual perturbations.

Figure 3 presents an expanding niche in which individual transport infrastructures rival for relative positions with respect to their share in the length of all infrastructures (and as we will see below also in terms of their market shares in passenger- and ton-km transported). *Figure 3* portrays a remarkable homeostatic behavior in the evolution of transport infrastructures in the USA, in that the saturation and later decline of individual infrastructures (canals first and later also railways) has up to the present been "filled" by the growth of newer infrastructures consistent with the logistic envelope of *Figure 3*. This feature is frequently observed in the evolution of dynamic, self-organizing systems in chemistry or biology. The growth of this envelope proceeds with a Δt of 80 years, i.e., slower than the growth of any individual infrastructure (ranging from a Δt of 30 years for canals to 64 years for the surfaced road network). Should this process continue to unfold as it has in the past, saturation would occur around 2030 at a level of around 7.6 million km, i.e., with a value around 25 percent higher than at present. (We estimate a 90 percent probability that the saturation level will be between 6.6 and 8.3 million km.)

Within an expanding niche individual transport infrastructures compete for their relative importance (measured by their respective share in the total infrastructure network) by replacing previously dominant transport infrastructures. *Figure 4* presents the structural evolution of the transport infrastructure in the USA, organized with the help of a multivariate logistic substitution model.[5] This particular representation shows the relative importance of competing infrastructures and the dynamics of the structural evolution process over the last 160 years. In any given period, there is a clear market dominance (i.e., more than a 50 percent share) and at the same time a simultaneous spread of transport activities over two or three different systems. Thus, while competing infrastructures are all simultaneously used, their mix changes over time.

Another observation from *Figure 4* is that the phasing out of transport infrastructures apparently takes increasingly longer time constants. While the decline in the relative importance of canals proceeded with a Δt of 45 years, that of the railways already required a Δt of 80 years. The decline in the relative importance of road infrastructure is expected to be an even longer process with an estimated Δt of 130 years. As a result, the maxima in the share of total infrastructure length between railways and surfaced roads is about 100 years, indicating the considerable time span involved

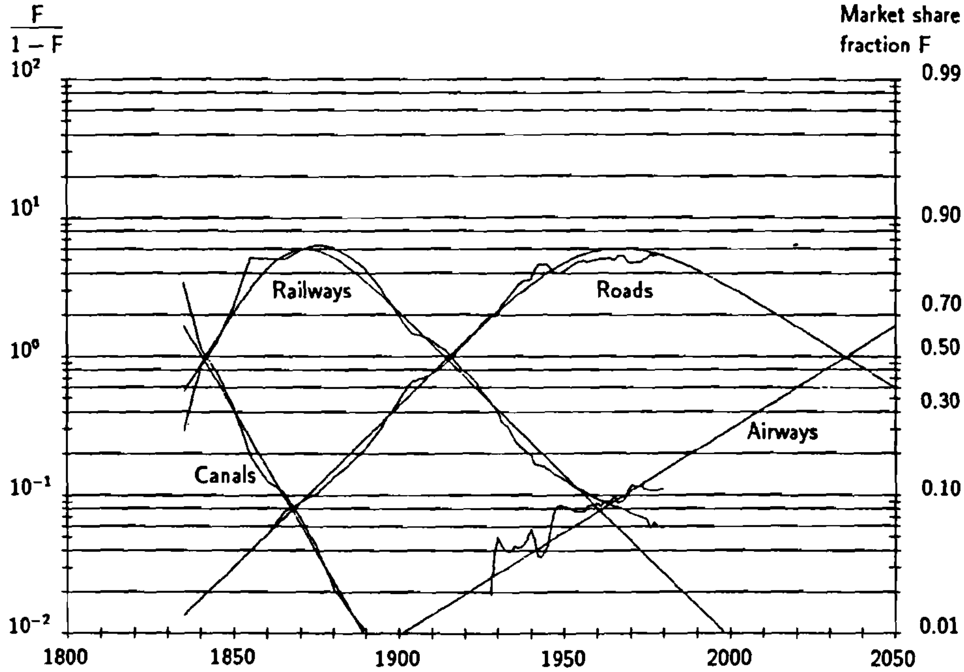


Figure 4. Substitution of transport infrastructures in the USA, shares in length, logit transformation. Source: Nakićenović (1988).

in the transition from the dominance of one infrastructure system to the next. Based on this assumption one could expect the period of maximum dominance for airways not to occur before the year 2050. This immediately raises the question of what could be the next dominant infrastructure system evolving after the year 2050; high-speed maglevs, supersonic aircraft, or some other competing new system?

The difference in the dynamics (Δts) of the growth of individual infrastructures and their relative shares in total infrastructure length may appear at first sight as a contradiction. However, this difference is the result of the complex coupled dynamics of total infrastructure growth, and the growth and decline rates of individual transport infrastructures. As the total length of infrastructures increases, even the rapid growth of individual infrastructures, such as airways, will translate only into slower growth rates in their *relative shares*. Once the growth rates of an individual transport infrastructure fall behind the growth of the total system, their relative share starts to decline. In the case of railways the share in total infrastructure length began to decrease in 1870, whereas the railway network continued to expand until the end of the 1920s. Similarly, the length of the surfaced road network still continues to increase (despite being close to apparent saturation at relatively low rates) although its relative share started to decrease in the 1960s.

Thus, the total length of an individual infrastructure can still be growing, and even be decades away from ultimate saturation and subsequent senescence in absolute network size, but its share in the total length of the whole transport system has already begun to decline. The saturation and decline in relative market shares precedes saturation in *absolute* growth in a growing market (an expanding niche). This implies that the eventual saturation of any competing technology may be anticipated by the substitution dynamics in a growing market, such as for railways as early as 1870 and for roads as of 1960. The infrastructure substitution model presented in *Figure 4*, may, therefore, be considered as an *precursor indicator model*, for the long-term evolution and fate of individual infrastructures.

We conclude this discussion on the long-term evolution of transport infrastructures in the USA by pointing out the regularity in the rise and fall of the importance of individual transport infrastructures. This regularity appears consistent even during very disruptive events like the depression of the 1930s or the effects of major wars. We conjecture that this stable behavior may be the result of an invariant pattern in societal preferences with respect to individual transport infrastructures, resulting from differences in the performance levels (seen as a complex vector rather than represented by a single measure) inherent to different transport infrastructures and technologies.

Figure 5 reports an analysis of the changing structure of transport infrastructures in Canada, using as an alternative measure the embodied capital stock.[6] The basic pattern of the sequence of replacements identified for the USA is confirmed by this analysis, although the relative importance of air infrastructure in the capital stock is, due to its "immaterial" nature, smaller than when considering its respective length or share in output of the transport sector. It is even more important to realize the very long time constants involved in the structural transition in the composition of the transport sector capital stock: the Δts for the decline of railways and growth of road infrastructure are in the order of 80 years, and the decline of canals and growth of air infrastructure even slower with Δts of nearly 200 years. Transport structures are built to last, they are almost immortal. Once their original use declines because of changing societal preferences and requirements, new applications may evolve, e.g., the Rideau Canal in Canada

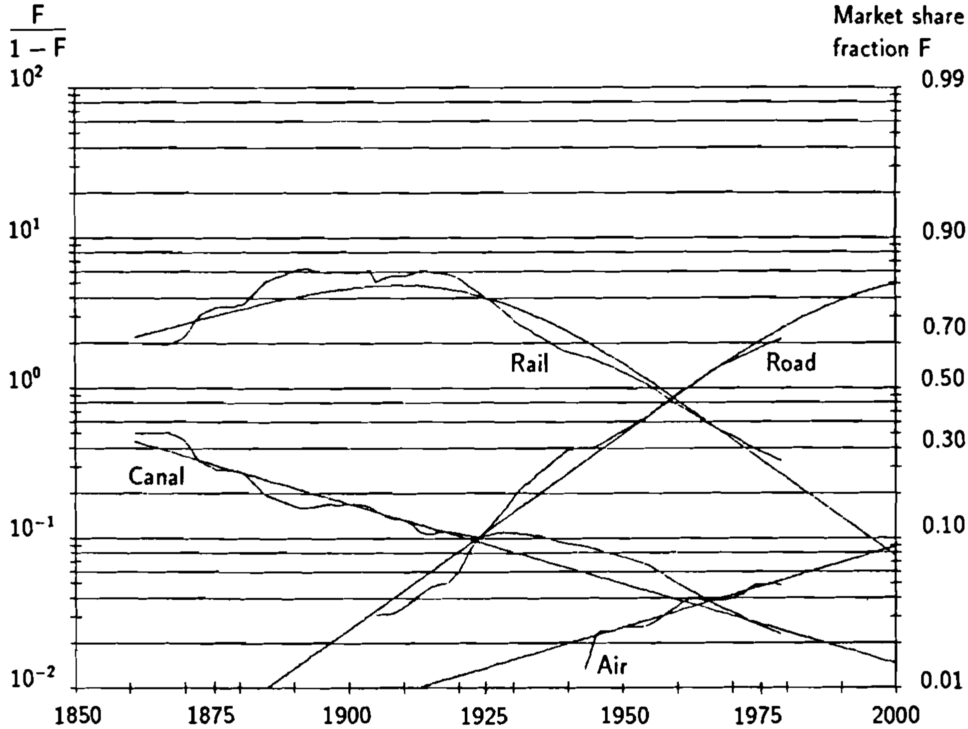


Figure 5. Share of canals, railways, roads, and air transport infrastructures in the quasi capital stock of the transport system in Canada, logit transformation.

has been converted into a leisure center and the former Gare d'Orsay in Paris, an impressive monument of the railway era, was converted into a museum and opened in the late 1980s.

Figure 6 reports the substitution of transport infrastructures in the Soviet Union and Tzarist Russia before the revolution. The pattern of temporal changes is marked by a high degree of regularity and quest for higher speed and productivity. The dynamics of the substitution process are characterized by similar time constants. The range of Δts is all in the vicinity of 100 years. Despite the similarity in the structural evolution between the USA and USSR, one should note that the timing of the phase transitions are lagged by a few decades, as illustrated in *Figure 7*. The decline of canals occurred much later and at a much slower pace in the USSR due to an extensive canal construction program after the October Revolution.[7] As a

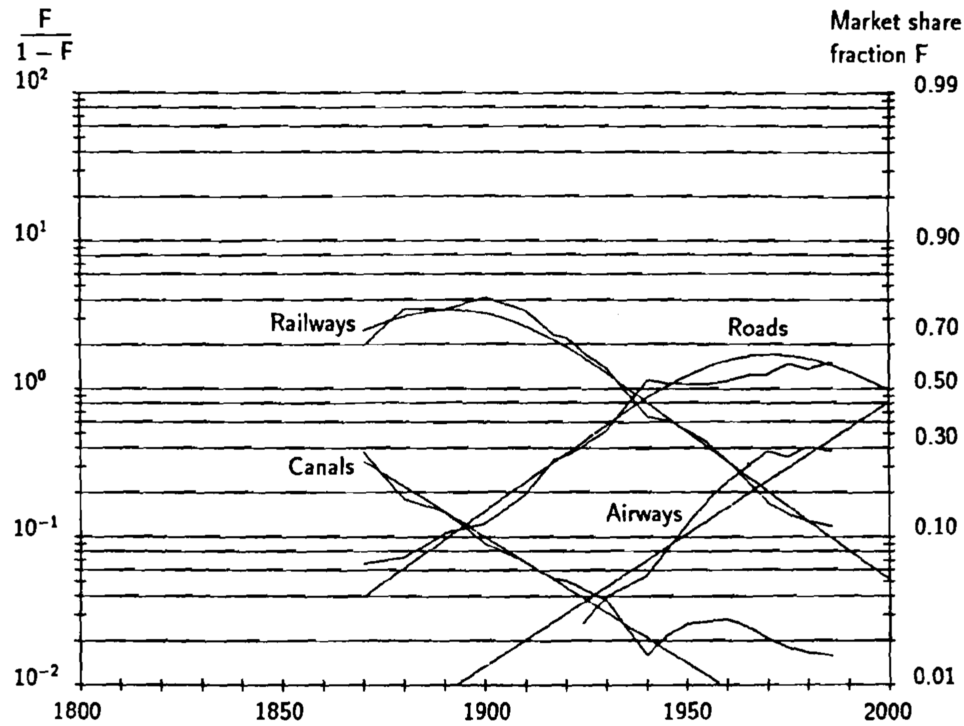


Figure 6. Substitution of transport infrastructures in the USSR, shares in length, logit transformation. Source: Grübler (1990).

function of planning, canals have enjoyed a period of revival over the last decades, hovering around the two percent market share.

During the last decades, the development of the transport infrastructure in the two countries has been converging. For example, the dominance of railways in the USSR lasted until the 1940s while in the USA it ended two decades earlier. The speed of phase out, however, is strikingly similar. Also the speed of growth in the importance of road infrastructure and its apparent saturation appears to be synchronized between the two countries. The growth of national airways in the USSR follows a similar path to that of the USA, and appears even to proceed somewhat faster. For the year 2000 and thereafter we may summarize the situation in both countries as follows: canals will be almost extinct (in terms of relative importance), and railways will account for only a few percent of the infrastructure length. The most

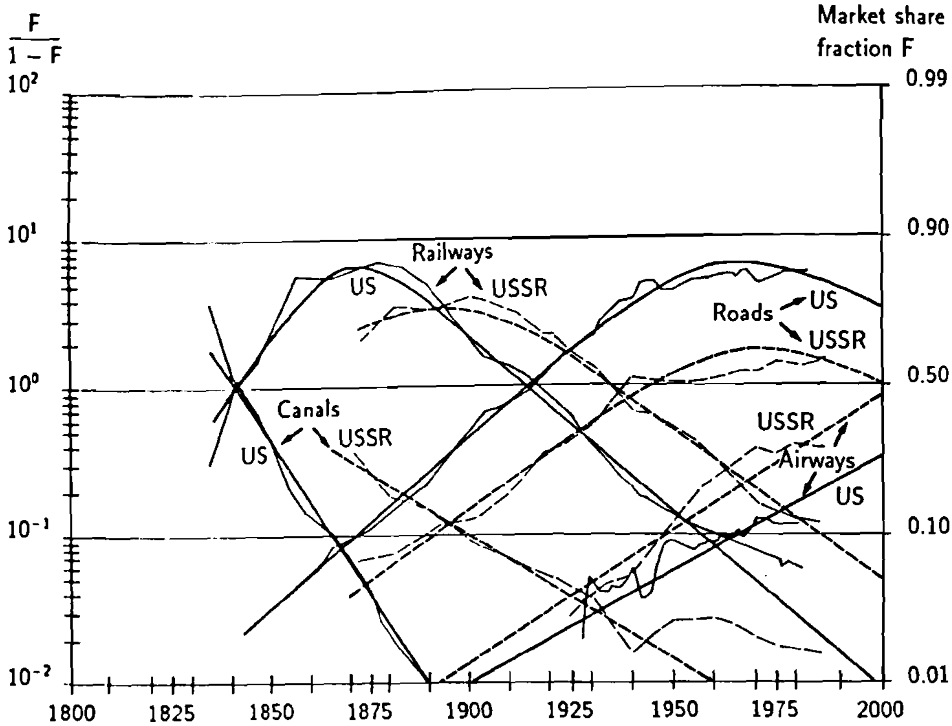


Figure 7. Infrastructure substitution in the USA and the USSR, shares in length, logit transformation.

important transport infrastructures in both countries will be roads with a decreasing share and airways with an increasing share.

We maintain, therefore, that the similar structural and functional evolution in the transport infrastructures of the two countries has deeper causality roots. These can be seen in the differences in performance levels of individual infrastructures, in particular transport speed and basic human decision criteria due to private and commercial user preference for more time-efficient and faster transport modes. To a large extent the similarity is 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.

3. Use of Transport Infrastructures (Modal Split)

In the previous examples we discussed the structural change in the transport infrastructure using the length of different infrastructures as a crude measure. Another way to assess the importance of individual transport systems is to consider their performance in terms of their share in the total output of the transport system, measured in passenger- and ton-km transported. Using this measure, the intensity of use for different transport infrastructures is more clearly reflected.

3.1 Passenger transport

In the following examples we will analyze the evolution of the long-distance passenger modal split, i.e., passenger-km transported by different transport modes. Long-distance passenger transport is a good indicator in that it constitutes the transport niche in which there is a higher premium for speed and quality of service. As such it also gives an anticipative picture of what could occur in lower-value market segments, such as goods transport.

Figure 8 presents the evolution of the domestic intercity passenger traffic in billion passenger-miles for the USA. The decline in the transport output of railways,[8] the stagnation of bus transport, the continuing growth in car transport, and finally the rapid, exponential growth of passenger air transport, characterize the situation of this premium market. The model forecasts presented in *Figure 8* are derived from the relative market share estimates of different transport modes (*Figure 9*) applied to (exponential growth) estimates of total market volume. Total intercity passenger traffic increased in the USA from 506 billion passenger-miles in 1950 to close to 1,820 billion passenger-miles in 1986, i.e., at an average annual growth rate of 3.6 percent. Despite the simplicity of our model, the fit to nearly 40 years of empirical data is noteworthy. If we extend the model projections into the future, air transport would reach parity in intercity passenger traffic with automobile transportation around the year 2010.

The positive or negative trends in the relative market shares of different intercity transport modes in the USA since 1950 underlie our estimate of intercity transport volume by mode. *Figure 9* shows a regular competitive pattern in the market shares of four different transport modes for long-distance passenger travel: private cars, public buses, railways, and aircraft.[9] The

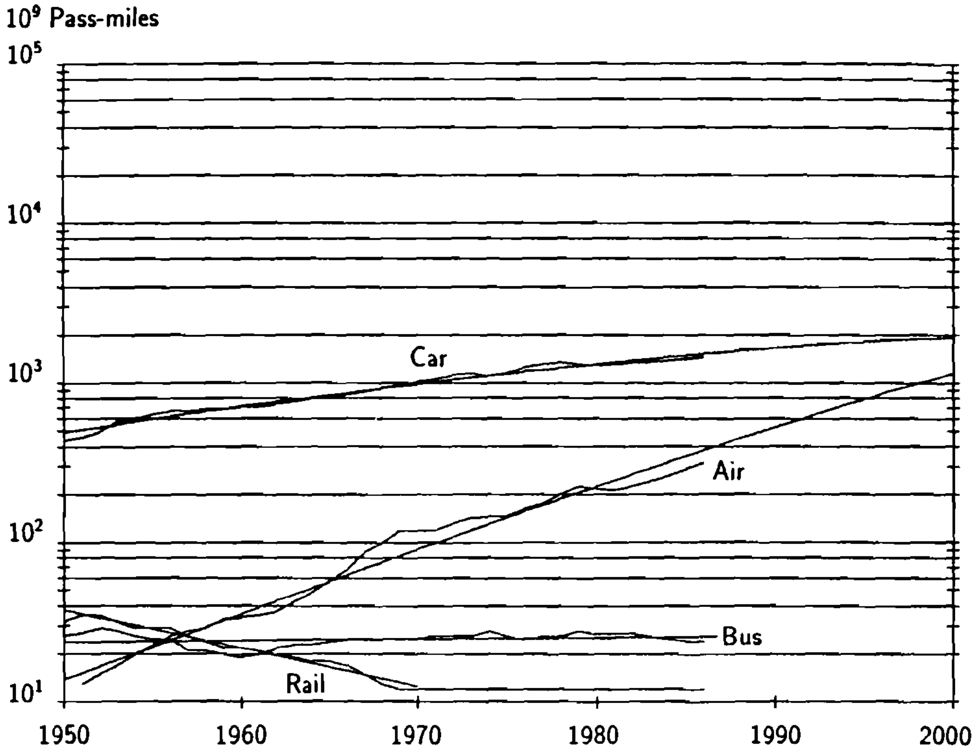


Figure 8. Volume of intercity passenger traffic by transport mode in the USA, in 10^9 passenger-miles (logarithmic scale). Source: Adapted from Nakićenović (1988).

analysis shows railways at the end of their technological life cycle for long-distance passenger transport in the USA. Since about 1970 railways transport less than one percent of the total passenger-miles of intercity traffic. The situation in the USA precedes similar tendencies in other countries by several decades. Bus transport appears to closely follow the long-term decline trend and, based on the model forecast, should fall below the one percent market share level by the mid-1990s.

The share of private cars reached its maximum market share in the early 1960s, when close to 90 percent of all intercity passenger-miles were performed by automobiles. It is perhaps ironic, but not incidental, that at the moment their decline in relative market shares began, due to growing air traffic, cars exhibited the secondary design characteristics of aircraft. This

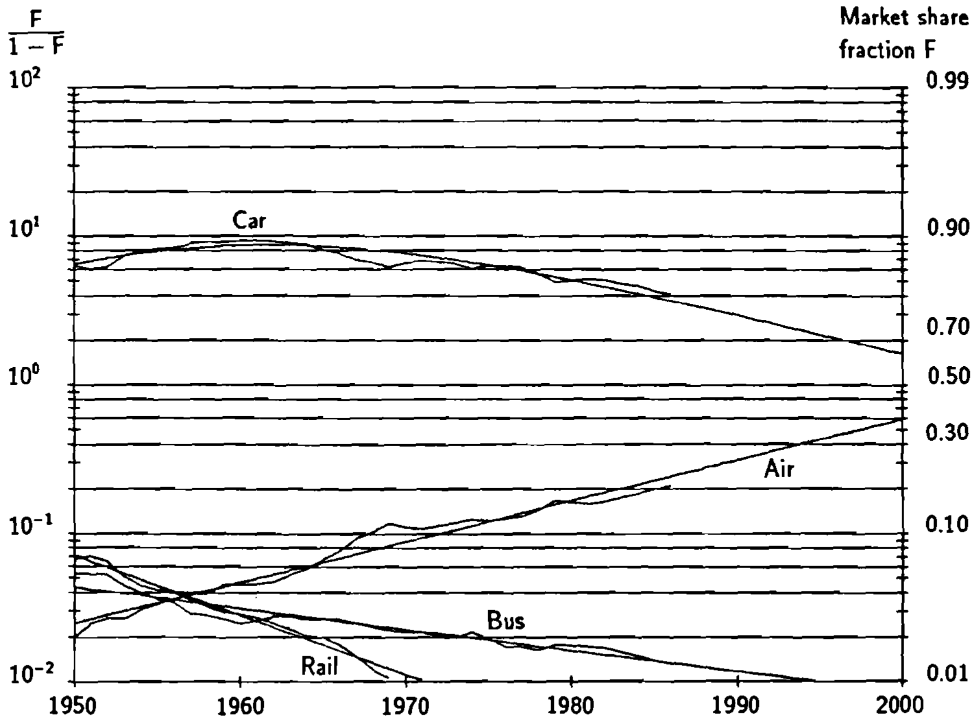


Figure 9. Modal split in intercity passenger traffic in the USA, in fractional share of passenger-miles performed, logit transformation. Source: Updated (US DOC, 1987) from Nakićenović (1986).

is illustrated by such models as the 1951 Buick LeSabre or the 1959 Cadillac Cyclone; perhaps a formalistic mimicry of the forthcoming competitive "drama."

The share of air transport in total long-distance passenger travel increases with a Δt of around 70 years (symmetrical to the decrease in the market shares of cars). Air travel presently accounts for around 18 percent of intercity traffic and, if the long-term growth tendency should continue, will become the preferred mode of long-distance passenger travel in the USA after the year 2010.

The principal driving force behind this structural change in the preferred mode of long-distance travel appears primarily related to the differences in performance levels of individual transport modes, particularly travel speed, and not so much to the relative transport cost structure. Since 1950 to the

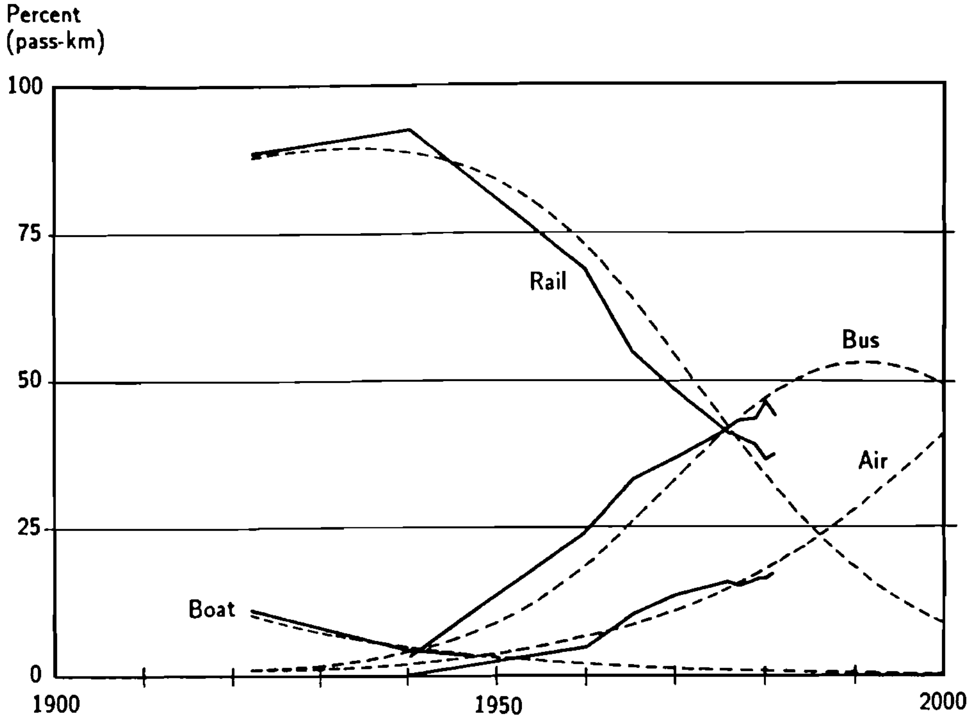


Figure 10. Modal split in intercity passenger traffic in the USSR, in fractional share of passenger-km performed. Source: Grübler (1990).

present, the average operating costs, including fuel, for private cars ranged between 10 and 13 US cents (base year 1967) per mile. Assuming on average two passengers per long-distance car travel, this results in an average cost of between 5 and 7 cents (1967) per passenger-mile. Air transport only reached such low costs by the mid-1970s, significantly after the market share of cars started to decline. Further, during the whole period under consideration, railway transport costs were consistently significantly lower, at below 4 cents (1967) per passenger-mile. We conclude, therefore, that it is not primarily economic variables that appear to influence long-distance modal split decisions.

The analysis of the long-term evolution of the modal split in intercity passenger traffic for the USSR is reported in *Figure 10*. Despite some structural differences a similar dynamic development pattern to that of the USA can be

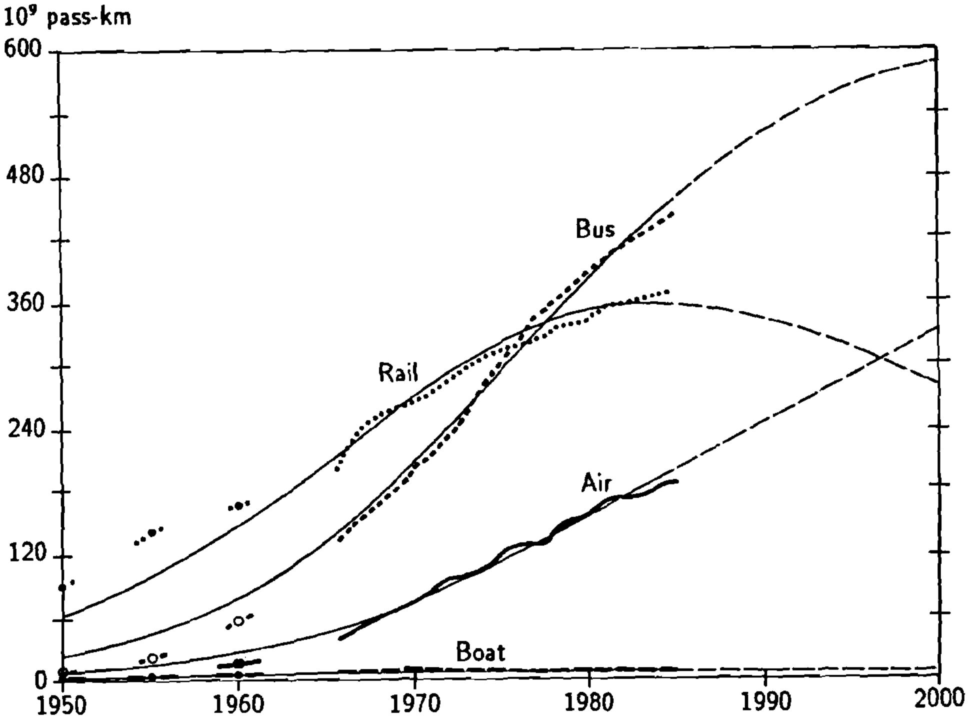


Figure 11. Intercity passenger-km by mode in the USSR, in 10^9 passenger-km and model estimates.

seen. Traditional, slow transport modes lose out logistically to new competitors such as road and air transport. Note, however, that road transport is not by private cars but by public buses instead. Inland water passenger transport has virtually disappeared as a long-distance transport mode, railways have been declining since the 1930s, and road transport is currently entering saturation and may become replaced in the long term by air transport.

Based on the relative market share model estimates and a scenario of total intercity passenger-km demand growth[10] *Figure 11* shows model estimates of the passenger-km performance of different transport modes in the USSR, together with historical data.

To illustrate the differences as well as the convergence in the two countries, *Figure 12* compares the historical development in the two countries in the logit transform. Whereas inland navigation for long-distance passenger transport in the USSR disappeared only in the mid-1970s, showing a

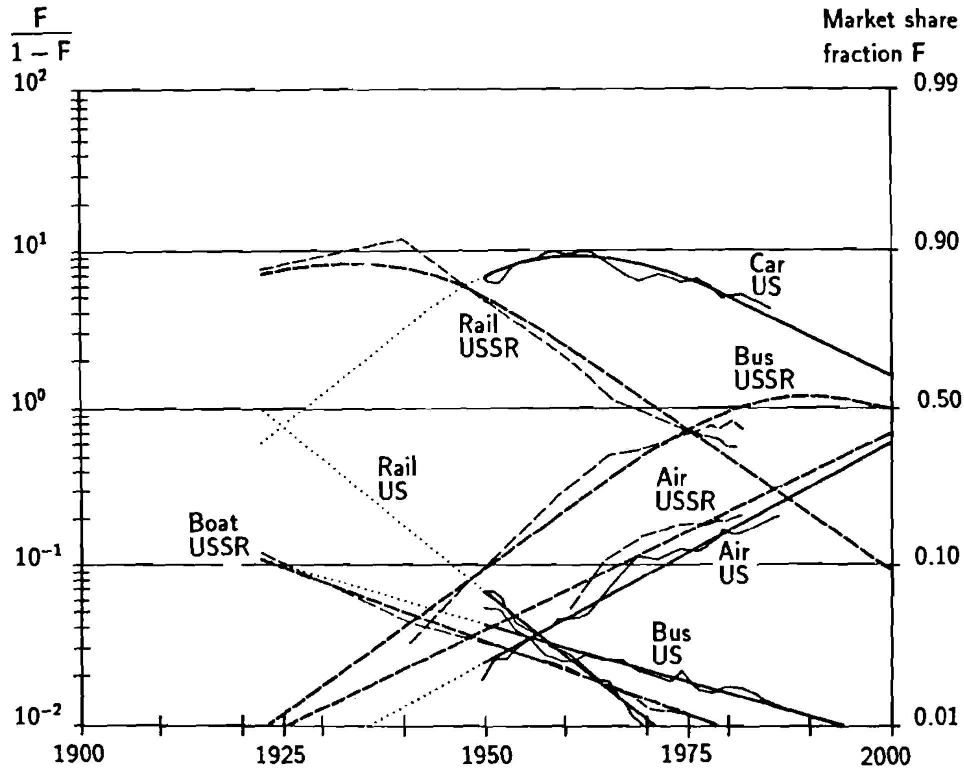


Figure 12. Modal split in intercity passenger traffic in the USA and the USSR, in fractional share of passenger-km performed, logit transformation.

similar dynamics in its displacement as public bus transport in the USA, a distinct difference exists in the relative role of rail transport in the two countries. Railways still presently account for some 37 percent of all intercity passenger-km in the USSR, whereas in the USA they have fallen below the one percent market share. Be that as it may, their displacement process, while lagged by some 50 years (t_0 1972 compared to 1921 in case of the USA) appears to proceed at a similar rate (Δt of 55 years compared to 48 years in the USA). Saturation in the market share of road transport (buses) in the USSR appears to occur somewhere in the 1990s, i.e., some 30 years after the saturation of the market share of cars in the USA.

The most striking similarity, however, occurs in the area of air transport. Air transport in the USSR presently accounts for some 18.5 percent of all intercity passenger-km, compared to 17.6 percent in the case of the USA.

The dynamics of market share gains of air transport in both countries is very close: t_0 is estimated to occur in 2006 in the USSR with a Δt of 77 years, and in the USA in 2008 with a Δt of some 70 years.

As reflected by their similar rates of change, this points to the very similar structure in the *comparative advantages* of the transport modes in the long-distance passenger modal split between the two countries. This is consistent whether one considers the negative comparative advantage, such as the decline in importance of railways, or the positive comparative advantage, as in the case of growing air transport. This similarity in the dynamics of structural change in the modal split is important especially considering the differences between a market and centrally planned economy, and additionally with respect to the transport policies pursued in the two countries: promotion and further railway construction in the USSR compared to decreasing network size and disappearance in the USA; road transport by public buses as opposed to private car ownership; monopoly of the largest airline company in the world AEROFLOT versus vicious competition between private airlines in the USA, etc.

We believe, therefore, that the inherent advantages of air transport in altering the human space-time activity framework, i.e., the increased travel range resulting from higher technological performance, in particular speed, is responsible for the market share gains of air transport in intercity passenger transport. As shown above for the USSR and the USA, this comparative advantage, resulting from fundamental human time allocation mechanisms, influences the individual time budgets and consequent long-distance transport mode preferences of people, regardless of economic differences.

A hierarchy of space and time territories emerges. As has been convincingly demonstrated in the work of Zahavi (1979 and 1981) and confirmed by the international time allocation survey coordinated by Szalai (1972), the average time devoted to traveling by an individual appears to be close to an anthropological constant: it ranges from 1 to 1.5 hours per day, both in rural-agricultural and in urban-industrial societies. A man walking or using waterways could cover a mean circle of a few kilometers diameter in one hour – the size of a village and its hinterland, or of imperial Rome at the time of Emperor Augustus. A person traveling by rail or horse could travel more than a dozen kilometers in the same period a hundred years ago. The automobile and rapid rail systems offer a larger range of up to 100 km, and can effectively connect cities, while air travel extends the radius to almost 1,000 km. As connected territory increases, so does travel, tangible goods transport, and information flow per unit of time. This explains the basically exponential growth path in the output of the transport system both for passengers and goods since the onset of the Industrial Revolution.

Consequently, beyond the year 2000 we foresee a similar structure for both countries: railways will have disappeared (in the USA) or account for only a few percent of passenger-km traveled (USSR); private (USA) or collective (USSR) road and air transport will become the dominant long-distance transport modes with approximately equal shares. If unchallenged by the appearance of a fundamentally new, high-speed, long-distance transport mode, the importance of air transport is expected to increase further at the expense of road transport. However, in view of the long lead times required for the introduction and growth of new transport technologies, it appears very unlikely that significant market impacts of such a system could be expected before the first decades of the next millennium.

The dynamics of the intercity passenger modal split in the USA and USSR analyzed above covered the periods from 1950 and 1920, respectively. We now extend our analysis even further back by analyzing the case of France since the beginning of the 19th century (*Figure 13*). Although there remain some inherent weaknesses in the data base we were able to trace in historical archives, e.g., it was not possible to distinguish between local (short-distance) and long-distance (intercity) passenger traffic, the picture emerging reveals interesting insights both in its phases of regular structural evolution as well as in its distinct nonlinearities and discontinuities as a result of external shocks to the system.

Before the advent of the railways the dominant modes of passenger transport in France were horse carriages and coaches, and barges on inland waterways. The improved travel speed and comfort offered by railways resulted in the displacement in terms of market share of the two previously dominant modes of passenger travel, despite efforts at improvement, e.g., the introduction of steam power on inland navigation. Inland waterways disappeared as a passenger transport mode by the 1850s, and although the market share of horse transport declined at a slower rate, it finally disappeared with the advent of the automobile around the turn of the century.

The growth of the market share of road transport depicted in *Figure 13* started around 1880, i.e., significantly before the introduction of large numbers of automobiles. This points to another frequent feature in the introduction of new transport systems: the preparation of the ground by early, precursor technologies. In the case of road transport these pre-automobile-age technologies were the bicycle and later the motorcycle.[11]

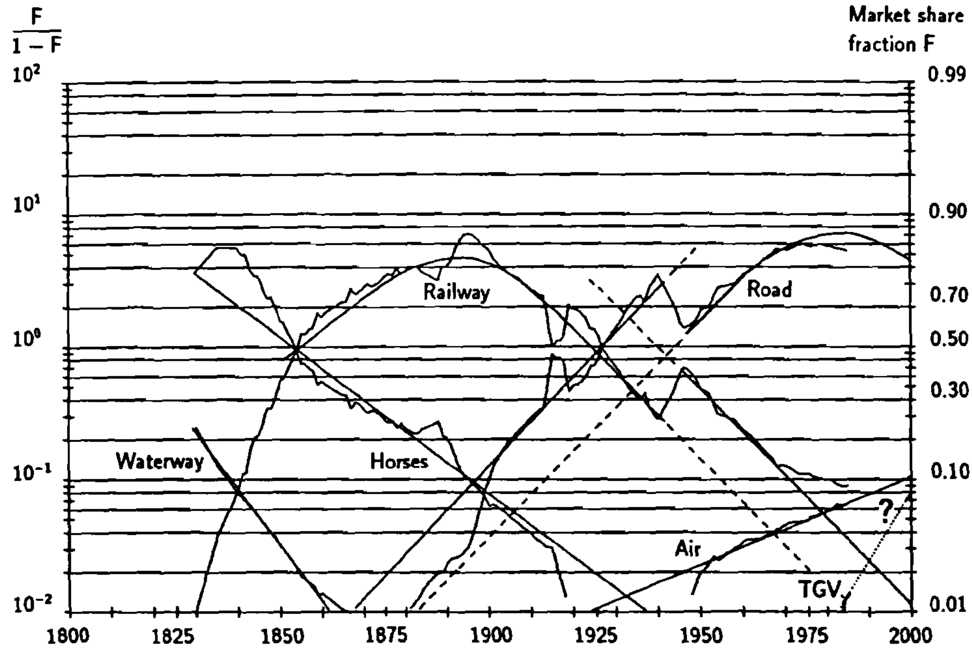


Figure 13. Model split in passenger (intra- and intercity) transport in France, in fractional share of passenger-km performed, logit transformation. Source: Grübler (1990).

Once motorcycles and later automobiles appeared in significant numbers to expand the competitive niche opened by the bicycle, road transport started to replace railways along a logistic substitution pattern, proceeding with a Δt of around 60 years. The turbulence in this substitution trajectory due to World War I was elastically absorbed and the process proceeds regularly up to 1939. Much more dramatic was the effect of World War II and the occupation by German troops of a large part of France. As *Figure 13* shows, World War II represented a major political, social, and technological discontinuity in the long-term development pattern of France. In fact, the disruption appears (contrary to World War I) so strong as to result in a major structural discontinuity and break in the long-term trend. During the war years the historical diffusion pattern of motorized road transport was reversed. Much more important, however, is that after the war the prewar diffusion level is attained in only about 15 years. As a result of this major discontinuity no continuous technological substitution model application is possible.

Another interesting fact also emerges from *Figure 13*: the *diffusion rates* (i.e., the slope of the substitution trajectories) did not change due to this discontinuity. Thus, after some 15 years the system reassumed its previous diffusion pattern after reaching the prewar level again. According to diffusion theory this is an indication that the relative comparative advantages (defining the speed of diffusion, i.e., Δt) between different transport modes was *not* affected by the discontinuity. The comparative advantage of road transport as represented in its Δt of around 60 years remained the same in both time periods, i.e., between 1900 and 1939 and after World War II; the substitution process is simply shifted by 15 years.

Railways continued their declining market share trajectory in symmetry with the growth of road transport. Since 1970 their decline rate has, however, slowed down, indicating that they are apparently phasing out more slowly from their last remaining (below ten percent) market share largely consisting of commuting and subsidized transport (e.g., for school children, military personnel, etc.). After its period of spectacular growth and market dominance of more than 80 percent of all passenger-km transported, road transport now appears to be saturating due to the growth of newer competitors such as air transport. The slower growth rates in air travel in France, compared to the situation in the USA or the USSR, is a direct consequence of the shorter distances traveled and of the resulting smaller comparative advantage (in terms of reduced travel time) compared to other transport modes.

In order to illustrate the possible emergence of new transport systems and its likely impact on the passenger modal split, we have plotted the market share of the TGV (*train à grande vitesse*) trains separately in *Figure 13*. The expansion and success of the TGV connections in France, in part via the construction of its own dedicated infrastructure lines and in part using the existing, traditional railway network, has frequently been seen as an indication of a *railway renaissance* in Europe. The TGV provides an interesting example of a combination of a new infrastructure network with a traditional technological base. In the past, successful new transport systems have been characterized by a combination of a new infrastructure *and* a new technological base, like railways with steam powered locomotives or surfaced roads with internal combustion engine automobiles. From such a perspective, we consider the TGV as a transitional system. Like many early pioneering systems, it combines elements of traditional and new infrastructures. As such, it is functionally more close to the *hybrids* of the early railway age, such as the *horse* railway between Linz and Budweis (the first railway line constructed in 1832 in Europe (excluding the UK), than a model for the ultimate high-speed, long-distance transit systems of the next millennium.

Despite its high visibility and success on certain routes (e.g., Paris–Lyon) the market impact of the TGV is still relatively minor with only slightly more than one percent of the total passenger-km in France. In the absence of an adequate historical data base to calculate a future scenario, we assume an entirely speculative growth trajectory for the TGV in *Figure 13* to illustrate the impact on the passenger modal split in France. If history is a guide, one might expect a continuation of the rapid diffusion up to a level of a few percent of the market share and then a transition to a slower substitution trajectory, consistent with observed historical market penetration rates. Even in our speculative high growth scenario, the dominance of the automobile in passenger transportation in France would not be affected noticeably before the turn of the century. The basic message from our discussion on France is that the competitive interaction between different transport technologies rivaling for market shares appears to be influenced in the long run only by the introduction of new, more productive modes of transportation.

The appearance of such systems for merging large urban corridors to single functional entities, along the lines of the Japanese Shinkansen, would be timely, especially in conjunction with the possible emergence of new high-speed air transportation with supersonic flight regimes. This could result in a new hierarchy of complementary high-speed infrastructures: advanced aircraft connecting the largest urban centers of the world in as little as two hours. Their hubs would be fed by high-speed maglevs and/or regional aircraft, which would also connect urban agglomerations on a regional, e.g., European or continental USA, scale. Finally road transportation (not necessarily based only on private vehicles but, for instance, on new organizational forms such as wider use of rented cars) and metros would provide spatial coverage at the last hierarchical level of the transport chain: final distribution in rural areas, agglomerations, and urban centers.

In France, the increase in the passenger transport volume has proceeded at a faster pace than the growth of GNP measured in constant money terms. As shown in *Figure 14* the passenger transport intensity has grown by over a factor of 53 since 1800, i.e., from 0.04 to 2.2 passenger-km per unit of GDP (in constant 1913 Francs), which corresponds to an average annual growth rate of 2.2 percent. For goods transport intensity this factor is lower: it increased between 1800 and 1985 from 0.2 to 0.8 ton-km per 1913 Francs

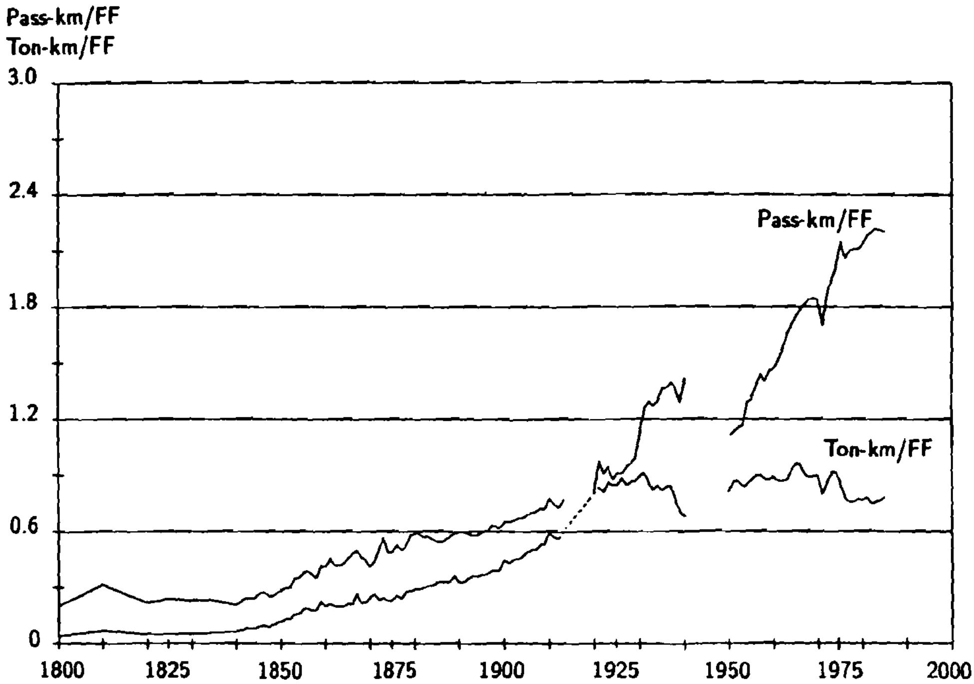


Figure 14. Total passenger- and ton-km per constant GDP in France since 1800, in passenger- and ton-km per unit of GDP (in constant 1913 Francs). Source: Grübler (1990).

GDP, i.e., by a factor of four or at an average annual growth rate of 0.75 percent.[12] Considering that moving people represents the highest value premium market segment of the transport sector, the much higher historical growth rates of the passenger transport intensity should not come as a surprise.

The passenger and ton-km growth in relation to GDP growth discussed above may also be analyzed in terms of the commonly used indicator of elasticity, i.e., the relationship of transport output growth to economic growth as shown in *Figure 15*. A first observation from *Figure 15* is that over most of the time period under consideration elasticity is significantly above one. Second, it shows typical fluctuations as a result of medium-term business cycles (in *Figure 15* the very strong annual fluctuations in elasticity are smoothed out by a 3-year moving average). It is noteworthy that up to the 1970s, elasticity for passenger and goods transport with respect to GDP growth

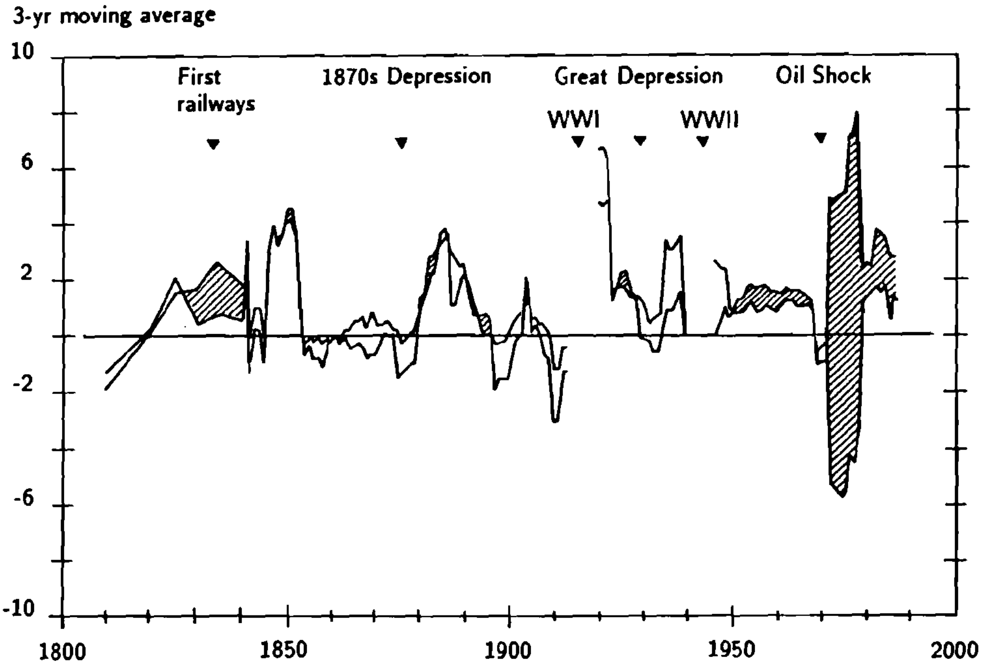


Figure 15. Total passenger- and ton-km to constant GDP growth elasticity in France. Source: Grübler (1990).

did not bifurcate, i.e., while being different in various historical phases, both showed a synchronous behavior and moved in the same positive or negative direction.[13]

Since the early 1970s however, we observe a complete bifurcation. Goods transport growth appears to progressively decouple from economic growth as shown by the negative elasticities over an extended period of time. In contrast, passenger transport elasticities have been positive. Whereas this may be a specific case for France (a similar analysis for the FRG showed no strong divergence), it is nevertheless an indicator that in future the transport demand for passenger and high-value goods may portray a different behavior to that of low-value products.

At present, it is not clear whether the trend observed in France is also representative for other countries, especially from a long-term perspective. Still, it appears likely that with increasingly affluent societies passenger transport demand will continue to grow in the future. In the goods transport sector, increasing affluence means an increase in the value and information (software) content, and a decrease in the material and energy input per unit value added of the goods produced and consumed. This implies that a further decoupling of ton-km transport volume from economic growth might be expected in the longer term. This decoupling of course does not mean that the total ton-km transported will decrease, rather that its growth rate will fall behind that of GNP growth, as much of the economic growth will be based on the service sector with many "immaterial" (information and value-intensive) kinds of products.

If one of the predominant features of a next step in economic development is the widespread application of new information and communication technologies, the question arises of how this would affect passenger traffic. It has often been claimed that it is precisely the widespread diffusion of new information and communication technologies that could result in a significant reduction of personal travel: that new communication technologies will eventually be a substitute for traveling.

In order to examine the long-term relationship between passenger transport and communication, we compare the total output of the two systems in France over a long period in time. This should allow for an analysis of whether the introduction of different new transport and communication systems has caused any change in their relationship. *Figure 16* reports the evolution of total passenger-km transported and total output of the communication sector (total number of messages sent, i.e., letters, telegrams, telexes, telefaxes, and telephone calls) since the beginning of the 19th century.

The two measures are not directly comparable but are normalized by using an index of 100 for their 1985 output levels. Both transport and communication have increased over four orders of magnitude since the beginning of the 19th century. The impact of both world wars, in particular World War II is clearly visible in *Figure 16*. Also visible is the fact that from a long-term perspective transport and communication have evolved in unison. This points to a complementary, synergistic type of relationship rather than to substitutability.

However, transport and communication have not always grown at exactly the same rate initially because of the introduction of railways and later automobiles. Passenger transport grew faster than communication over a period of several decades; in the long term, however, the two have always reestablished parity. This long-term parity rate appears to be in the vicinity of around six passenger-km traveled per message transmitted. As shown in

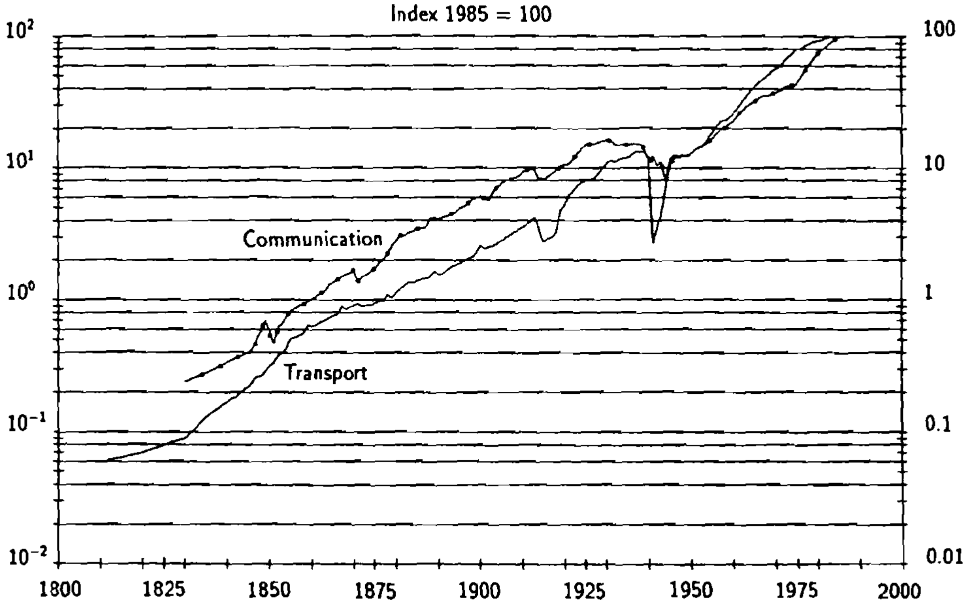


Figure 16. Growth of passenger transport and communication in France, measured in total passenger-km transported and total number of messages transmitted, index 1985=100. Source: Grübler (1990).

Figure 17, this is not only true for France but also Germany (FRG after 1945) and the UK.

The ratio presented in *Figure 17* reflects the relative increases in communication through actual physical travel (i.e., face-to-face communication) compared to communication through information channels. From *Figure 17* it becomes apparent that this ratio started increasing in 1830, peaked around the 1860s (due to the growth of railways) and remained more or less constant between 1880 and 1920. As a result of the diffusion of the automobile, this ratio increased substantially from 1920 until the 1970s, when a trend reversal occurred.

Presently, communication via information channels is increasing more rapidly than passenger travel. Advanced electronic systems, as well as the emerging photonic technologies, will increase the relative information capacity of transmission channels by a few orders of magnitude. New communication services are rapidly expanding, such as the use of facsimile integrated into personal computers or mobile telephones. New and more productive

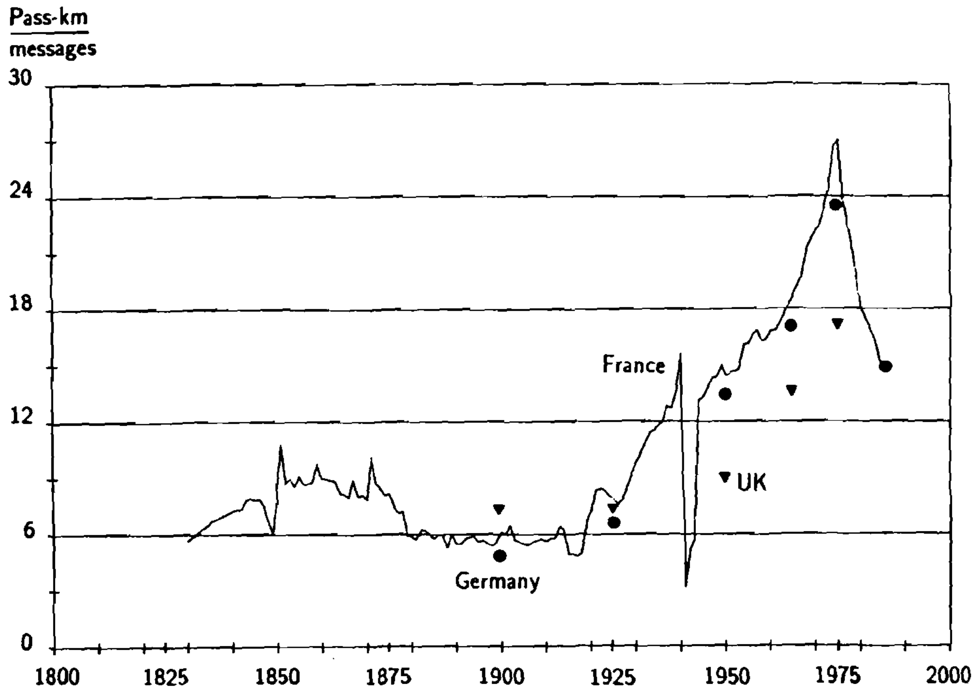


Figure 17. Ratio of passenger travel to messages sent in France, Germany (FRG after 1945), and the UK. Source: Nakićenović (1989).

communication technologies may indeed substitute a number of business or commuting trips. At the same time, new communication technologies may in turn also *induce* additional travel, e.g., a reduction in travel for business and daily errands could lead to more time being devoted to leisure and holiday trips. This kind of conservation principle of the travel time budget counterbalancing business travel reductions owing to new communication technologies is observed, for instance, in the case of the FRG (Cerwenka, 1986).

From this standpoint, one might conclude that whatever growth potential becomes realized, as a result of new communication technologies, it may just be sufficient to bring the ratio of face-to-face to information channel communication back to long-term parity. Thus, while the growth of transport and communication was not totally in unison, they do enhance each other and show many parallel developments. Consequently, new communication technologies may be seen as *catch-up* instruments in the long-term complementary and synergistic relationship between transport and communication, a hypothesis at least consistent with 200 years of history.

3.2 Goods Transport

Time is a valuable resource. With the possibility of a constant travel time allocation, the demand for faster passenger transport modes (and thus travel range) tends to increase (subject to money constraints). We have shown above that the long-term structural evolution of the transport infrastructure and of the passenger modal split have and continue to favor faster transport modes for passenger travel. The situation with respect to the driving forces behind the modal split for goods is, to some extent, different. Here we deal with a nonhomogeneous product mix between bulk, low-value density (value per unit weight or volume) to very high-value density products. As the value density of a product increases, the more stringent are the requirements imposed on the transport system. Long transport times require larger inventories and tie up corresponding working capital. Risk of loss and damage tends to increase with exposure time so that more valuable goods are transported by faster transport modes and require a higher quality service and usually smaller shipment sizes.

Figure 18 illustrates the development of the modal split for the transport of domestic goods in the FRG. The share of waterways and of rail transportation is decreasing while that of road transport is increasing. Because of the low tonnage transported by air, air transport does not even appear on *Figure 18*. *Figure 19* reports a similar analysis for Japan with the goods modal split portraying similar dynamic tendencies. For both countries, this can be modeled quite accurately by a simple multivariate logistic substitution model.

There is another reason why Japan is of interest: of all industrialized countries the share of rail transportation is the lowest – only around 5 percent of all ton-km is transported by rail. This is certainly not coincidental. The whole philosophy of inventory minimization and just-in-time production regimes is probably the most advanced in Japan, imposing additional stringent criteria on the performance of the goods transport sector. Judged by the continuous decline in the market share, railways have so far failed to fulfill these stringent requirements.

Air transport again does not appear on *Figure 19*, as it is still significantly below the one percent level. Using the historical data of air transport

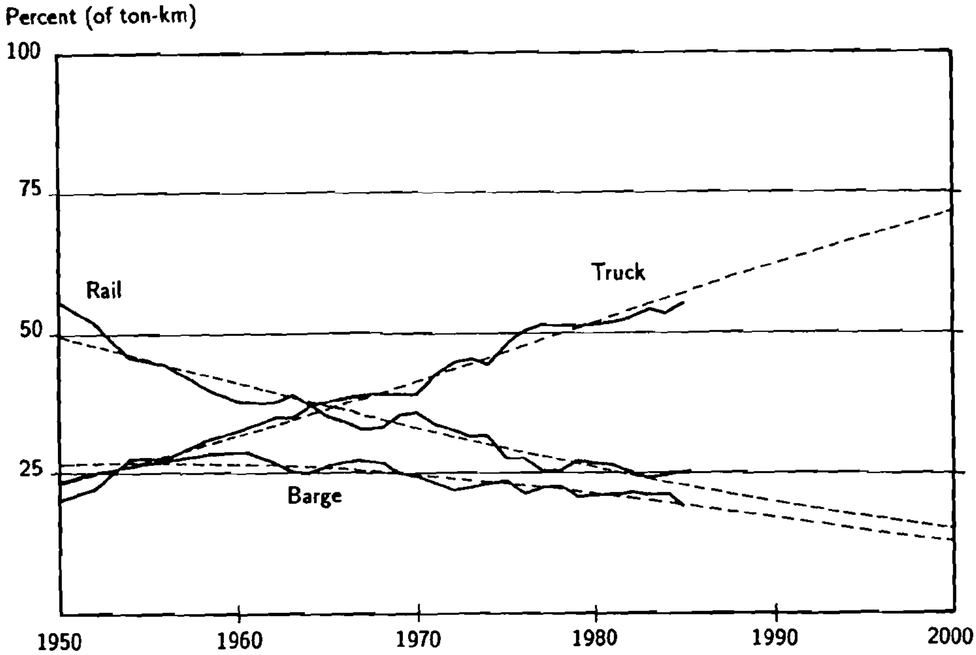


Figure 18. Modal split in domestic goods transport in the FRG, in shares of transport modes in ton-km transported. Source: Grübler (1990).

growth (increasing with an estimated Δt of around 60 years, i.e., the dynamics are similar to the introduction of road transport) we have projected a scenario of when advanced high-speed transportation in Japan (either aircraft or maglevs) should rise above the one percent level. The resulting "phantom" scenario appears well after the turn of the millennium, around 2017, indicating that road transport will continue to grow and remain the dominant mode of goods transport in Japan over the next few decades.

In *Figure 20*, in order to obtain a longer-term dynamic picture, we analyze the evolution in France since 1800. By using the logit transform of the fractional shares of different transport modes the various phases in their life cycle are more clearly revealed. In the past, typically new transport modes for goods have grown along a four-stage, life-cycle model. Once introduced, their rapid growth quickly displaces existing transport modes, first by carrying higher-value goods, i.e., passengers and information, and later high-value density products. This rapid first phase of market share gains lasted from 1830 to 1870 in the case of railways, from 1910 to the end of

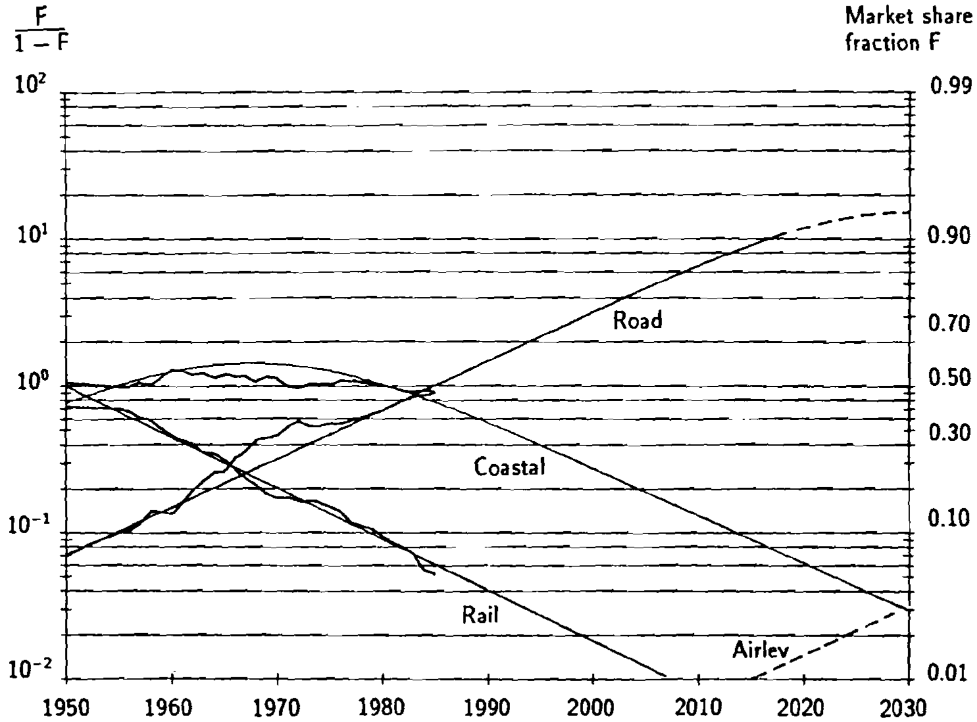


Figure 19. Modal split in domestic goods transport in Japan, in shares of various transport modes in ton-km transported and model estimates, logit transformation.

the 1930s for trucks, and from 1955 to 1965 for oil and gas pipelines. The size of the respective market shares gained in this first phase was highest for railways, with more than 50 percent of all ton-km. Truck transportation also rapidly filled its first market niche, but, with around 25 percent market share, it was already smaller. The specialized market segment for pipelines never exceeded 15 percent of all ton-km transported.

Once the initial niche has been conquered, growth proceeds at a significantly slower pace with additional shares being won from the traditional, slower transport modes, primarily via tariff competition. This second phase is completed once a system reaches maturity and complete market dominance. In France, this second phase lasted from about 1870 to the 1920s for railways, with over 70 percent of all ton-km in France being shipped by rail. For truck transport this second phase still appears to be continuing, as shown in the growing market share projections in *Figures 18* and *19*.

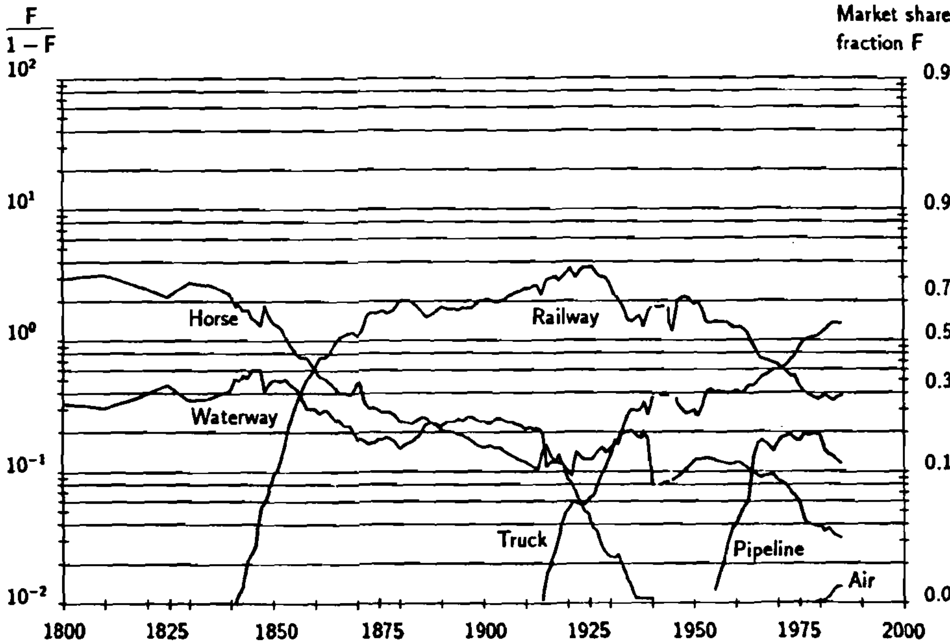


Figure 20. Goods modal split in France since 1800, in fractional share of ton-km transported, logit transformation. Source: Grübler (1990).

The third phase of the four-stage, life-cycle model consists of a relatively long saturation period during which a transport mode loses market shares but maintains a dominant position. For the railways in France, this third phase lasted until the 1950s and 1960s, when their respective market share fell below the 50 percent barrier for the first time. The last phase is the period of fall and decline under vicious competition from newer transport modes. This has been the case for railways since the 1950s. Railways are progressively retreating into the market niches with the lowest value for the goods transport sector by transporting bulk, low-value raw materials, e.g., gravel, scrap, or coal, where low transportation costs are a more important criteria than quality of service or speed.

The main driving forces for the changing structure of the goods modal split may be summarized as follows: increasing value density of tangible goods and decreasing material intensity also tend to generate higher value added in the transport sector. Higher quality of service, smaller batch sizes,

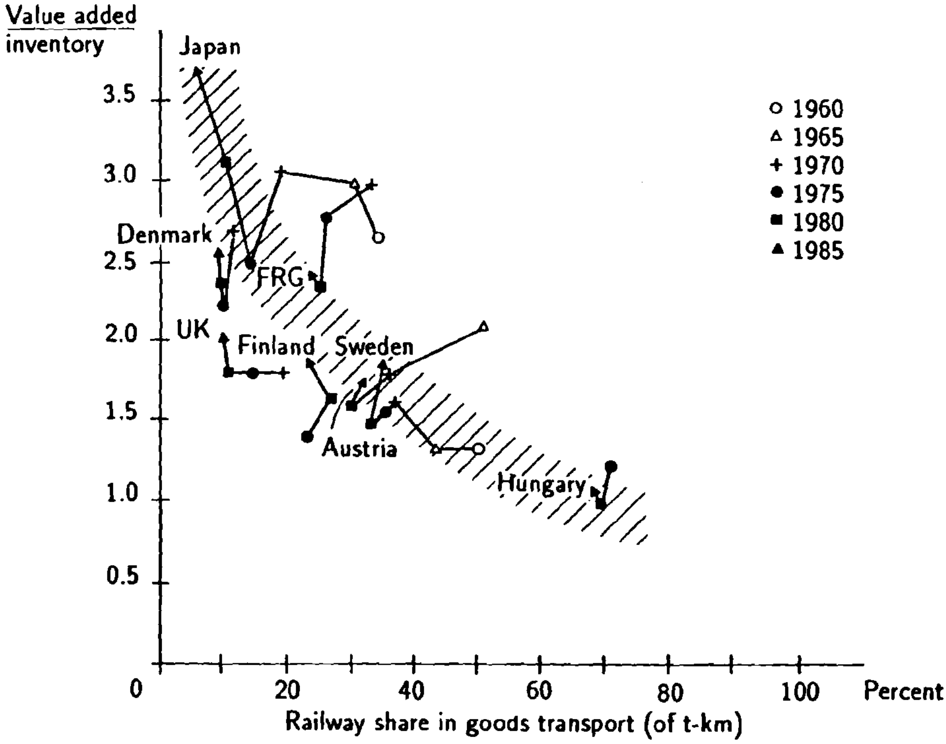


Figure 21. Ratio of value added over inventories in the manufacturing sector of selected countries versus railway share in goods transportation 1960–1985. Source: UN, Yearbook of Industrial Statistics, 1977 and 1987; IRF, World Road Statistics and National Transport Statistics, 1970 to 1987.

and faster and reliable deliveries are required for the transportation of high-value density goods. Despite higher ton-km tariffs the total transport costs incurred are lower, due to quicker turn-around times that allow for a significant reduction in inventories and working capital that would otherwise be tied up in goods waiting to be shipped.

The quest for inventory minimization and ever higher turnover in the manufacturing sector is illustrated in *Figure 21* for a number of European countries and Japan. As an indicator of the performance of the manufacturing sector we take the ratio between the value added over inventories. A value of one, such as the case for Hungary, implies that a whole years' worth of value added is tied up in inventories, either at the place of production, with wholesale and retail dealers, or in transit. On the other hand, a high value of three, as for Japan, indicates that the total value added in manufacturing has an annual turnover of three. In order to minimize warehousing and inventory, and to allow for an increase in the turnover of working capital, speedy and reliable delivery is expedient. Thus the performance of the transport sector may explain some of the variances in the turnover rate in the manufacturing sector of different countries. We use the share of railways as an indicator of the transport system speed because railways are generally slower than road transport, and because high tonnage railway cars represent larger shipment sizes.

Although the relationship between both variables changes discontinuously, as indicated by the vectors of the five-year intervals between 1960 and 1985, over time, there appears to be convergence between the turnover performance of the manufacturing sector and the performance of the transport systems. This is particularly reflected by the percentage of goods *not* transported by railways along the performance frontier shown in *Figure 21*. In addition to being the driving forces for future improvements in the turnover of the manufacturing sector, inventory minimization and just-in-time production regimes also require higher quality of service in terms of high transport speed, fast pick-up and delivery, and smaller batch sizes. All this should favor truck transportation rather than rail.

Developed economies are in a transitional phase with regard to their output mix, moving in the direction of information- and value-intensive, but material-extensive products. This *dematerialization* (i.e., increasing the value generated per kg material input) of manufactured goods is made possible by the availability of higher quality and lighter substitutes in the form of advanced materials; and through the increasing value of products through higher software and information content.[14] The implications of this for the transport sector are illustrated in *Figure 22*, where the share of different transport modes in the imported value of manufactured goods as a function of value density is reported for the FRG in 1986. In 1986 imports of manufactured goods into the FRG accounted for 424 billion DM for a total of 349 million tons (i.e., an average value of 1.2 DM/kg). For the import value, 50 percent arrived by truck, 7 percent by rail, 24 percent by sea or waterway vessel, 6 percent by pipeline and 10 percent by air (we cannot account for the remaining 3 percent). It is interesting to note that while trucks account for 50 percent they transported only 18 percent of the imported tonnage. For air transport this is even more extreme: 10 percent of the import value represent only 0.1 percent of import tonnage, resulting in an average value density of air freight of 166 DM/kg. Therefore the importance of the various

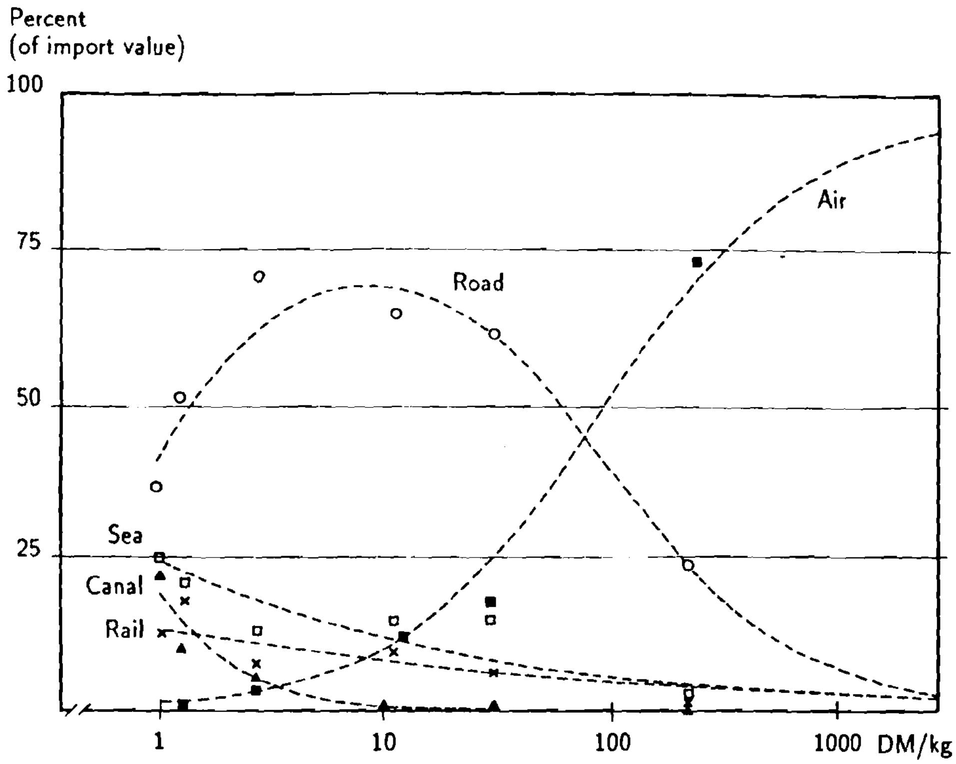


Figure 22. Share of different transport modes in the value of imported manufactured goods versus value density of products in the FRG in 1986, in percent of import value versus average product value in DM per kg. Source: Grübler (1990).

transportation modes changes significantly as a function of the *value* of the products shipped.

Figure 22 illustrates that basic materials such as coal, gravel, scrap, and raw materials in the value range of below a few DM per kilogram are mostly transported by sea, canal, and rail. As the value of the products increases, trucks become more competitive and constitute the dominant transport mode in the value range up to 100 DM/kg. Most manufactured goods such as automobiles or machine tools fall into this range. Higher value densities, i.e., goods with values exceeding 100 DM/kg, such as electronics, computers or precision instruments, are usually shipped by air. Incidentally, the highest value manufactured goods (excluding precious metals, drugs or caviar) are aerospace products and aircraft themselves, all exclusively transported by air.

Because of the increase in demand for high-value goods and just-in-time production regimes, the importance of air transport will grow substantially. In future, lower-value density products may also be transported by air. This is probably best illustrated by the case of the Cadillac Allanté, a car body manufactured by Pininferina in Torino, Italy and transported by air freight to Detroit for final assembly of engine, power train, and electronics by General Motors. This 5000 km "production line" is apparently economic despite all the direct and indirect costs of potential damage risks, insurance, and the production inventories that would be locked in ocean freighters for weeks. The increasing importance of air transport for freight will most likely result in the additional collocation of production facilities and services close to airports, similar to industrial activities condensed along the previous transport infrastructures: first canals, followed by railways, and later on highways and roads.

So far, we have discussed the transport system in terms of infrastructures, and the modal split for passengers and goods. We have shown that the long-term evolution of the transport system is characterized by a sequence of replacements in which faster and higher-quality transport modes substitute for traditional ones. The basic pattern identified appears invariant between different countries or even between different economic systems, pointing at deeper underlying long-term driving forces than normally enter short-term transport demand and mobility models (such as relative transport price structure, private car ownership rates, etc.).

Passenger transportation, as a premium market segment particularly over longer distances, appears to be a good indicator of the likely developments for lower-value market niches. The future evolution of the transport system will be shaped by the quest to increase speed, flexibility, and quality in transportation turnover. By analyzing the interaction between the different transportation modes we have concluded that these quality criteria are apparently best met by air transportation, followed by road transport.

Through our analysis of the whole transport system and of various market segments we have described the competitive interaction between the individual modes. The stage is thus set to concentrate on a more detailed analysis of individual transport systems in order to derive a quantitative scenario of their future growth consistent with the structural tendencies revealed above. Proceeding by historical analogy we will first analyze the dominant transport mode of 50 years ago, the railways, introducing two important concepts in the growth of a particular infrastructure system: *interrelatedness* in the diffusion at the international level, and *heterogeneity* in the ultimate realization (i.e., in density levels) of the expansion of particular transport systems between different countries. This will serve as an introduction for analyzing the diffusion of the automobile in more detail and for developing a scenario for the forthcoming global saturation of car diffusion, consistent with the above principles.

4. Diffusion and Density Levels of Transport Systems

4.1 Railways

Railways were the major form of transport from the second half of the 19th century up to the 1930s. By the turn of the century railways had a dominant position in the transport sector of all industrialized countries, transporting between 80 and 90 percent of all passenger- and ton-km. Thus their dominance (a *technological monoculture*) in the transport sector was even stronger than is currently the case with the automobile. The takeoff of the railways, following the opening of the 20 km Stockton & Darlington Railway in 1825, illustrates the importance of the *simultaneous* and *complementary* character of transport infrastructure and technology development. The merging of the iron wagonway (introduced in the 18th century for coal transport in mines) and the steam engine as a new prime mover technology, facilitated a quantum leap in the performance and quality of the transport system.

Railways spread over the whole world and their growth, in terms of kilometers of track constructed and in passenger and goods transport, has been so spectacular that economic historians have called the second half of the 19th century the "age of the railways." If we analyze the growth of railways at the global level, we see that the growth process started in the 1830s and lasted around 100 years. When saturation occurred the length of the global railway network was around 1.3 million km; it has remained constant ever since. The main thrust of this growth was due to the development of extensive railway networks in a number of core countries, basically Europe, Russia, and the USA. The latter developed the largest railway system of any country.

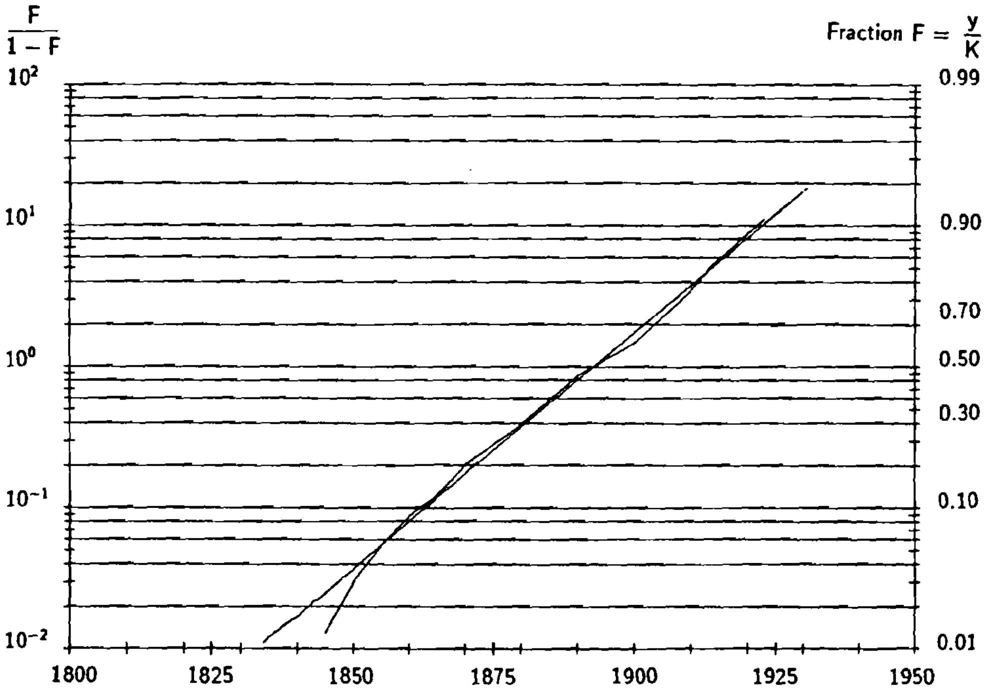


Figure 23. Growth of the world's railway network (K 1.323 10^6 km, t_0 1983, Δt 57 years). The length of the network has remained constant at a level of 1.3 million km since the 1930s. Source: Grübler (1990).

The growth process of the railways enables us to check whether we can describe *ex post* their diffusion process in time and space,[15] and in particular whether simple growth and technological diffusion models are capable of anticipating the saturation level of railway expansion in the 1930s. *Figure 23* illustrates that railway growth at the global level can be described accurately by a simple three-parameter, logistic-equation model. The expansion of the global railway network proceeds with a Δt of 57 years and the inflection point, when half of the growth potential is realized and growth rates begin to level off until saturation is reached, occurred around 1893. Therefore, the saturation in the expansion of the global railway network could have been predicted as early as 1900. Of particular importance is the fact that the estimated saturation level of the diffusion process of 1.323 million km is very close to the empirical data of 1.3 million km.

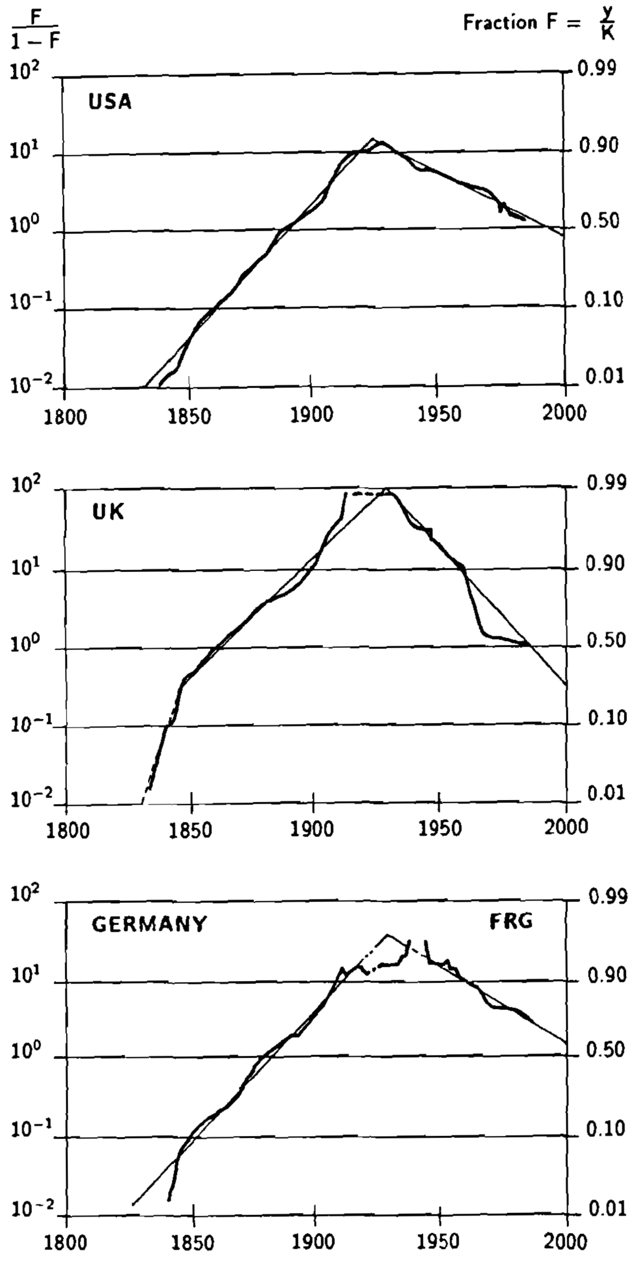


Figure 24. Rise and fall of railway networks in the USA, the UK, and Germany (FRG after 1945), in fractional share of estimated saturation level, logit transformation. For model parameters see *Table 1*. Source: Adapted from Grübler (1990).

Figures 24 and *25* illustrate that the growth process of the railway network at the country level and its contraction after saturation in the late 1920s can also be described by the same model. The growth of railways in the USA, the UK, and Germany in *Figure 24* proceeds at a similar rate (where Δt is between 55 and 57 years). Saturation is perfectly synchronized, the maximum size was reached in 1928 in the UK and in 1929 in the USA. In the German Reich, maximum network size was reached in 1913 and decreased after World War I due to the return of Elsaß-Lothringen to France. If we take this territorial change into account, we observe that railway construction continued in the remainder of the German Reich up to 1928, thus saturating at the same time as in the USA and the UK.[16]

Figure 25 shows the expansion and contraction of railroads in the Austro-Hungarian Empire (Austria after World War I[17]), France, and the two growth pulses in Tzarist Russia and the USSR. While the growth pulses proceed at similar rates for Austria–Hungary and France (Δt of 52 and 47 years, respectively), the latecomer Russia grows faster (Δt of 37 years) and is, in effect, catching up. Again there is a high degree of congruence in saturation in the late 1920s.

The interesting cases are France and the USSR since they show departures from the development pattern of other countries. In France there are two features worth noting. The first is that the turbulence during the saturation phase is very large compared to other countries, primarily due to the impact of both World Wars; the second is the introduction of the TGV in the railway grid during the 1970s. Without the additional infrastructure dedicated to the TGV, the length of the French railway system continues to decline, while inclusion of the TGV links could indicate a trend reversal. As already discussed, the TGV might effectively be a transitional system to a new rail-based, high-speed infrastructure, and we have indicated this possibility by plotting the TGV lines separately in the lower right-hand corner of the graph.

The development path of Tzarist Russia is almost identical to the pattern observed in the other five countries until the onset of saturation in the 1920s, indicating (partial) *integration* of Russia in the development pattern of the rest of Europe (in fact a large part of the Russian railway network was constructed with French capital). The second expansion phase in the USSR doubled the railway network compared to pre-revolutionary times. In our interpretation this is an indication that, to a large extent, the USSR was *decoupled* from the development and economic growth pattern of the rest

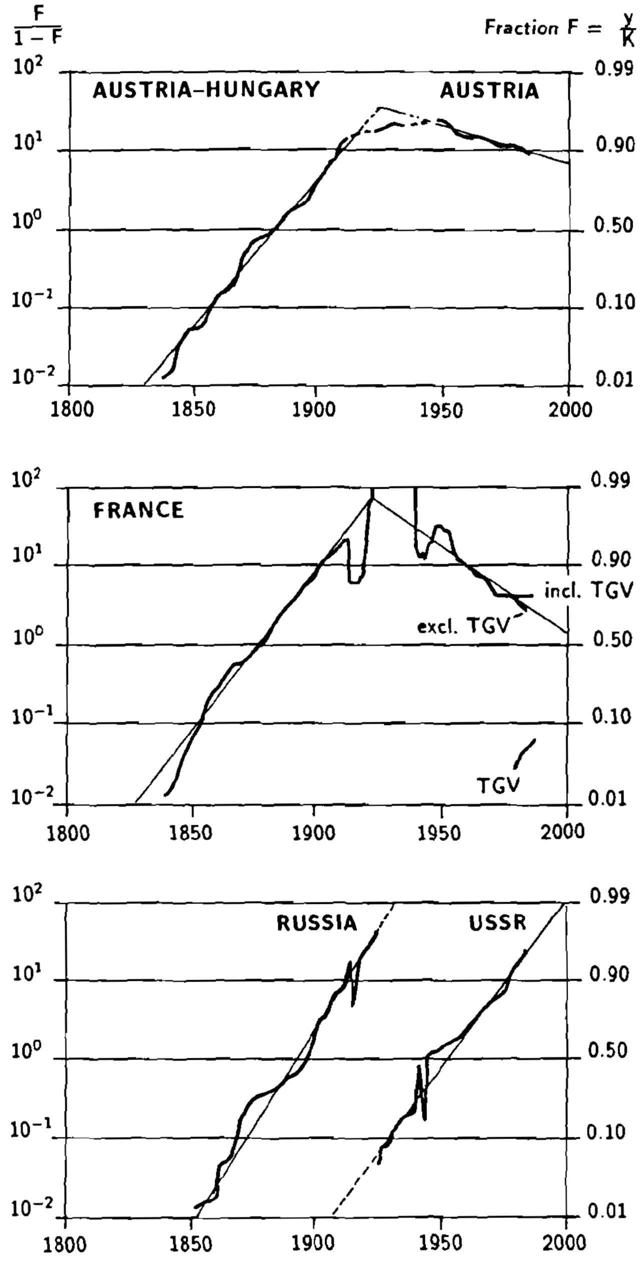


Figure 25. Rise and fall of railway networks in Austria–Hungary (Austria after 1919), France, and the first and second phase of railway construction in Russia and the USSR, in fractional share of estimated saturation level, logit transformation. For model parameters see *Table 1*. Source: Adapted from Grübler (1990).

of Europe. In retrospect this does not appear to be an altogether successful model for economic growth and technological catching up. Interestingly enough, the second growth pulse followed a similar trajectory and time constant as the first one. The growth trajectory was strongly perturbated by the effects of World War II, the disruption was however elastically reabsorbed by 1960. Currently railway expansion in the USSR appears to be entering its own phase of saturation. *Figure 26* summarizes the spread of railroads and associated technologies in a number of countries, including the six examples given above.

The first cluster in *Figure 26* shows a rather narrow band in the growth of railway networks, i.e., an *international diffusion bandwagon.* This growth at the world level was primarily due to construction, in a cluster of industrializing core countries in Europe and the USA. These countries display an interrelated and synchronized pattern in their railway construction, as expressed by their similar diffusion rates (Δts). Together the core countries of the railway bandwagon in *Figure 26* account for the largest segment (70 percent) of railways ever constructed. This implies that the particular development model, in the form of extensive construction of national railway networks, *is not repeated* by latecomers, i.e., by those countries not forming part of the particular infrastructure expansion bandwagon.

As a result of synchronized development and of catching up, all core countries completed expansion in the late 1920s and the 1930s. This *season of saturations*, i.e., they all saturated within ten years, is even more noteworthy when considering the long time period required to build up such large pervasive systems: about 100 years. This *season of saturations* is not limited to the six countries discussed above. A quick look in the available statistics (Mitchell, 1980) suggests that a similar statement can be made for an even larger sample of European countries. All of them reached their maximum railway network length around the 1930s, including the Netherlands (1929), Denmark (1932), Belgium (1933), Switzerland (1937), Sweden and Greece (1938), and Italy (1940). This provides further evidence for the clustering (*season*) of saturations observation presented above. The *railway bandwagon* was *rolling* for a large number of core countries, all saturating around 1930. No comparable growth in railway networks was later achieved in the countries decoupled from the core countries.

The second band of trajectories in *Figure 26* shows another important innovation in the railway system that diffused during the period when most of the world's railways were already declining: namely, the replacement of steam by diesel/electric locomotives. This development trajectory is again

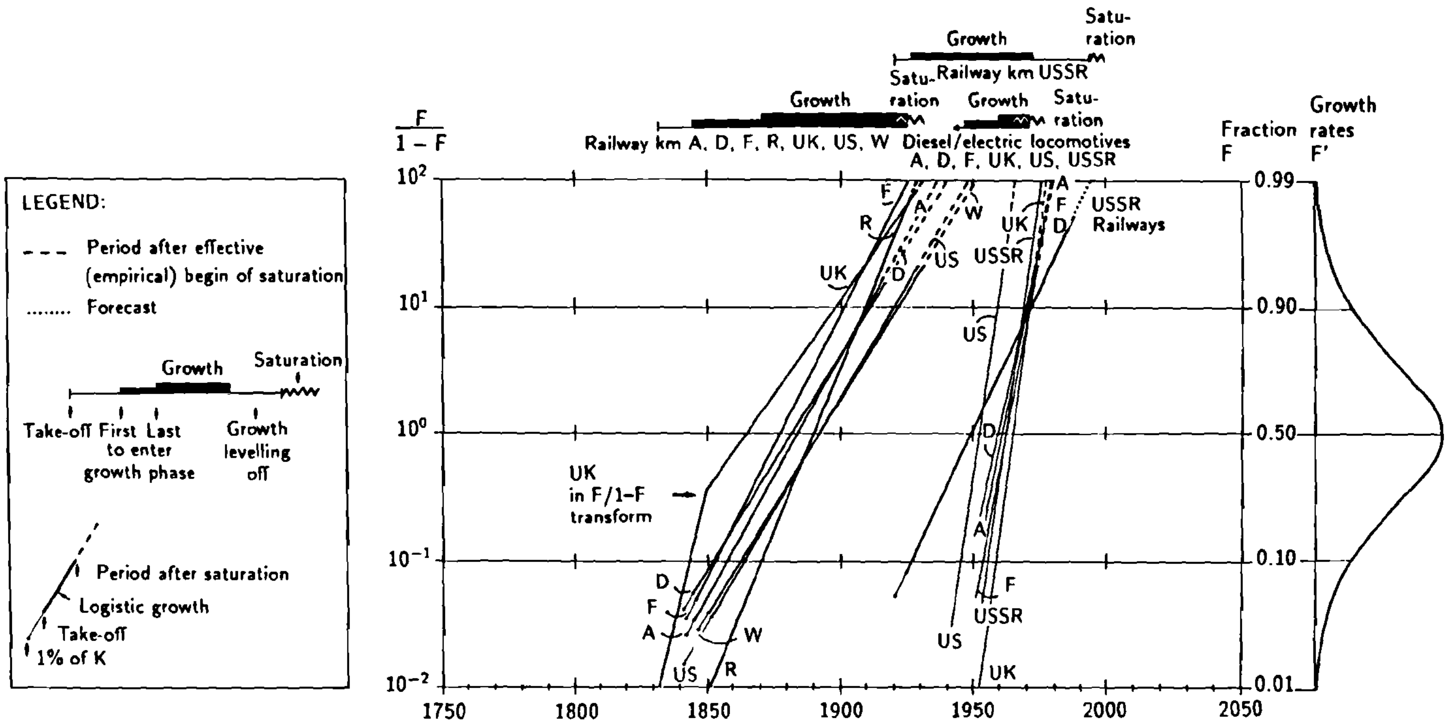


Figure 26. Growth pulses in the expansion of the railway network and in the replacement of steam locomotives, in fractional share of growth (market share) achieved, logit transformation. Source: Grübler (1990).

confined to a rather narrow band that intersects with the second growth pulse of railways in the USSR. *Figure 26* illustrates that the replacement of the rolling stock, symbolized by the diffusion of diesel/electric locomotives, was much faster than the development of railroad infrastructures, with a Δt in the order of 15 years, compared to a Δt for the expansion of railways of around six decades. In a similar way we observe here a *substitution bandwagon*, in that the replacement process appears to be an interrelated, synchronized phenomenon at the international level, completed almost simultaneously by the end of the 1960s in all countries outside the USA, where the replacement was completed ten years earlier.

Table 1 summarizes the data on railway expansion in the core countries of the *railway bandwagon* as well as on the global level. Estimated diffusion model parameters, in particular the saturation level K, are given with empirical data on the year and length of the maximum size of the railway network. The start of the diffusion process, defined as the year when the network extended over one percent of its ultimate level, as well as the year of saturation and maximum network size are also presented. Note, in particular, the excellent agreement between the estimated saturation levels of our simple model and the empirical data (deviations below ten percent). The fit of the empirical data is also excellent (R^2 in all cases is well above 0.99).

As can be seen from *Table 1*, even the railway density between the core countries promoting this particular infrastructure development was, in fact, very heterogeneous. The resulting *densities*, i.e., the km railway lines per country area and per capita at the period when the expansion process was completed, were very different even between the countries promoting the most construction. Based on this historical example we may conclude that although the diffusion of infrastructure networks and systems, although comparable in terms of their dynamics (Δts), resulted in different absolute as well as relative density levels. Different diffusion levels (densities) are the result of the diverse geographical, economic, and social environments (boundary conditions) prevailing in different countries. It appears in addition (see *Figure 27*) that the ultimate density level also depends on when the system is introduced. Early pioneers in the introduction of railways, such as the UK, achieve the highest railway density levels. Latecomers, while sometimes catching up by growing faster, do not realize densities any way comparable to the early starters.

Consider the density levels presented in *Table 1*. The spatial railway densities range between 0.7 (USSR in 1986) and 16.0 (UK in 1925) km of railway lines per km^2 of territory, i.e., by a factor of more than 20. Per

Table 1. Growth of railway networks (km).

Country	Estimated saturation length (K) (1000 km)	Maximum length achieved (1000 km)	t_0 (year)	Δt (years)	1% of maximum length (year)	Maximum length (year[a])	Density[b] length in 1925: per 100 km^2	Density[b] length in 1925: per 10,000 inhabitants
Austria–Hungary[c]	24.5	23.0*	1883	51.8	1841	1913*	8.0	10.2
France	42.5	42.6	1876	47.1	1841	1933	9.7	13.7
Germany[d]	66.8	63.4*	1882	57.0	1841	1913*	12.2	9.6
Russia	73.9	70.2*	1890	37.4	1851	1913*	0.3–1.5	4.8–8.4
USSR	147.8[e]	145.6	1949	43.6	1921	1986	0.7[e]	5.5[e]
UK[f]	33.9	32.8	1858	56.6	1834	1928	16.0	8.8
USA	526.1	482.7	1891	54.5	1840	1929	4.3	38.1
Core countries in 1925[g]		715.0					2.0	16.7
Rest of world in 1925[g]		540.0					0.6	3.7
World	1322.9	1255.0[h]	1893	56.9	1844	1930	1.0	6.7

*Important territorial changes thereafter.
[a]Source: Mitchell (1980).
[b]Density as calculated by Woytinsky (1927) for 1925 except Russia and the USSR (own calculation). The range of figures for Russia corresponds to total density and the European part of the territory, respectively. Density figures for the USSR are for the 1986 network size.
[c]Austria after 1919.
[d]Including Elsaß-Lothringen (E–L); excluding E–L, maximum network size was approximately 60 10^3 km by 1938.
[e]Including intercept (73.9 10^3 km); 90% probability that K lies within 145–150 10^3 km. Density figures for 1986 network.
[f]Parameters refer to a Gompertz function ($t_0 = K/e$ instead of $K/2$).
[g]Core countries including Russia. Rest of the world is the difference between world total and core countries.
[h]Source: Mothes (1950).
Source: Adapted from Grübler (1990).

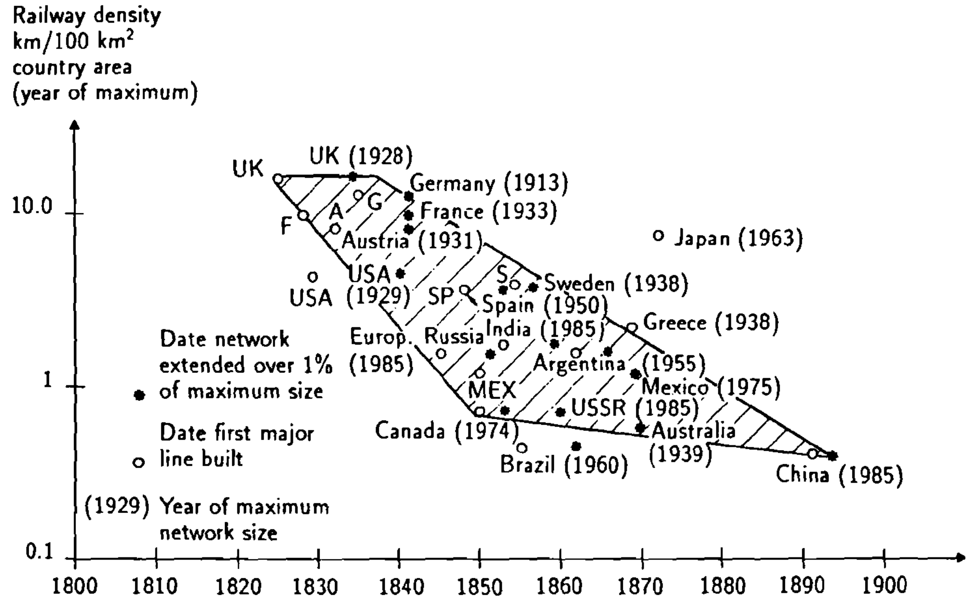


Figure 27. Spatial railway density envelope versus network construction start-up date, in km of railway network at peak year (1985, for networks still expanding) per 100 km^2 of the country. Source: Grübler (1990).

capita railway densities range from 5.5 (1986 USSR) to 38.1 (USA in 1925) km per 10,000 inhabitants, i.e., by about a factor of 7.

It is also interesting to extend our analysis to those countries that were not part of the *railway bandwagon* of *Table 1* and *Figure 26* with respect to ultimate density levels achieved in a particular infrastructure development phase. A number of developing countries continued railway construction after the saturation and contraction of railways in the industrialized core countries. In analyzing the diffusion level, i.e., the railway density per km^2 of the country,[18] of the *railway latecomers*, we observe an interesting fact: the diffusion levels appear to decrease the later a country started construction, as illustrated in *Figure 27*. Two empirical measures are developed to assess the starting date of construction. First, the year the network initially exceeded one percent of its final maximum size, using either historical dates or, in cases such as China where the network is still growing, the latest data year. The second measure records the date the first railway line of national importance was constructed.

Figure 27 suggests that the railway densities can be regrouped by a declining *density envelope* as a function of the date railway construction began, i.e., the later a country started, the proportionately fewer railway lines it constructed. The only exception appears to be Japan, where construction started rather late (in the 1870s) but a network of similar density as in the *railway bandwagon* core countries was constructed.

Two main conclusions can be drawn with respect to density levels. First, diffusion levels are different even within the core countries developing along a similar trajectory in various economic expansion periods. This is because of different boundary conditions prevailing in individual countries and the time available for development and growth. Therefore it is absolutely pointless to infer from the diffusion level achieved in early starter countries (e.g., the UK for railways or the USA for automobiles) what would happen in other countries. The railway network of the USA was highly developed by 1930, but its spatial density was only one fourth of that of the UK. No one could seriously suggest that the railway network in any of the countries presented in *Table 1* was not sufficiently developed by 1930. Still the diffusion levels (network density) were very heterogeneous even among the countries forming the railway bandwagon.

The fact that the passenger car density in the USA presently exceeds 560 cars per 1,000 inhabitants, does not imply that such a level is a good or even a desirable target for Austria or France. The heterogeneity in diffusion levels, and also in the technological and institutional design and embedding options, becomes even larger when considering a country that is not one of the core countries in a particular infrastructure development phase. Returning to our example of the railway network densities we observe that China would have to increase its present railway network by a factor of 20+ in order to achieve a spatial railway density similar to that of the industrialized core countries in the 1930s. This does not only appear infeasible, it also would be simply absurd to suggest repeating[19] a growth trajectory of a past development phase. We contend that a similar statement also holds true for the massive diffusion of car ownership to levels anywhere near those presently achieved in the industrialized countries. We will try to support this scenario by a more detailed analysis of automobile diffusion.

4.2 Automobiles

The advent of the automobile around the turn of the century initiated a new era in the development of transportation. Its growth, up to the present number of around 400 million passenger cars registered worldwide, proceeded through two distinct diffusion phases marked by different growth rates and a structural discontinuity in the 1930s. The automobile first diffused rapidly into the market niches previously held by horse-drawn carriages, where its comparative advantage was particularly high. This rapid diffusion was essentially completed by the end of the 1930s in all industrialized countries.

During this early phase, the automobile did not enter into an effective competitive relationship with railways. In fact, cars had an essentially complementary role, improving the transport services to and from railway stations and providing local distribution functions. Two developments mark the transition to the second growth phase: technological improvements in the car itself, in particular the introduction of closed car bodies, and saturation of railway expansion, both occurring during the 1930s. The saturation of the railways, in terms of infrastructure length and market importance, could have provided an *opportunity window* for the emergence of a competitor for long-distance travel in the form of the automobile.

Before we discuss automobile diffusion in more quantitative detail, we first have to define what we mean by an automobile (car). The first cars were a long way away from the predominant technological design of today and can be characterized as "horseless carriages", often with open (and thus rather uncomfortable) bodies. Their structural design and construction material, axles, interior design and seating arrangements, steering design, etc., were all directly taken from horse carriage designs or direct derivates. This provides a clear picture of the market niche in which early automobiles competed: the automobile emerged and grew, by replacing horse-drawn vehicles. Even the new technology base of fossil energy as a fuel source was far from being standardized. In fact, four technological designs competed as prime movers: steam, diesel and gasoline engines, and electric motors. Once the dominant technological design emerged, however, mass production and significant cost reductions became possible. The most prominent example is of course Ford's Model T – the selling price was reduced from US$850 in 1908 to US$290 in 1926 (Abernathy, 1978). Therefore, the technological and productivity stage for the diffusion of the automobile and the replacement of the horse carriage was set.

Another factor contributing to the rapid first growth phase of the automobile was that cars could make use of an already existing infrastructure developed for horse-driven carriages: surfaced roads. Contrary to popular belief, the car did not enforce the construction of surfaced roads, as the growth of the latter significantly precedes the growth of the automobile fleet.

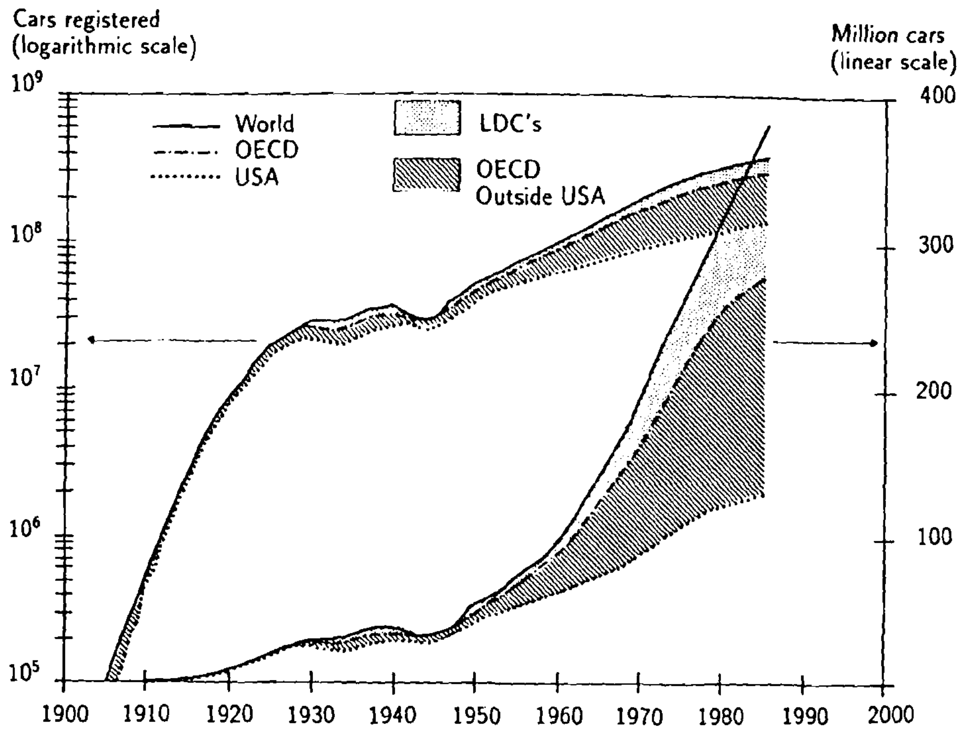


Figure 28. Passenger cars registered worldwide, linear and logarithmic scale. Source: Adapted from Grübler (1990).

Finally, another precondition for the diffusion of the automobile was to overcome institutional and societal barriers. As an example we mention the abandonment of the 1836 *Red Flag Act* in the UK. This act (see Voigt, 1965) required a person with a red flag and a bell to walk 20 yards ahead of all road vehicles (at that time only steam driven) to warn others. In addition, steam vehicles were not allowed to go faster than 4 km/hr. Yet another factor that prepared the social ground for automobile diffusion was the increasing awareness of the negative externalities resulting from the dense horse carriage traffic in urban areas: problems of congestion, energy (feed) supply, stabling, high accident rates, and environmental pollution from horse manure (see Barker and Robbins, 1975, for an account of the road traffic situation of 19th century London).

Figure 28 illustrates the expansion of the automobile in terms of passenger cars registered at the world level, as well as for the USA and OECD countries outside the USA. Three important features are worth noting:

- The two growth phases are clearly indicated by the different slopes on the logarithmic scale. The first very rapid expansion phase lasted until the 1930s with an average exponential growth rate of around 30 percent per year; the second phase had a significantly slower growth rate of 5 percent per year on average from 1930 to 1985.
- Prior to World War II, automobile growth was greatest in the USA; the shaded areas of *Figure 28* indicate car registrations in OECD countries,[20] outside the USA and outside OECD (i.e., the difference between OECD and the world total), and clearly reveal the absolute dominance of the USA in the first phase of the diffusion of the automobile. Up to 1930 the USA accounted for as much as 80 to 90 percent of all passenger cars registered worldwide. By 1950 this share had fallen to around 76 percent, the remainder of OECD accounted for 16 percent and the rest of the world for around 8 percent of passenger cars registered. Since 1950, the share of the USA has fallen to around 35 percent, while that of the remainder of OECD has risen to about 40 percent of the world total.
- The share of countries outside OECD remains basically very small, below ten percent of the world total up to 1960. Since 1960 the share of countries outside OECD has risen to about 25 percent.

In the first phase of diffusion, between 1900 and 1930, the number of passenger cars registered worldwide increased by more than four orders of magnitude to some 30 million passenger cars, over 23 million of which were registered in the USA. The high automobile density in present day America should not come as a surprise, considering the already high density of individual road transport means before the advent of the automobile. The density of riding horses and mules in the USA in 1900 exceeded 40 draught animals per 1,000 inhabitants, a value exceeding today's car ownership rate in Hongkong, and comparable to the present world average car density outside the USA of around 50 passenger cars per 1,000 inhabitants.

The second growth period of the automobile is characterized by its diffusion into those market niches previously held by railway transport, or those newly developing (e.g., leisure and weekend travel, commuting, etc.) in the post World War II period. In this period the other OECD countries started

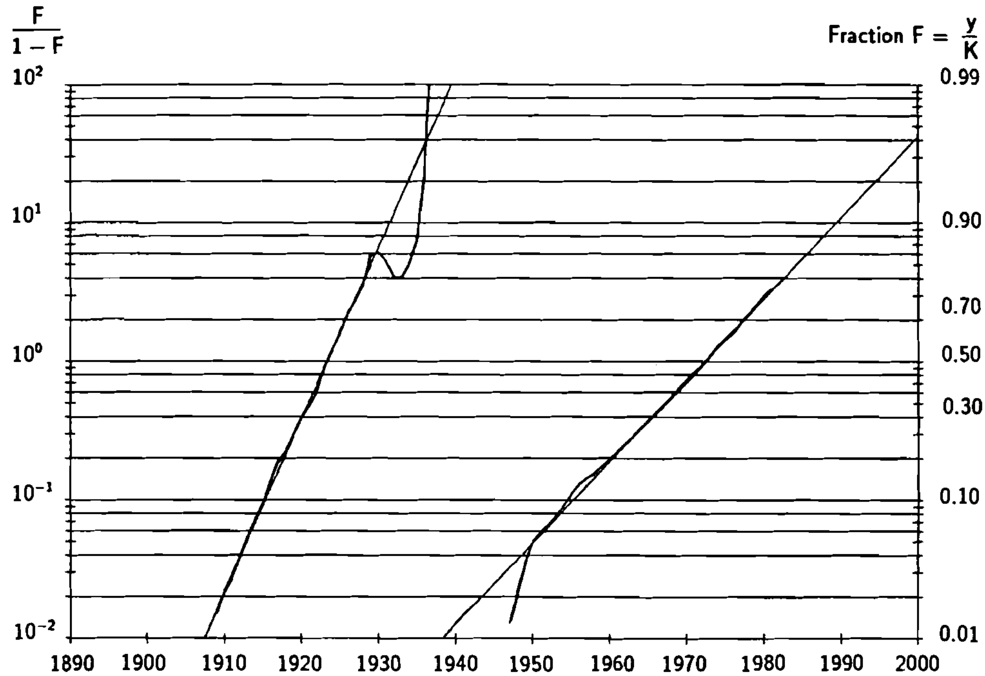


Figure 29. Two diffusion pulses in the expansion of the number of passenger cars registered worldwide. [First pulse: K 35 million cars, t_0 1923, Δt 15 years; second pulse K 464 million cars (including intercept), t_0 1974, Δt 36 years.] Source: MVMA (1987), for period prior to 1930 own estimates.

mass motorization and since about 1960 car diffusion has also become significant in some of the COMECON and developing countries.[21]

Figure 29 describes the two phases of automobile diffusion at the world level for two diffusion periods and analyzes the growth of the number of passenger cars registered worldwide by two consecutive logistic growth pulses. The first phase is characterized by a regular, rather fast diffusion process (Δt of 15.4 years) which reached a saturation level of 34.6 million cars by 1938. The downward deviation occurring after 1930 is the effect of the Great Depression. This deviation was, however, absorbed again by 1936.

The second worldwide diffusion phase occurs in the period after 1950 (by which date the effects of World War II had been overcome). This phase appears to proceed smoothly, and is characterized by a time constant twice as large as the first pulse (Δt of 36.2 years compared to 15.4 years). An interesting observation is that the post-1973 developments in the oil market did not appear to have a noticeable effect on the diffusion process. If the diffusion pattern continues to unfold as in the past, saturation will occur around the year 2010 at a level of around 464 million cars.[22]

Based on an extrapolation of our nonlinear diffusion model, the growth of passenger car registrations worldwide appears to be approaching saturation, with between 27 and 44 percent additional growth potential remaining, taking best fit and high estimate, respectively. Such a scenario would imply a progressive exhaustion of the economic growth stimulating effects of the expanding automobile industry, characteristic for the "oil and car" age. Before we focus our analysis on a number of countries let us corroborate our hypothesis that automobile diffusion successively fills two market niches by analyzing how cars replaced horses and horse carriages as a means of road transport.

The first phase of automobile diffusion

Before the advent of the automobile, the USA had a relatively high ownership density of individual road transport means in the form of horses and mules (around 40 transport animals per 1,000 inhabitants). From these initial conditions, the dominance of the USA in the first growth phase in the world automobile fleet and its present high car density may be better understood. By analyzing the number of horses and mules used for transport purposes (i.e., excluding farm animals) and the number of automobiles in use, a clear substitution picture emerges. Analyses for the UK and France show an identical pattern. When analyzing the relative share horses accounted for in the total number of road "vehicles", a regular logistic substitution pattern is revealed.

The substitution of horses by automobiles is illustrated in *Figure 30* by plotting their respective absolute numbers, and the estimated numbers based on the logistic substitution model. The substitution process resulted in a decrease in the number of draught animals used for transport from four million in 1910 to less than 400,000 by the end of the 1920s, with a corresponding increase in the number of cars from 400,000 to around 23 million over the same time period. By the time this substitution process was completed at the beginning of the 1930s, the automobile density was close to 200 passenger cars per 1,000 inhabitants. This is a value comparable to the car density of present-day Japan (240 cars per 1,000 inhabitants in 1987). This points again to the unique initial starting conditions for the

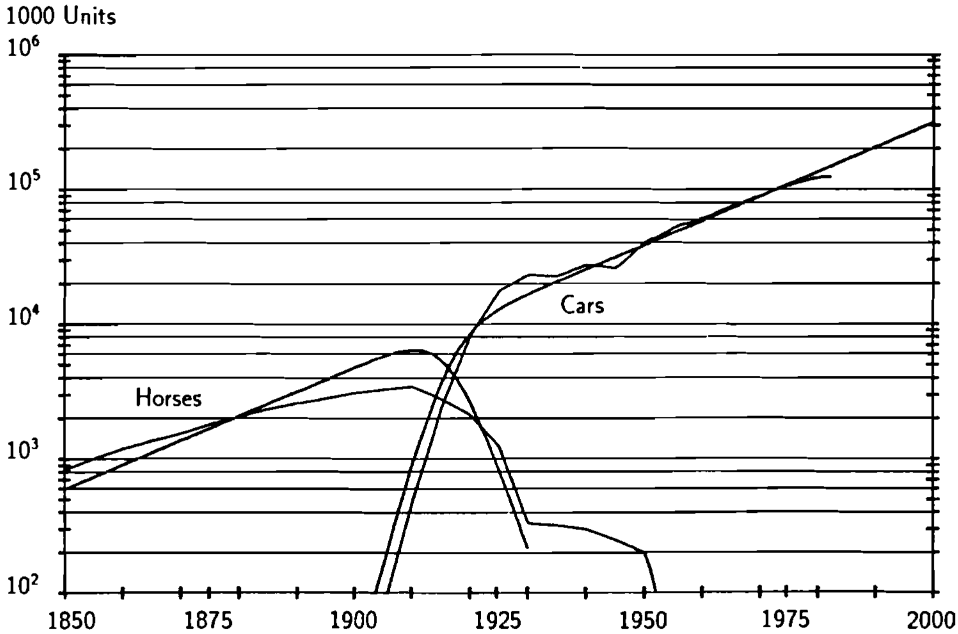


Figure 30. Number of draught animals (horses and mules) used for transport and number of cars in the USA, empirical data and model estimates resulting from logistic substitution model, in thousands. Source: Nakićenović (1986 and 1988).

automobile age in the USA, therefore, making it unrealistic to use the US situation as a guide for similar developments in other countries. *Figure 30* clearly illustrates that the rapidity of the first growth phase of the automobile was largely due to the fact that it found and swiftly took over the existing market niche occupied by draught animals (Δt of around 15 years).

Another observation that can be made on the basis of *Figure 30*, is that the total number of road vehicles (i.e., horses plus cars) appears to have evolved along an exponential secular trend with an average growth rate of above four percent per year since 1850. Note the congruence of the exponential growth trends for the growth in the number of horses prior to the advent of the automobile and the continuation of this growth trend after the effective disappearance of the horse as a means of transport by the 1950s. This observation would suggest an analysis of the diffusion of all road vehicles, irrespective of the replacement process between horses and cars occurring inside the total road vehicle population. If the evolution of the total number of road vehicles in the USA is analyzed under the hypothesis of a single diffusion process, it appears that the growth in the number of road vehicles proceeds after initial significant turbulences (but still along the long-term diffusion pattern) finally to "lock in" in a regular evolution pattern along a long-term diffusion trajectory. The implications of this process, should it continue its historical trend, are particularly noteworthy with respect to the estimated saturation level of around 350 million road vehicles – this corresponds to a doubling of present day figures and a resulting road vehicle density of over one road vehicle per inhabitant.[23] Although such a conjecture would appear unrealistic based on present organizational patterns of car ownership and usage, there are some tourist areas where car densities exceeding one car per inhabitant can be observed today. Could it be that such large numbers of additional road vehicles will be in the form of rental cars or similar organizational schemes to provide local and regional transport, with long-distance transport being provided for by other modes of transportation (e.g., aircraft or Maglevs)?

We have analyzed and concluded elsewhere (Grübler, 1990) that the replacement of horses was practically complete in all industrialized countries by the 1930s, independent of what specific indicator was used to describe the process. The speed of displacement of horses in road transport was rather fast, with Δts ranging from around 15 years in the case of the USA, between 15 (substitution measuring passenger-km) and 17 (substitution measuring ton-km) years in France, and around 20 years in the UK. This means, that within a period of one to two decades 80 percent of the stock of horses (and carriages) in the road transport sector was replaced.

What are the driving forces behind such a rapid process of technological change? We would like here to put forward some tentative propositions. Clearly, a complex vector of comparative advantages of the automobile over the horse exists. Among these comparative advantages we rank in first place *improved performance* in terms of speed, range, and ease of use. Average transport speeds of automobiles increased quickly from around 30 to some 50 km/hr. The average on highways was even faster, for 1940 an average speed of 60 km/hr is reported (US DOC, 1975), compared with some 10 km/hr typical for horse carriages. Higher speed and ease of use (no changing of horses during long-distance journeys) meant a considerable extension in the travel range which could be covered. Another aspect of ease of use of the automobile was a significant reduction in inventories and weight of energy sources [stables, storage of food – a horse consumes over 25 kg of food per day in the form of bulky hay, oats, etc. (Montroll and Badger, 1974)].

Finally, one should not forget an additional advantage of the automobile, especially in urban areas: cars produced considerably less emissions than the previous dense horse population. Although the quality (toxicity) of emissions of automobiles and horses are of course different, the automobile nevertheless offered relief from one of the most urgent environmental pollution problems of urban areas around the turn of the century: horse manure. Montroll and Badger, 1974, estimate that a horse produces about 1,000 grams of excrement per mile traveled (635 g/mile solid and 300 g/mile liquid). This compares to 1980 piston engine standards in the USA of around 5 g/mile (CO, NO_x, and hydrocarbons). Thousands of so-called "crossing sweepers" were employed in London, who, for a halfpenny, would clean a path before anyone crossing the street. Today this may sound anecdotal, but it constituted a serious environmental problem at the turn of the century.

We draw two conclusions from our discussion on the first phase of the diffusion of the automobile: (a) it was characterized by a process of substituting horse drawn vehicles, and (b) this first phase of the diffusion process was essentially complete by the 1930s. Technological improvements in automobile design, like the widespread adoption of closed body car designs, further improved performance, and comfort of automobiles prepared the ground for the second phase of the diffusion of the automobile, i.e., its emergence as a mass transport mode and the beginning of competition with traditional long-distance carriers, in particular the railroads.

The second phase of automobile diffusion

The diffusion of private car ownership for a number of countries will be discussed below under two main assumptions. First, empirical evidence and similarities in the growth of earlier transport systems such as railways, suggests that the diffusion pattern closely follows a logistic trajectory. Our second assumption is based on conclusions from our analysis of the first phase of diffusion of the automobile. Since horses did not disappear as a means of road transport until the end of the 1930s, it is only after that date that one can consider the number of cars as an appropriate indicator for passenger road vehicles. Consequently (and further ignoring the disturbances resulting from World War II) we analyze the second phase of diffusion by using data from the period 1950 to the present only. Diffusion will be analyzed on the basis of both absolute and relative measures, that is the number of cars registered and the number of cars registered per 1,000 inhabitants, respectively.

Table 2. Passenger car diffusion, 1950–1987,[a] in million passenger cars registered.

Country	t_0	Δt	Passenger cars (million) K	K-range[b]	Present (1986–87)	Present in % of K[c]	R^2 of estimate
Australia	1972	43.6	8.6	7.4–9.7	6.8	70–80	0.9996
Austria	1972	27.6	2.9	2.6–3.1	2.7	85–94	0.9978
Canada	1972	51.8	15.0	12.9–17.1	11.5	67–77	0.9969
France	1969	33.8	23.8	21.4–26.1	22.0	84–92	0.9958
FRG	1971	28.9	29.7	26.7–32.7	28.3	87–95	0.9949
Italy	1973	25.7	24.6	22.1–27.0	23.3	87–95	0.9924
Japan	1975	16.6	30.1	27.1–33.1	29.5	89–98	0.9993
Spain	1976	21.2	11.1	10.0–12.2	10.3	85–93	0.9989
Sweden	1965	32.4	3.4	3.1–3.7	3.4	92–100	0.9925
New Zealand	1970	47.7	1.9	1.7–2.1	1.6	76–86	0.9965
UK	1966	33.3	18.1	16.4–19.9	17.0	85–94	0.9977
USA[d]	1970	59.7[d]	157.7	141.4–174.0	135.7	78–86	0.9985
World[e]	1974	51.6[e]	463.9	403.6–524.3	364.8	70–79	0.9998

[a]Data period used for parameter estimation: 1950–1986/1987.
[b]With 90 percent probability.
[c]Range corresponds to high estimate and best fit case respectively.
[d]Two growth pulses (Δt = 14.4 + 45.3 years).
[e]Two growth pulses (Δt = 15.4 + 36.2 years, see *Figure 29*). Latest data available: 1984. World total includes centrally planned economies.

Table 2 presents the estimates of the diffusion of passenger cars in a number of OECD countries, as well as the total for the world (including COMECON countries). We show the timing (inflection point t_0, i.e., at $K/2$) and the duration of the diffusion process (Δt), the estimated ultimate level of saturation K, together with the corresponding uncertainty bands for the estimates (at 90 percent probability level). The next column gives the present actual car density (registered passenger cars 1986–1987). As can be seen from these figures, our estimates show that the automobile density is close to saturation in most of the countries and at the global level, ranging from between 83 and 100 percent of the estimated saturation level. In fact, in a few cases the lower uncertainty band has already been surpassed by actual density. For this reason, we will use the *best fit* and *higher* uncertainty band as representative figures in subsequent scenarios.

A number of observations can be made from *Table 2*. First, the growth of passenger cars registered appears to be close to saturation in all the countries of our data sample. The growth potential remaining is (with the exception of the USA and Canada) very small indeed for all OECD countries analyzed, whereas for the world, a figure up to 30 percent higher than at present would be expected based on our model. The second observation is the very large heterogeneity in both the diffusion speed (Δts ranging from 16 years in Japan to over 50 years for Canada and the USA) and in the remaining growth potential. Third, the diffusion rates (Δts) appear to accelerate the later the diffusion process began.

Both the diffusion rate and the level of saturation appear to be a function of when the diffusion process was initiated (measured by the year when one percent of the saturation level was reached, i.e., t_0 minus Δt). Early starters grow slower and achieve higher ultimate density levels. But late starters have higher diffusion rates and therefore tend to catch up the leaders, albeit with a lower saturation level. This is exactly the same phenomena as seen for the spread of railways. For instance, the automobile diffusion process was initiated in Canada and the USA around the turn of the century, grew slowly (Δt around 50 years) but achieved very high car density levels as shown in *Table 3*. In Japan the diffusion process started some 60 years later, but because of higher diffusion rates grew faster (catches up with a Δt of some 16 years) and appears to be saturating at the same time as the USA and Canada but at a lower level. *Table 3* complements the analysis reported in *Table 2* by using the relative car density (passenger cars registered per 1,000 inhabitants) as an additional indicator.

Table 3. Passenger car diffusion, 1950–1987,[a] in passenger cars registered per 1,000 inhabitants.

Country	t_0	Δt	Passenger car density per 1,000 inhabitants				R^2 of estimate
			K	K-range[b]	Present (1986–87)	Present in % of K[c]	
Australia	1965	46.7	495.6	441.6–549.5	431.6	79–87	0.9990
Austria	1971	27.2	366.4	330.0–402.8	336.0	83–92	0.9975
Canada	1968	69.6	615.4	526.4–704.4	454.0	65–74	0.9924
France	1967	34.5	422.5	380.6–464.4	394.0	85–93	0.9953
FRG	1971	30.7	493.1	443.8–542.4	463.0	85–94	0.9941
Italy	1972	26.1	426.5	384.0–469.0	408.0	87–96	0.9920
Japan	1974	16.6	245.2	221.2–269.1	241.0	90–98	0.9991
Spain	1976	21.9	283.9	255.5–312.2	265.7	85–94	0.9988
Sweden	1964	32.8	401.8	362.0–440.8	401.0	91–100	0.9950
New Zealand	1967	60.7	581.0	508.1–654.0	487.5	75–84	0.9946
UK	1966	36.5	333.3	300.2–366.3	318.0	87–95	0.9895
USA[d]	1970	57.8[d]	611.0	568.0–654.0	562.0	86–92	0.9950
World[e]	1970	34.1[e]	62.7	58.0–67.3	61.0	91–97	0.9950

[a]Data period used for parameter estimation: 1950–1986/1987.
[b]With 90 percent probability.
[c]Range corresponds to high estimate and best fit case respectively.
[d]Two growth pulses ($\Delta t = 14.5 + 43.3$ years).
[e]Two growth pulses ($\Delta t = 14.2 + 19.9$ years). Latest data available: 1984. World total includes centrally planned economies.

In comparing *Tables 2* and *3*, one can conclude that the results of diffusion analysis using both absolute and relative measures are consistent. Differences in the estimated Δts for Canada, New Zealand, and the world total are the result of strong divergences between population growth and passenger car registration growth rates. We again point to the strong heterogeneity in the ultimate saturation density levels that emerge from our analysis. Early starters such as the USA and Canada may reach saturation density levels as high as around 600 passenger cars per 1,000 inhabitants, whereas late starters such as Japan or Spain reach saturation density levels between 250 and 300 cars per 1,000 inhabitants.

Figure 31 summarizes the diffusion envelopes resulting from our analysis of the two phases of automobile diffusion in industrialized countries. The horse replacement and car diffusion trajectories are summarized by plotting the respective logit transformation of their logistic diffusion and substitution curves. Together these diffusion curves represent international diffusion bandwagons, i.e., rather narrow bands, in which all the diffusion processes of the industrialized countries analyzed are confined. *Figure 31* identifies two such diffusion bandwagons. First, the *horse-replacement bandwagon*, in which the diffusion rates are swift and very uniform in all countries. In fact the speed of replacement is similar to another process of technological change in the USA shown in the figure – diffusion of environmental control technologies, i.e., the replacement of cars without emission controls by those with catalytic converters.[24] This first diffusion bandwagon reaches saturation in the 1930s. The second one, consisting of the diffusion of passenger cars, is progressively converging towards the saturation period, showing a distinct acceleration for those countries starting motorization later.

We have complemented *Figure 31* by incorporating the diffusion trajectories of other infrastructures and technologies representative of the "automobile and oil age". These include the growth of surfaced road infrastructure in the USA and the USSR, oil pipelines in the USA, and the replacement of coal-fired steam ships by oil consuming motor ships. The associated large infrastructures of the "oil age" have tunneled through the first saturation phase of the growth of the automobile. In turn, these infrastructures appear to be approaching saturation around the year 2000, in tune with the cluster of saturations in the growth of the passenger car registrations in all industrialized countries. Presently, only the growth of surfaced road infrastructure in the USSR appears to have the potential to "tunnel" through this *season of saturations.*

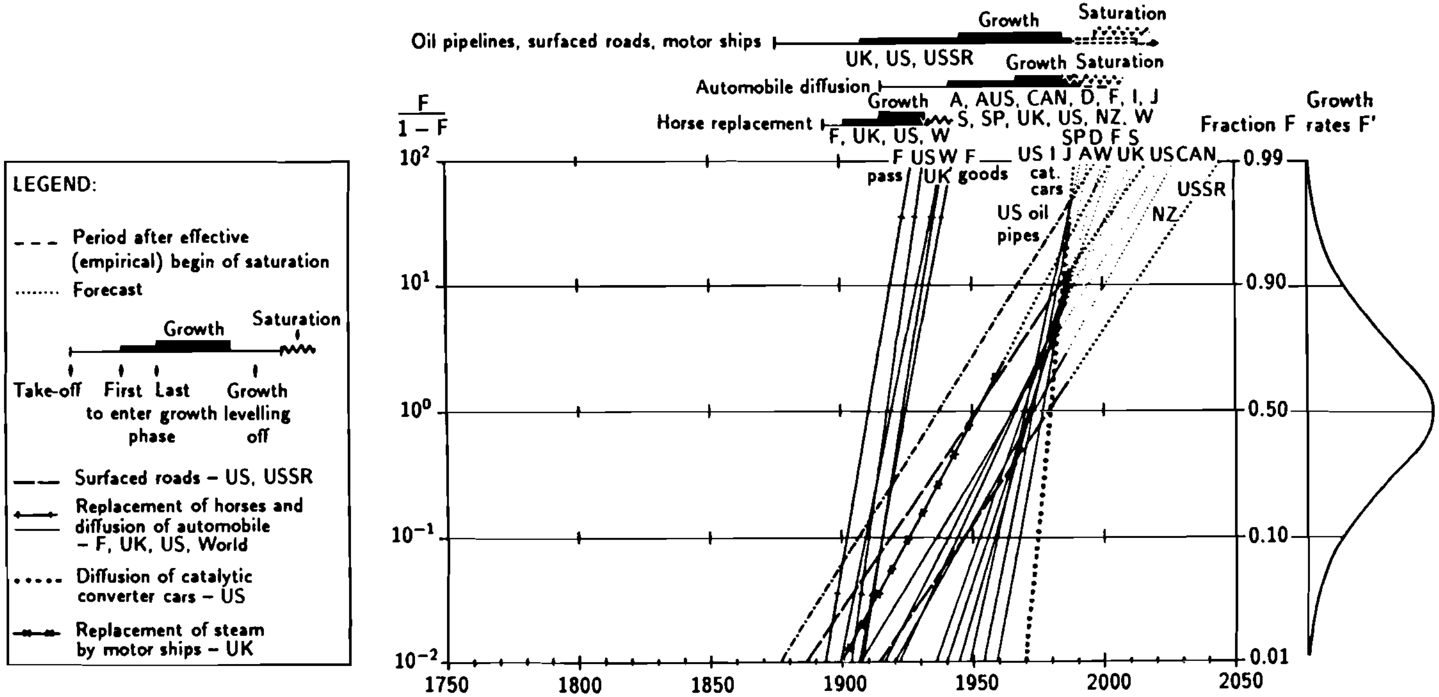


Figure 31. Growth pulses in the expansion of the oil/internal combustion engine technological cluster in industrialized countries: replacement of horses, growth of automobiles and road infrastructure, oil pipelines, and diffusion of motor ships, in fractional share of saturation level or market share respectively, logit transformation. Source: Adapted from Grübler (1990), Grübler and Nakićenović (1987), and Nakićenovic (1988).

Figure 31 therefore presents a condensed summary of the growth of a technological paradigm associated with the use of oil and the internal combustion engine as prime mover sources. The apparent start of saturation (i.e., the "growth to limits") of the largest part of this technological cluster is probably best characterized by the fact that the market share of oil as a primary energy source also starting saturating during that time. From such a perspective a major structural discontinuity in the evolution of a technological paradigm responsible for much of the economic upswing after World War II, appears consistent.

The difference in the high saturation density of OECD countries compared to the world total (below 70 cars per 1,000 inhabitants) implies that most of the developing countries (with most of the world's population) will not reach car diffusion levels anywhere close to that of developed countries. In order to corroborate this working hypothesis we have performed diffusion analyzes for selected COMECON and developing countries to investigate whether a similar saturation is imminent. Supported by empirical data, *Tables 4* and *5* show that this is indeed the case, implying that car diffusion in these countries will not "tunnel through" the forthcoming saturation in industrialized countries. This also makes our scenario of global car saturation at very divergent density levels internally consistent.

We analyzed the diffusion of registered passenger cars in centrally planned economies and developing countries based on both absolute and relative measures. The diffusion trajectories from both measures are compatible. It is also noticeable that the ultimate diffusion densities which may be achieved will be as heterogeneous, or even more divergent, as those emerging from our analysis of industrialized countries. In general, the uncertainty of the estimated saturation level in these countries is higher than for industrialized countries (see in particular the much wider uncertainty bands for the estimated saturation level K). In most cases, this is because the diffusion process is not yet close enough to the saturation level to allow for a higher statistical certainty. In some of the countries analyzed, in particular, India, Indonesia, South Korea, the Philippines, and Thailand, we were not able to determine an estimate for the saturation level, as the growth process is still in its early (exponential) phase. This implies that the ultimate saturation level for these countries might be larger than the present car density by at least a factor of three. However, considering the present low density levels of passenger cars per 1,000 inhabitants in these developing countries, e.g., two for India, 11 for Thailand, and 16 for South Korea, even growth by a

Table 4. Passenger car diffusion 1950–1987, in COMECON and developing countries,[a] in million passenger cars registered.

Country	t_0	Δt	Passenger cars (million) K	K-range[b]	Present (1986–87)	Present in % of K[c]	R^2 of estimate
Czechoslovakia	1977	26.2	3.5	3.1–4.0	2.7	68–76	0.9942
GDR	1976	28.6	4.1	3.6–4.7	3.3	71–80	0.9995
Hungary	1979	21.3	1.9	1.6–2.1	1.5	73–82	0.9991
Poland	1985	25.6	7.2	5.1–9.2	3.3	36–46	0.9980
Argentina	1979	39.1	6.0	4.8–7.3	3.9	53–65	0.9970
Brazil	1979	27.8	13.6	12.6–15.8	10.1	64–74	0.9986
Mexico	1984	33.1	9.9	6.2–13.0	5.2	40–53	0.9768
Nigeria	1979	14.4	1.0	0.9–1.1	0.9	82–95	0.9934
Taiwan	1988	20.4	2.8	0.3–5.9	1.0	17–26	0.9985
Venezuela	1996	44.1	9.1	2.5–35.4	2.4	7–26	0.9994

[a] Data period used for parameter estimation: 1950–1986/1987.
[b] With 90 percent probability.
[c] Range corresponds to high estimate and best fit case respectively.

factor of three would not noticeably affect our average estimated saturation density of less than 70 cars per 1,000 inhabitants at the global level.

Of the developing countries analyzed, only Venezuela appears to have a motorization pattern that allows for significant growth well into the next century. Venezuela appears to be an example of a country that started early and grew slowly to high density levels. Taiwan, on the other hand, is similar to Japan: both countries were late starters but caught up quickly as shown by their rapid Δt of diffusion.

This brings us to the last level of our analysis: the substantiation of the global car diffusion scenario by an empirical test consisting of two characteristic observations in the pattern of car diffusion. We have observed an *acceleration* of diffusion speed and a *decrease* in ultimate diffusion levels as a function of the "learning time", i.e., the time period between the beginning of the diffusion process and the time available for growth (i.e., Δt). *Figure 32* summarizes the results of *Tables 3* and *5* by analyzing the relationship between the length of the growth process of automobile diffusion (Δt), the ultimate saturation level of this process, and the time a country started motorization. The acceleration of diffusion for late starters is not a unique observation, we observed a similar relationship in the growth of the railway networks. Similar analyzes for the development of inland navigation and canals in a number of countries indicate an identical pattern (Grübler, 1990).

Perhaps the most striking finding that emerges from *Figure 32* is the straightforward mathematical expression for the "acceleration" phenomenon of diffusion in relating the log of Δts to the time period in which private cars achieved a one percent level of their saturation.[25] This functional relationship was first hypothesized by the late Ed Schmidt (1983). *Schmidt's Law* describes the acceleration of the diffusion rates of latecomers and their lower diffusion levels. Using linear regression, we arrive at the functional expression shown in *Figure 32*. The data confirm the acceleration tendency at a statistically highly significant level, and explain as much as 89.4 percent (R^2 adjusted for degrees of freedom) of the variance in the observed data. If one extrapolates the catch-up tendencies, one arrives at the conclusion that a country starting the diffusion of private cars now, would have a diffusion rate lower than ten years. Such rapid diffusion of car ownership appears quite infeasible from a practical viewpoint and could not in any case result in a significant growth of both absolute and relative car registration figures.

We continue by analyzing the relationship between the estimated ultimate car diffusion level and the start of motorization. Early starters such

Table 5. Passenger car diffusion 1950–1987, in COMECON and developing countries,[a] in passenger cars registered per 1,000 inhabitants.

			Passenger car density per 1,000 inhabitants				
Country	t_0	Δt	K	K-range[b]	Present (1986–87)	Present in % of K[c]	R^2 of estimate
Czechoslovakia	1977	27.0	225.9	196.1–420.0	173.5	41–77	0.9936
GDR	1976	28.6	249.2	216.0–282.3	198.0	70–80	0.9994
Hungary	1979	21.9	178.3	154.7–202.0	144.9	72–81	0.9990
Poland	1985	27.3	194.7	136.2–253.1	112.1	44–58	0.9972
Argentina	1975	42.2	173.3	149.0–197.6	127.0	64–73	0.9894
Brazil	1977	32.4	96.7	83.6–119.5	74.0	62–77	0.9949
Mexico	1975	34.5	87.7	76.3–99.0	65.0	66–74	0.9593
Nigeria	1977	14.4	9.4	9.1–10.6	9.0	85–90	0.9855
Taiwan	1986	20.3	112.0	63.0–150.0	54.0	36–48	0.9981
Venezuela	1987	58.7	286.2	57.2–420.0	136.0	32–48	0.9919

[a] Data period used for parameter estimation: 1950–1986/1987.
[b] With 90 percent probability.
[c] Range corresponds to high estimate and best fit case respectively.

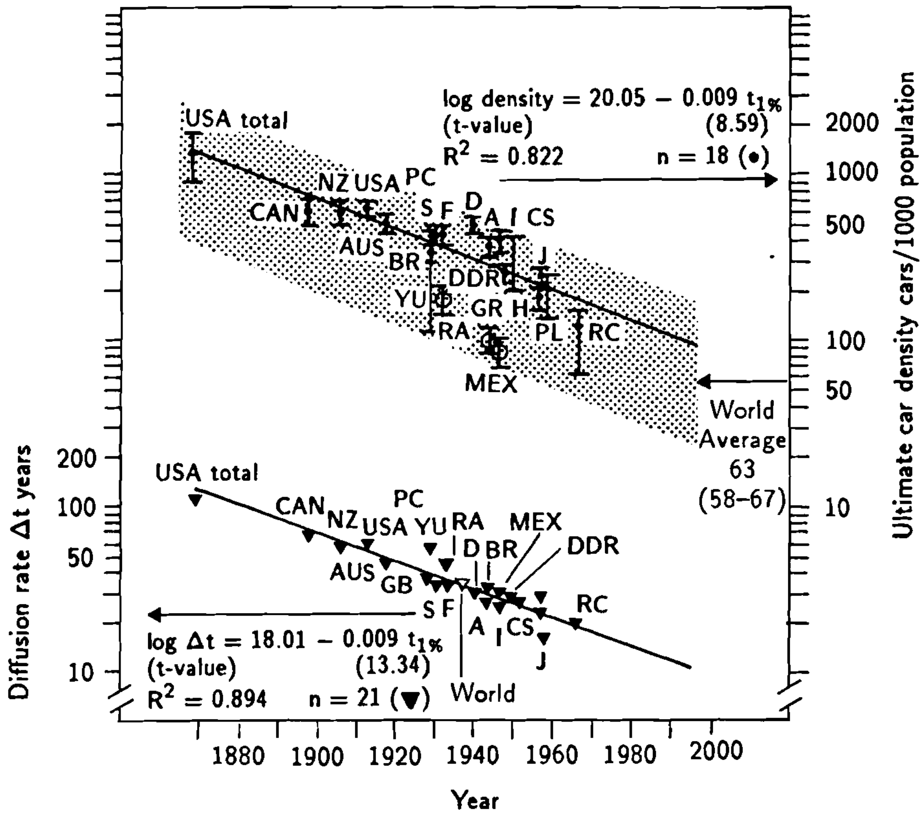


Figure 32. *Schmidt's Law:* Diffusion (growth) rates and densities of passenger car ownership as a function of the introduction date of the automobile.

as the USA and Canada will have significantly higher car density saturation levels (above 500 passenger cars per 1,000 inhabitants) than countries like Hungary, Japan or Taiwan, where density levels of about half the level appear typical. The estimated regression equation of the declining density trend explains as much as 82 percent of the variance in the estimated saturation density levels of industrialized countries.

Developing countries can be regrouped into three categories. Countries like Argentina, Brazil, and Mexico appear to follow the same declining density trend as industrialized countries, albeit at a significantly lower level. Venezuela and Taiwan are midway between developing and industrialized countries. All the developing countries, however, seem to follow a similar declining density trajectory similar to industrialized countries. Only Nigeria falls far below, indicating that motorization levels between developing countries will be even more divergent than in industrialized countries. In the same way that the USA does not provide a model for car diffusion in a country like Japan, car diffusion in Brazil or Mexico does not imply a realistic model for Nigeria, India or even China. A density level of below ten passenger cars per 1,000 inhabitants appears more likely for these countries.

The declining density envelope and the trend line of *Figure 32* suggest that any country starting diffusion now with a rapid growth in the number of cars registered would progress greatly with respect to the resulting diffusion levels. If we extrapolate the density envelope trends for the future, we arrive at the conclusion that an industrialized country starting motorization now would grow very fast (Δt of around ten years) but at the same time achieve a density level below 100 passenger cars per 1,000 inhabitants. Newly Industrialized Countries (NICs) may achieve figures close to our estimated world average of around 70 cars per 1,000 inhabitants, whereas "developed" developing countries like Brazil or Mexico might achieve density levels in the vicinity of 20 to 30 passenger cars per 1,000 inhabitants should motorization begin now. For those developing countries that do not have the necessary initial conditions for motorization to take off (primarily in terms of disposable income), like India or China, even these values are probably an order of magnitude too high: these countries fall outside the diffusion density envelope and are not part of the *automotive bandwagon* shown in *Figure 32*. We conjecture that within the next twenty years no car densities similar to those in industrialized or newly industrializing countries will emerge in developing countries such as China.

We postulate, therefore, that the acceleration tendency in private car diffusion has two implications. First, it appears unlikely that a similar diffusion will occur in countries that are not part of the present diffusion *bandwagon* of industrialized and industrializing countries. The second implication is that, with very few exceptions, the expansion in passenger cars registered will approach saturation by the turn of the millennium. Based on such a scenario one could expect a significant structural discontinuity in the evolution of the world automotive industry, a transition phase that could well be accompanied by a period of high market volatility and intensified international competition for survival in saturating markets.

The relative diffusion levels ultimately resulting from motorization are different between individual countries as a result of their different geographical, economic, etc., boundary conditions, and the related accumulated "experience" involved in the diffusion process. Our observation on the different car densities in various countries is consistent with the results of our analysis on the spread of the railways as the dominant transport mode prior to the automobile.

Cars in the year 2010

Table 6 summarizes the resulting scenarios of passenger car registrations derived from our analysis of passenger car diffusion. It regroups 1985 values and scenario ranges for the year 2010 by broad geographical regions based on the sample of 21 countries analyzed. For a better comparison with other projections we have also aggregated the 12 OECD countries analyzed (representing 98 percent of all passenger cars registered in the OECD) as a proxy for industrialized countries, and the residual to our global projection as a proxy for the sum of developing and centrally planned economies (CPEs). The latter regional aggregate is limited, however, to the degree to which it is comparable with other projections usually made on an outside CPE basis. Our scenario suggests that passenger car registration at the global level may grow by the year 2010 to between 440 and 500 million. This is an increase of between 21 and 38 percent compared to the 1985 level. For Less Developed Countries (LDCs) and CPEs our scenarios project an increase to levels of between 120 and 150 million cars, i.e., between 54 and 92 percent of the 1985 figures.

Our scenarios are lower than other projections especially for developed countries as we have postulated different density levels, with latecomers catching up but not achieving levels comparable to the first countries that started motorization. For this purpose, we do not consider the USA or Canada to be a guide for likely future developments in other industrialized countries. Car density saturation in urban areas, an increase in air transport for longer journeys, as well as the availability of new high-speed ground transportation systems, provide the rationale for our scenario of developed countries.

For the rest of the world our scenarios still allow for significant growth, both in absolute as well as in relative (percent increase over present values) terms. Again we consider, however, that the growth of passenger car registrations will be very heterogeneous within developing and centrally planned

Table 6. Scenario of passenger car registrations for the year 2010.

	1985			2010		
Region	10^6 cars	10^6 population	Cars/1000	10^6 cars[a]	10^6 population	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.

economies. Different initial conditions, degrees of economic development, and the development of road infrastructures, explain the present diverse car ownership rates, even for similar per capita income levels. Countries like Argentina, Brazil, Mexico or South Korea have per capita GNP values of a similar order of magnitude (between 2,000 and 2,500 1982 US$/capita in the Latin American Countries and 1,530 1982 US$/capita in South Korea) whereas their car density levels differ by as much as between 64 and 124 cars/1,000 inhabitants in the Latin American countries and 16 cars/1,000 in South Korea (1986 values). In our viewpoint, the diversity in diffusion levels will continue to be a characteristic feature of developing countries. The high growth rates in the urban population 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.

4.3 Air Transport

The evolutionary change in transport systems as described in the preceding sections indicates that faster modes are favored in long-distance traffic. Furthermore, the bulk of future growth in passenger and freight transport across continents and the globe is likely to be absorbed by air carriers, especially if economic blocks like Europe, North America, and Japan ultimately fuse to single functional entities. This suggests that a new growth pulse in commercial aviation and ground transport may be due in about two decades. Cruise supersonic and possibly air-breathing hypersonic aircrafts connected to 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 passenger travel and freight services.

Figure 33 documents the increase in air transport worldwide, measuring all operations and including centrally planned economies. Ton-km transported by air include cargo, mail, and passengers (following IATA conventions, one passenger-km corresponds to 90 kg-km). A logistic function has been fitted to the actual data and indicates that the inflection point in the growth of air carrier operations occurred around 1980. Thus, after a period of rapid exponential growth, about one doubling is left until the estimated saturation level is achieved after the year 2000 at around 290 billion ton-km. *Figure 33* also shows the statistical uncertainty bands associated with our

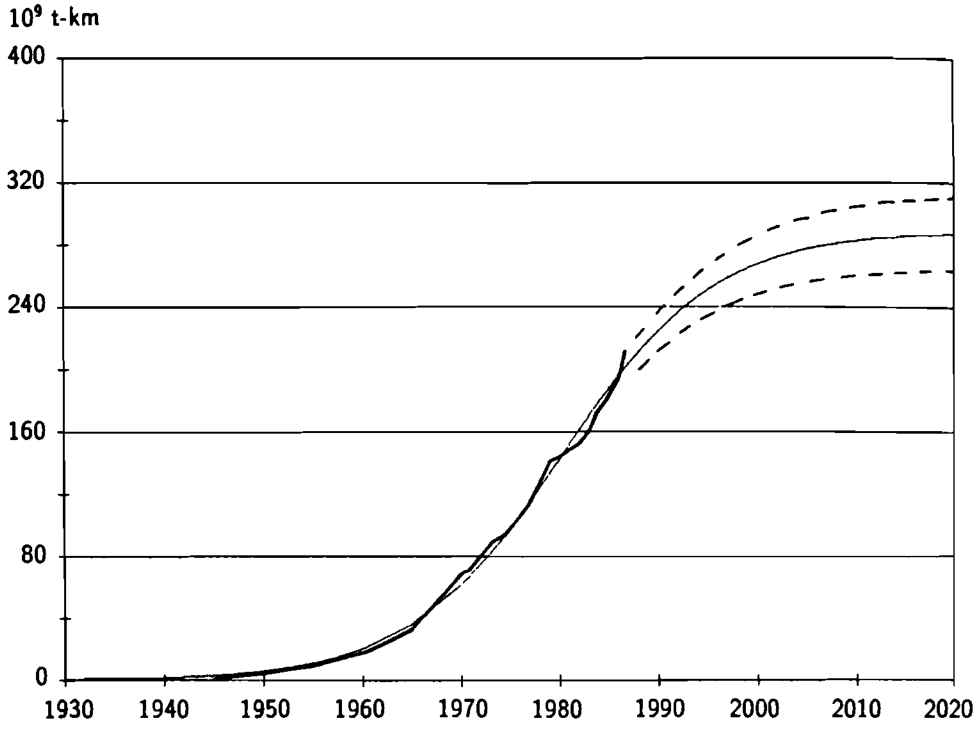


Figure 33. Volume of air transport worldwide (including centrally planned economies) passenger, cargo, and mail, in billion ton-km transported, linear scale. Diffusion model parameters: K 289.2 10^9 t-km, t_0 1980, Δt 34.5 years, and uncertainty bands.

estimate. The estimated saturation level, with a 90 percent probability, lies between 243 and 335 billion ton-km, and it is likely that the estimate will lie between the best fit and the upper value respectively, as the growth process has barely proceeded beyond the inflection point.

Perhaps the most interesting result is that it took about 35 years for world air transport to reach the inflection point (about half of the estimated saturation level) and that within less than three decades the saturation level will be reached. This raises a crucial question: What could happen after such a saturation?

The global fleet of commercial aircraft can be described in a number of ways. One obvious way of describing it is by the number of commercial aircraft in operation worldwide. This number increased from about 3,000 in the 1950s to almost 10,000 in the 1980s. At the same time, however, the performance or carrying capacity and speed of aircraft increased by about two orders of magnitude. Thus, the size of the fleet is not the most important feature, because 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 system for destinations with a lower volume of traffic.

Figure 34 shows the improvement in carrying capacity and speed (often called productivity) measured in passenger-kilometers per hour. Each point on the graph indicates the performance of a given aircraft when used in commercial operations for the first time. The DC-3 was introduced in 1935 with a performance of about 7,400 passenger-km/hr (21 passengers at 350 km/hr); the Boeing 747 (B-747) was introduced in 1969 with a performance of about 500,000 passenger-km/hr (500 passengers at 1,000 km/hr). The largest planned B-747 (500 series) will carry almost 700 passengers. The B-747 family is therefore about a hundred times as productive as the DC-3 was 50 years ago. The upper curve in *Figure 34* represents a kind of performance feasibility frontier for passenger transport. At any given time there appears to be only one appropriate productivity specification for long-range (most productive) passenger planes. All commercially successful long-range transport was introduced along this frontier. *Figure 34* may also explain why Concorde was not a commercial success, which, despite being a technological marvel, significantly fell short of the productivity of the B-747 introduced around the same time period. The Concorde would have required around 250 passenger seats (instead of 100) in order to achieve a similar productivity level as a B-747 (i.e., an hourly "throughput rate" of 500,000 passenger-km).

The saturation level of the aircraft performance curve is estimated to be about 1,200 passengers at subsonic speeds. A superstretched B-747 could achieve this level but this is probably the upper limit with regard to any gradual change that is possible for the current generation of aircraft. Furthermore, the productivity of all passenger aircraft is confined to a rather narrow band between the performance feasibility curve, and a "parallel" curve with a lag of about nine years. This curve represents the growth of world air passenger-km transported, and is identical in its growth dynamics to the total air transport volume presented in *Figure 33* above. The growth of air travel and the productivity of the best aircraft have, therefore, increased in parallel, indicating a consistency in the evolution of the global air transport system.

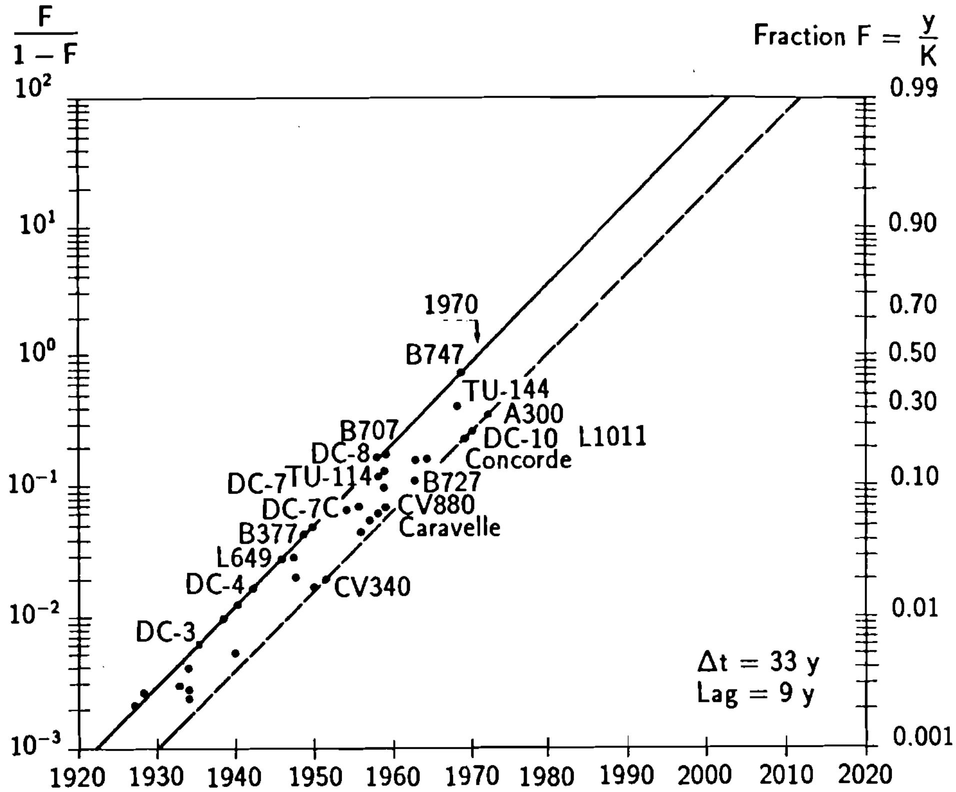
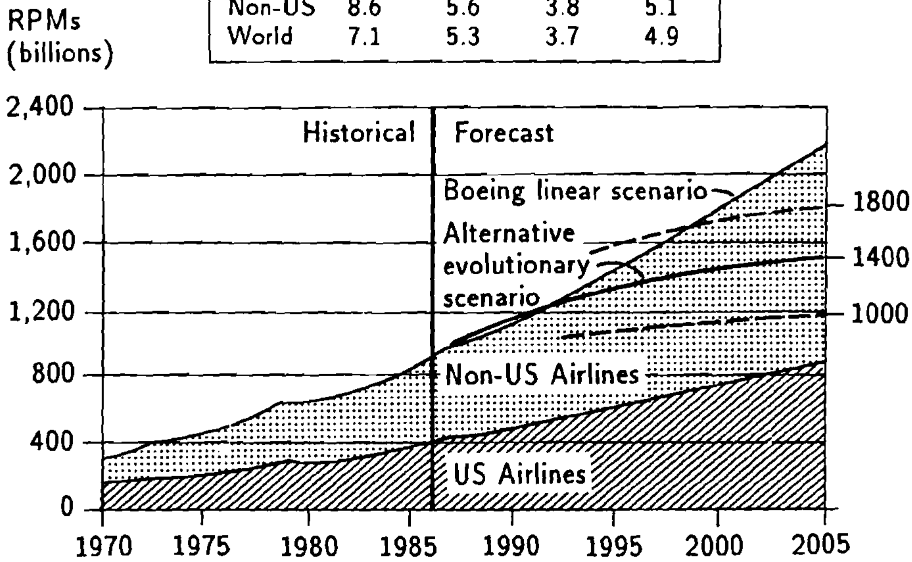


Figure 34. Passenger aircraft performance, in fractional share of the estimated saturation level (1.2 10^6 million passenger-km per hour), logit transformation. Source: Nakićenović (1988).

Figure 35 compares the resulting estimate of total world passenger-miles transported by air by a recent Boeing market volume forecast. In addition our scenario of air traffic volume includes the USSR, so that the difference between the two scenarios is in fact larger than suggested by *Figure 35*.

The reason for the lower estimate of future world air traffic compared to the Boeing forecast, is not only due to the fact that we employ a nonlinear growth model (as opposed to the linear trend forecast apparently underlying Boeing's projection), but also that our scenario takes the forthcoming saturation of future productivity increases of existing aircraft into consideration. With aircraft productivity saturating, future growth in demand could only be achieved by either large increases in the number of aircraft in operation

	Boeing Scenario Annual Growth Rates			
	1970–1986	1986–2000	2000–2005	1986–2005
US	5.6	4.9	3.6	4.5
Non-US	8.6	5.6	3.8	5.1
World	7.1	5.3	3.7	4.9



Note: Boeing scenario excludes USSR and non-ICAO nations, but includes Peoples Republic of China and Taiwan.
Evolutionary scenario is for world total including USSR.

Figure 35. Volume of world revenue passenger-miles, Boeing market forecast, projection of logistic growth model (ultimate saturation level K 1,570 billion passenger-miles, t_0 1982, Δt 33 years), and 90 percent probability uncertainty bands of logistic estimate, in billion revenue passenger-miles.

or by a quantum leap in technology, similar to the introduction of the jet engine.

The fastest airliner, Concorde, and the most productive jet transport, Boeing 747, both flew for the first time almost twenty years ago. Ever since, the volume of all airline operations has continued to increase while the productivity of the B-747 increased only marginally through stretching. Most of the subsequent technological development focused on gradual improvements such as noise reduction and the improvement of fuel efficiency. Unavoidably, this leads to an impression of diminishing returns in the further advancement of airliners and, consequently, the possibility of an approaching saturation in commercial air transport. An alternative view could be to expect an increase in the number or capacity of aircraft in order to keep up with increases in the volume of traffic. Our analysis of the development of transport infrastructures and passenger travel indicates that large increases in the volume of operations are indeed likely. This is because air transport continues to take larger shares of traffic and total passenger-kilometers traveled worldwide with an increase in economic growth. If we consider current airport overcongestion and the many inconveniences associated with an increase in the size of aircraft, the likelihood of hyperjumbos being developed with a capacity of a few thousand passengers is slim. A third possibility out of this stalemate could be an increase in productivity of the fleet by increasing aircraft speed; this would represent a revolutionary change in technology and a whole host of possible positive and negative externalities.

Another alternative, which could result in increases in commercial air transport well into the next century, might materialize if the renewed research programs in advanced, high-speed airliners by the aerospace communities on both sides of the Atlantic bear fruit. Recently, plans were announced to study, and eventually develop, supersonic (SST) and hypersonic transport (HST). The most daring of the proposed designs could fulfill even more ambitious objectives and lead to the development of an air-breathing spaceplane.

Assuming that such a development is technologically possible and economically viable, it poses a number of fundamental questions associated with the expected side effects of a large fleet of hypersonic passenger aircraft. Certainly, the noise problem must be overcome by both a reduction in the inherent noise profiles and the removal of hubs and routes for such aircraft from populated areas. A more important concern, however is the possible adverse effect of such a fleet on the chemistry of the upper atmosphere. In view of the observed ozone depletion of the stratosphere, such concerns are timely while the design and configuration of proposed hypersonic transports are still in an early development phase. Aircraft capable of operating at high Mach numbers would be powered by methane or hydrogen. At hypersonic speeds in excess of Mach 5, hydrogen would be the fuel of choice since, among other things, it would create the most environmentally benign emissions.

If possible adverse effects from the continued increase in transport operations could be overcome, the maximization of range through productivity increases and speed would be consistent with the observed evolution of transport systems since the onset of the Industrial Revolution. Marchetti (1987) postulated that this evolutionary process will be complete when any place on the whole earth becomes reachable within an hour. A gigantic ecumenopolis could be serviced by highly productive aircraft and maglev infrastructures, providing that such developments become socially acceptable and that the current prolonged phase of economic restructuring is followed by renewed growth leading to unprecedented levels of welfare. Perhaps an indicative precursor of this development is the deployment of B-747 aircraft for short-distance commuting along the Tokyo-Osaka corridor in addition to the Shinkansen rapid rail transport; in the not too distant future a maglev link could convert two metropolitan areas into a truly integrated hypercity that could be traversed within an hour. The off-shore Kansai airport could then provide an extremely productive hub for long-distance, transcontinental travel. We will present below a *Gedankenexperiment*, showing the possible market response, if such high productivity transportation systems would indeed become available after the turn of the century.

Let us now return to our discussion of the evolution of the world air transport market on a shorter time horizon in order to discuss what the likely regional disaggregation of our scenario of global air transport operations could be. Air transportation is carried out through a spatial hierarchy of long- to medium-term distances. Shorter-distance domestic or short-distance international flights, as in Europe, provide the necessary feeder functions for air transportation over larger distances on a continental or even transcontinental scale. Thus we consider that the growth rate that is realized at the higher spatial hierarchies of air transportation will result in equivalent growth at lower hierarchical levels. To illustrate the complementary character of long and medium distances in air transportation *Figure 36* shows the evolution of the domestic and international ton-km transported by air (passengers included on the basis of 90 kg per passenger).

Europe, with its many small countries and short distances in international air transport has been considered as functionally analogous to domestic feeder traffic in larger geographical spaces such as North America. As can be seen from *Figure 36*, domestic flights (short to medium distances) have, after initial predominance over long-distance international flights, reached parity with international air transport volume since the early 1970s. This supports the complementary character of short-, medium-, and long-distance

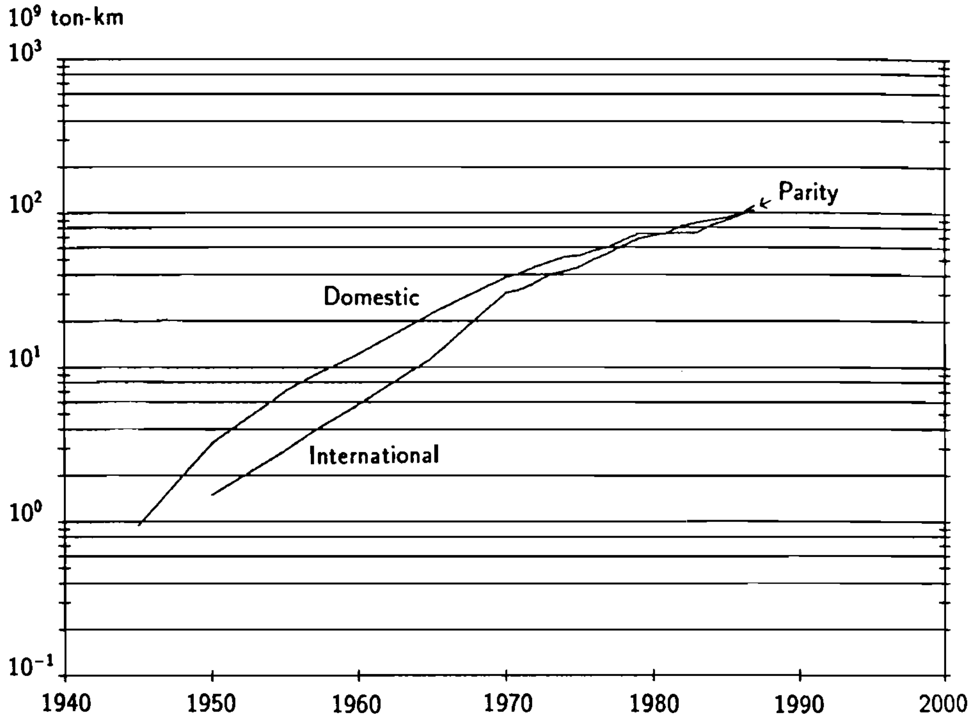


Figure 36. Growth of domestic and international air transport volume (passengers, cargo, and mail), in billion ton-km flown, logarithmic scale.

air traffic and we therefore propose a scenario for the future in which the growth of world air transportation will be divided equally between international and domestic destinations.

As regards a regional breakdown in the volume of air transport, we face a serious data problem in that no consistent data on the regional disaggregation of all air transport operations are available. For international, scheduled air traffic, IATA statistics allow the analysis of its evolution by major geographical area (as reported in *Figure 37*). An interesting finding from our analysis is the stability in the regional breakdown of international air transport operations of IATA members. Only the share of Europe declines from around 20 percent of the market share in 1949 to the present level of 12 percent, but as discussed above, it is better to consider European air traffic as a domestic air operation. Particularly noteworthy is the fact that despite the much discussed emergence of the Pacific rim countries, their share in

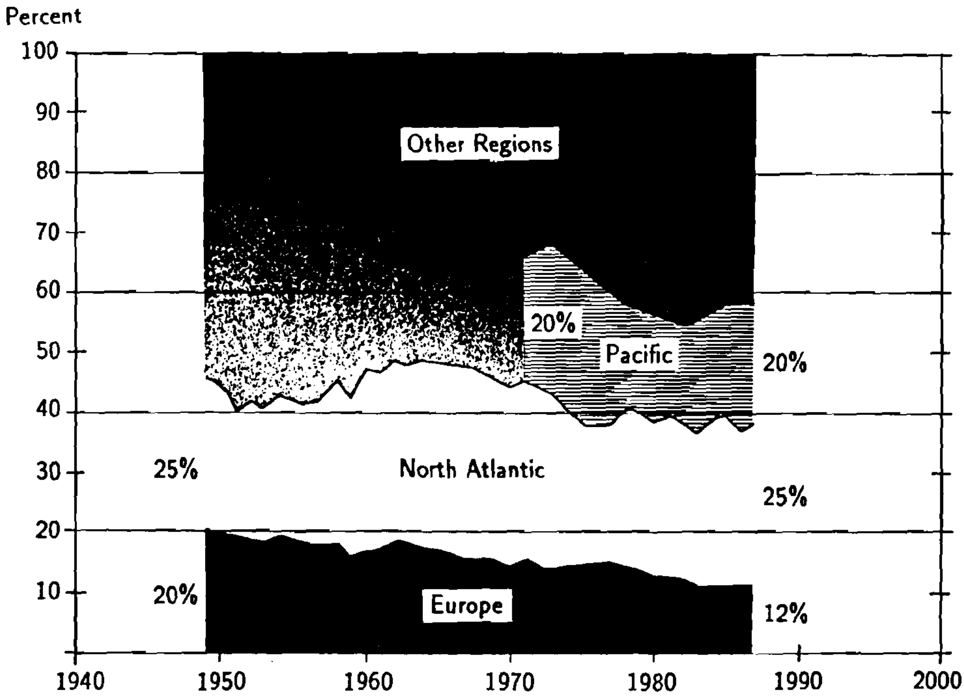


Figure 37. Share of different regions in scheduled international IATA air traffic. Source: IATA (1961 to 1987).

international air transport volume has remained constant at a level of 20 percent ever since the first time statistics were collected for that region. In the absence of available statistics and on the basis of *Figure 37*, we thus adopt a working assumption that the growth rates in air transport operations will *grosso modo* not change significantly between broad geographical regions.

Gedankenexperiment

Based on our assumption that air transport will grow along a nonlinear trajectory, saturation in market volume could occur around the year 2015 at a level which is about one third higher than at present. We have also discussed the fact that the next growth pulse in air transport could result in advanced technologies meshing the world's principal gravity centers into a single functional entity. A technological revolution such as the introduction

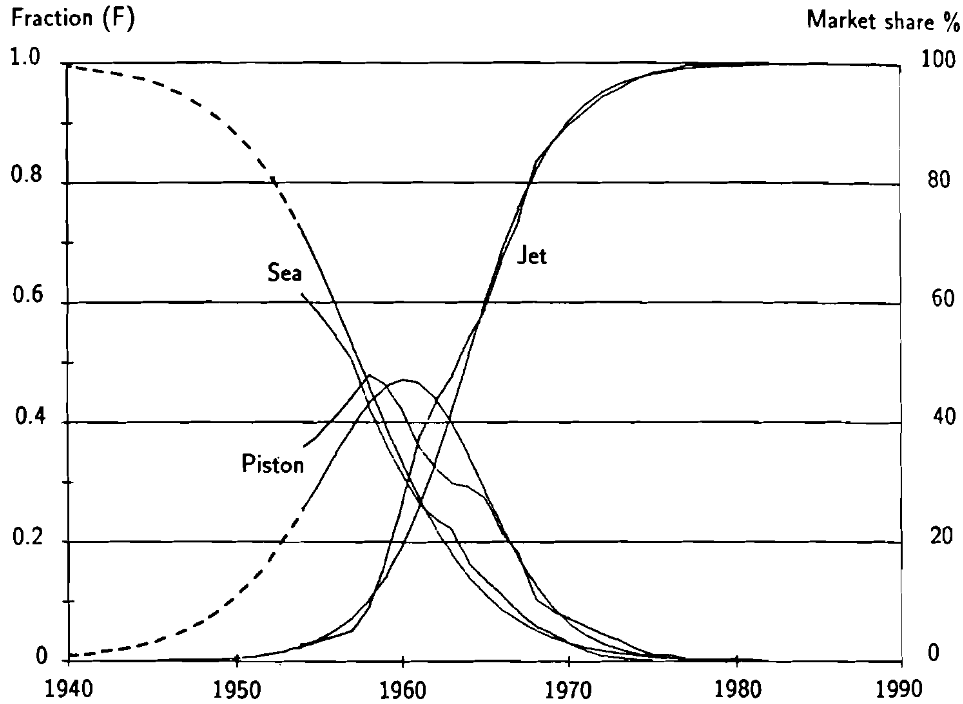


Figure 38. Share of ship and piston and jet aircraft in transatlantic passenger crossings, measured by the fractional share of passengers transported.

of aircraft capable of super- or hypersonic flight regimes would be of similar importance to the introduction of aircraft itself for long-distance travel.

Once a new transport mode enables the extension of the spatio-temporal range of human activities, a very strong impact on travel demand can be expected. *Figure 38* illustrates such a technological revolution in the transport sector: the replacement of transatlantic passenger crossings on ships, first by the piston-propelled aircraft and later jet aircraft. As can be seen from the figure, it took around 30 years to replace ships by aircraft. *Figure 39* shows the same process of technological substitution by analyzing the total number of passengers transported by the three technologies.

The peak rate of transatlantic passenger crossings by ship occurred in the late 1920s with over two million passengers transported annually. The emergence of the piston-propelled aircraft reduced by half the number of passengers crossing by ship, whereas the total market volume did not change noticeably. Thus, by the mid-1950s when jet aircraft were introduced, around

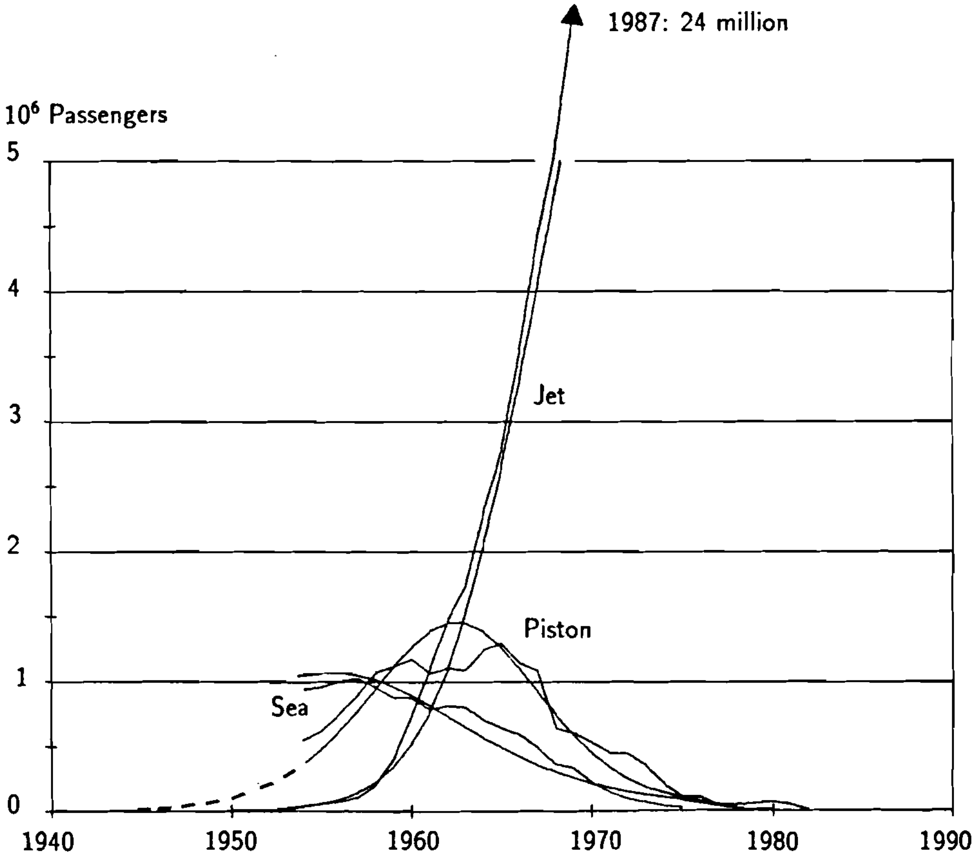


Figure 39. Number of passengers crossing the Atlantic by ship and piston and jet aircraft, empirical data and estimates based on logistic substitution model, in million passengers.

one million people were crossing the Atlantic by ship and an equal amount by piston aircraft. Much more decisive, however, was the impact of jet aircraft on the number of passenger crossings. As can be seen from *Figure 39*, the market volume increased dramatically as a response to the availability of such a new, fast, and convenient form of transatlantic travel. Compared to its pre-introduction time the jet aircraft increased the market volume by a factor of 10 over 30 years.

This increase in traffic flux by one order of magnitude serves as an illustrative case to conjecture about the likely market response to the availability of a new air transport technology in the form of super- or hypersonic aircraft.

A new growth pulse in air transport traffic, leading to levels at least one order of magnitude above our estimated saturation level of world air transport based on present technology, could emerge after 2010, i.e., about the time when conventional aircraft technology reaches its estimated saturation level. Such advanced air transport would however require new infrastructures in the form of hubs, appropriate feeder systems – either by advanced ground transportation technologies such as maglevs or regional feeder aircraft, and finally also new energy infrastructures, based on either methane or hydrogen as fuel.

5. Implications for Energy Demand

Future energy requirements for automobiles and aircraft will depend on their diffusion levels, usage, and efficiency of energy use. Our scenarios of future fuel demand for automobiles are based on their diffusion levels and a compound efficiency improvement rate consisting of specific energy requirements and changes in usage. We assume that the latter will be relatively small in the case of automobiles compared to fuel efficiency improvements. In the case of aircraft, the diffusion levels are already expressed in terms of volume of all operations so that efficiency improvements represent fuel requirements per passenger- or ton-kilometer.

The main feature of this scenario is that it is based on a gradual saturation in automobile diffusion and the volume of air transportation in the next century. In both cases the remaining growth potential is relatively modest until the year 2010. With respect to 1985 figures, the automobile fleet is expected to increase by about 20 to 37 percent, and the volume of air transportation by about 56 to 81 percent. The two ranges correspond to the two diffusion trajectories that we have called the *best fit* and *high case*, respectively.

With this overall scenario of the future development of automobile ownership and air transport we assume two alternative efficiency improvement rates. One is based on the long-term historical efficiency improvement rates that have prevailed in most of the industrialized countries, and the second corresponds to more vigorous efficiency improvements in the future. In addition, we have estimated fuel demand for the year 2010 based on current fuel efficiency of aircraft and automobiles. We call these *evolutionary*, *high*, and *1985* efficiency cases. The first case corresponds to an annual efficiency improvement of one percent, the high case to an improvement of 2.5 percent per year, and the 1985 reference case to no improvement at all. In all three cases we assume identical improvement rates for world regions, but due to the different structure of current energy requirements, fuel efficiencies, and future diffusion, the resulting aggregate fuel demands by the year 2010 portray different overall rates of change and consequently different patterns of fuel demands.

The *evolutionary* case is based on the aggregate efficiency improvement rate in industrialized countries. The overall efficiency of converting primary and final energy to energy services has improved radically since the beginning of the Industrial Revolution. Some efficiency improvements resulted from improved technologies, others from substitution of old by new technologies, and finally some were due to changing consumption patterns. The extent of these changes and improvements can be expressed at an aggregate level by the amount of primary energy consumed per unit of gross national product (energy intensity). In most of the industrialized countries the overall energy inputs into the economy decreased at an annual rate of about one percent over the last hundred years.

Figure 40 shows the ratio of energy consumption over GNP for the USA. The average reduction in energy consumed in order to generate one constant dollar of GNP was about 0.9 percent per year over the last 180 years. It shows that a regular decline in energy intensity for the whole economy prevailed over a long period in history, indicating that energy conservation is a historical process that was rediscovered as a concept only during the last decade. This decrease in energy intensity fluctuated considerably around the decreasing secular trend of 0.9 percent per year. In fact, there are clearly visible periods when the amount of energy needed per unit of value added increased, while in other periods the rate of decrease appears to have accelerated. *Figure 40* shows that the major periods without longer-term improvements in energy intensity occurred in the 1820s, 1900 to 1920, and most recently, from about 1945 to the early 1970s. After the OPEC oil embargo another phase in improving energy efficiencies was initiated. Since 1973, the decrease in energy intensity in the USA has been twice as fast as its long-term historical rate and almost three times as fast in Japan, with improvements in the UK, the FRG, and France somewhere in the middle. In contrast, the average improvement in energy intensity for the USA since 1950 has decreased to the long-term average of 0.9 percent per year despite the great improvements since 1973! Apparently the rapid economic growth and expansion of the 1950s and 1960s retarded improvements in energy efficiencies at the level of the whole economy, and the accelerated energy savings

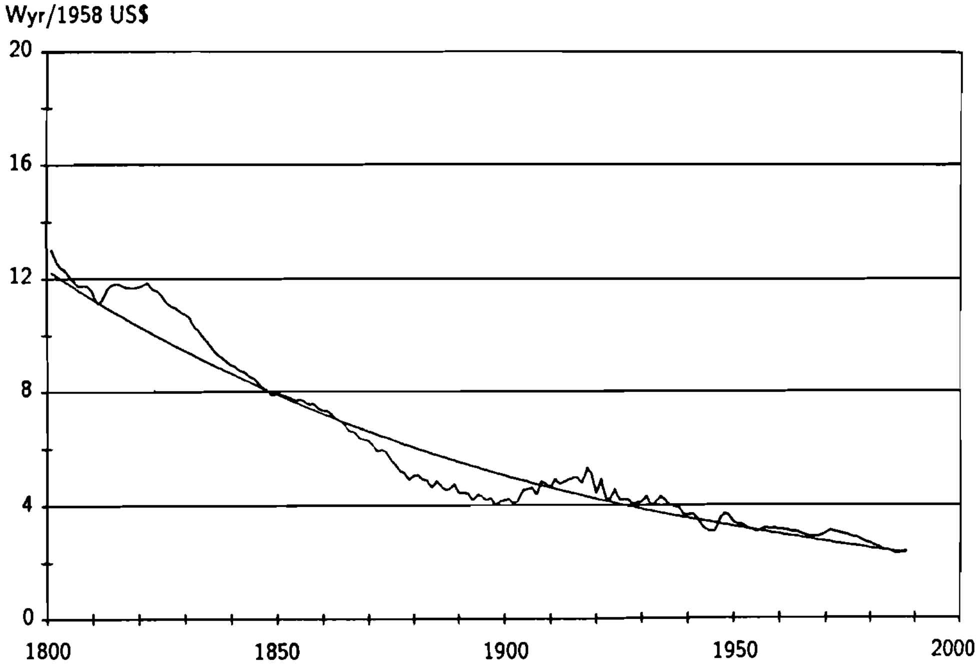


Figure 40. Primary energy consumption per constant GNP in the USA from 1800 to the present, in KWyr per 1,000 1958 US$. Source: Updated from Nakićenović (1984).

and efficiency programs launched after 1973 can be seen as a correction and reversal that brought the trajectory back to the historical average. While the other four countries use energy much more efficiently than the USA, relative improvements since the 1950s have been on the order of 1.3 percent in the UK and the FRG, about 1.1 percent (since 1960) in Japan, and about 0.6 percent in France.

This brief description of long-term efficiency changes illustrates that an improvement of one percent per year in our evolutionary scenario could indeed be achieved in the future without any radical measures, i.e., they would not have to be more radical than those achieved by industrialized economies in the past. In fact, this is not too far away from the actual efficiency improvements achieved for cars and aircraft during the last decades. In the USA the average automobile fleet consumption was about 13.1 mpg in 1950. By 1985 the average efficiency of the fleet increased to about 18.2 mpg. This translates into an average improvement of about 0.9 percent per year and is thus identical to the aggregate average for improvements in energy intensity for the whole economy. A similar improvement trend can be observed in other industrialized countries, e.g., one percent per year in France between 1970 and 1985. Another example illustrates almost identical rates of fuel efficiency for aircraft in the USA: in 1950 the average fuel consumption was about 160 ton-km/gal and by 1985 this improved to 231 ton-km/gal (Borderon, 1989). This corresponds to a reduction in fuel consumption of one percent per year.

While these may be typical aggregate improvement figures they are certainly not representative for more revolutionary changes that characterize our high-efficiency scenario. For example, the replacement of horses by automobiles improved the efficiency of road transport enormously. A horse has an overall efficiency of about four percent in converting feed energy (energy content of hay) to mechanical energy, while the modern internal combustion engines transform the chemical energy in fuel to mechanical energy at much higher efficiencies; about 20 percent for gasoline engines and up to 32 percent for large truck and bus turbo-diesel power plants. This translates into an average efficiency improvement for road vehicles of about 2 to 2.6 percent per year over the whole period of 80 years. Furthermore, even less radical improvements achieved since the energy crisis were higher than the historical average of one percent per year. Incremental and cumulative improvements of automobiles since 1970 in the USA increased efficiency at a rate of two percent per year, from 13.5 to 18.2 mpg in 1985. In other words, the improvements were very small between 1950 and 1970. Examples of relatively large improvements since the early 1970s abound. In South Korea vehicle efficiency has improved at a rate of 2.8 percent per year since 1971.

The most fuel-efficient automobiles actually require less than half of their currently-designed efficiency level. A number of small Japanese cars such as the Daihatsu Charade, Subaru Justy, or Toyota Starlet have an average fuel efficiency of about 60 mpg. In addition there are a number of diesel passenger cars with lower fuel consumption. Most of the manufacturers have prototypes of the same size with even lower fuel consumption. The complete replacement of an automobile fleet takes about 30 years. Thus if we assume that all current vehicles will be replaced by twice-as-efficient vehicles in 30 years this will lead to an implicit improvement of 2.3 percent per year.

Air transport efficiency improvements have also been higher for individual aircraft than our aggregate figure of one percent improvement per year suggests. Already today the best of the new transports consume about 15 percent less fuel per passenger-kilometer than their model predecessors. For example, the new Airbus 320 and Boeing 757-200 consume at least 15 percent less fuel than similar aircraft of only ten years ago (e.g., Boeing 737-400 needs about 20 percent less fuel than the older version Boeing 737-200). However, these are all short- to medium-range aircraft, and are not representative of the whole fleet. Long-range aircraft efficiency has also improved substantially since the introduction of the jet. The Boeing 707 had fuel requirements of about 250 kg/seat for a 4,800 km range when it was introduced in 1958 as the most productive passenger transport. The most advanced long-range transport Boeing 747-500 will require about 120 to 150 kg/seat on a similar route. This represents an efficiency improvement of about 1.7 to 2.3 percent per year.

In view of these impressive efficiency improvements in automobiles and air transport of between two and three percent per year, we assume a representative figure of 2.5 percent for the future annual reduction of specific fuel requirements in the high-efficiency scenario. This high improvement rate would change the average fuel efficiency of automobiles from the present world average of about 20 mpg to almost 40 mpg by the year 2010, and air transport fuel consumption from about 230 ton-km/bbl today to some 430 ton-km/bbl in 2010. In the evolutionary scenario the fuel efficiency improvements are more modest at about 25 mpg for the global automobile fleet and about 300 ton-km/bbl for air transport by the year 2010.

Table 7 summarizes the relative (i.e., compared to 1985 figures) evolution of transport energy demand resulting from the combination of our diffusion scenarios, the hypothetical energy demand based on 1985 efficiency rates (*1985 efficiency* scenario), and the two scenarios on future usage/efficiency improvements (*evolutionary* and *high efficiency* scenarios, respectively). The range of figures in the scenarios stems from the range in the estimated diffusion levels by the year 2010, considering the best fit and high estimate of the diffusion level, respectively.

Taking our scenarios on forthcoming saturation in passenger car growth and later air transport, the hypothetical energy demand compared to 1985 and with no further efficiency improvements (*1985 efficiency scenario*) in the year 2010 would result in an increase in world automotive fuel demand of between 22 and 41 percent. The hypothetical world air fuel demand would be between 55 and 82 percent higher than in 1985. These hypothetical demand figures are, however, rather unlikely to emerge, as we can assume, with a high degree of probability, further efficiency improvements in the transport sector.

Table 7. Diffusion of passenger cars and air transport, and evolution of transport energy consumption relative to 1985 with three scenarios for efficiency improvements (rounded figures).

	Diffusion level[a]		1985		2010 energy demand index		
	1985	2010	Efficiency mpg	Energy demand index	1985 efficiency	Evolutionary efficiency	High efficiency
Automobiles							
North America	147	170–190	18	100	115–127	90–100	63–69
Rest of OECD	142	150–170	26	100	107–118	82–89	57–64
Rest of world	76	120–140	16	100	153–190	120–147	80–100
Total	365	440–500	20	100	122–141	95–109	65–76
Air transport							
World total	182	285–330	230[b]	100	155–182	118–141	82–96
Air/car energy				100	←	126–129	→

[a]Units: for automobiles 10^6 passenger cars, for air transport 10^9 ton-km.
[b]Air transport efficiency indicator: t-km/bbl.

In the *evolutionary efficiency* scenario (based on an average annual compounded usage/efficiency improvement rate of one percent) automotive fuel demand would remain practically at the 1985 level in the year 2010 (between five percent lower and nine percent higher than in 1985) at the world level, whereas world air transport fuel demand would be between 18 and 41 percent higher than in 1985.

Finally in the *high efficiency* scenario (based on an average annual improvement of the compounded usage/efficiency rate by 2.5 percent), our diffusion saturation scenarios, together with the significant reduction in specific energy requirements per vehicle or air ton-km, result in a drastic reduction in the world transportation fuel demand. The *high efficiency* scenario would imply that by the year 2010 automotive fuel demand would be between 24 and 35 percent lower than in 1985. Even in world demand for aircraft fuel, the *high efficiency* scenario would imply a decrease in fuel demand of between 4 and 18 percent compared to the 1985 consumption level.

Two characteristics are common to all scenarios. First, due to the fact that the growth potential for air transportation is higher compared to the remaining diffusion potential for automobiles, the relation between automotive and aircraft fuel demand would shift in favor of aircraft fuel. This shift in the relative transport fuel mix is, in all scenarios, between 26 and 29 percent over the 1985 ratio on the world level. Depending on the remaining growth potential of passenger car diffusion in different world regions this ratio would of course be higher in favor of aircraft fuels in countries where automobile diffusion is close to saturation.

The second characteristic common to all scenarios concerns the regional breakdown of automotive fuel demand. As a result of the different growth potentials remaining in various world regions, in particular the higher growth potentials remaining in the NICs and the CPE countries compared to OECD countries, automotive fuel demand evolves differently in these regions. The differential resulting from our diffusion scenarios is accentuated by lower energy efficiency and higher use rates, resulting in higher specific energy consumption figures for the automobile fleet in these countries.

The *evolutionary efficiency* scenario illustrates this situation more clearly. Whereas world automotive fuel demand in 2010 remains basically around the 1985 level, the situation is different as a result of automobile diffusion saturation in OECD countries. North America would have an automotive fuel consumption somewhere between the 1985 consumption (i.e., a zero demand growth) level and about a ten percent lower demand than in 1985. The remainder of OECD, due to its earlier saturation (combined with efficiency improvements), would see automotive fuel demand decreasing between 11 and 19 percent of the 1985 consumption figures. This no growth or even negative growth situation in OECD countries is in sharp contrast to developing and centrally planned economies, where automotive fuel demand would increase between 20 and 47 percent compared to 1985 figures.

Even in the case of a combination of diffusion saturation and very high efficiency improvements, developing and centrally planned economies would see a slight reduction in their automotive fuel demand by 2010, ranging from no change compared to 1985, to 20 percent less demand than in 1985. OECD countries would, in the *high efficiency* scenario, have decreases in their automotive fuel consumption of up to 43 percent less than their 1985 demand figures. This provides a clear illustration of the significant oil demand impact of scenarios combining forthcoming saturation in the diffusion of automobiles and ultimately also of air transport with vigorous efficiency improvement scenarios.

6. Conclusions

We have demonstrated that the long-term evolution of the transport system is characterized by a sequence of replacements in which faster and higher quality transport modes substitute for traditional ones. The basic development pattern identified appears invariant between different countries or even between different economic systems, pointing to deeper underlying long-term driving forces than enter more conventional transport demand and mobility analyzes. We have shown that transport systems and their infrastructures evolved from an early development phase characterized by slow growth to a vigorous expansion phase that finally culminates in saturation; the period when change and transition to the next generation of transport systems occurs.

Replacement processes proceed according to a schedule that apparently defines the opportunity windows for the development of particular systems. In the leading countries, diffusion leads to a long, sustained period of development with all the characteristics of pervasive systems that lead to high adoption levels. In countries where adoption occurs later, growth proceeds faster but results in lower adoption levels. This catch-up effect induces simultaneous saturation both in the leading and following countries, albeit at significantly different diffusion levels. As the evolutionary development path that follows saturation is based on fundamentally new techno-economic solutions, further development of the transport systems is based on new technologies and infrastructures rather than on a repetition of the growth paradigm characteristic of the previous development phase.

The development of individual transport infrastructures and associated networks is a long process, lasting many decades. A further finding is that the future of the transport system will be shaped by the quest to increase speed, flexibility, and quality of transportation turnover. In the analysis of the interaction between the different transportation modes we have concluded that these quality criteria are apparently best met by air transportation, followed by road transport. As a consequence, the expansion of global air transport will be higher, growing by another 60 to 80 percent during the next 20 to 30 years compared with a more subdued growth of the vehicle fleet by 20 to 40 percent during the same period. Such developments in global road and air transport could have significant impacts on oil demand.

The resulting modest growth rates of air and road transport, combined with vigorous efficiency improvements of about 2.5 percent per year during the next decades would reduce the current motor fuel demand by up to one third, while aircraft fuel needs would be only 4 to 18 percent lower than at present.

Notes

[1] The growth of roads significantly *preceded* the diffusion of the automobile, i.e., roads were built first for horse carriages as shown in Nakićenović (1988) and Grübler (1990).

[2] We define Δt as the time interval between the achievement of one and 50 percent of the saturation level K, i.e., in this example $\Delta t = 30$ years. Due to the symmetry of the logistic function, the same time is required for the increase from 50 to 99 percent of the saturation level. An alternative definition of Δt is the time interval between the achievement of the 10 and 90 percent level (i.e., the main growth period). In this case the value of Δt would be slightly different from the other definition, but for all practical applications both definitions can be used interchangeably.

[3] The evolutionary path of successive replacements of traditional by new forms of development and economic growth, driven by the diffusion of technologies and institutions, and interlaced by economic restructuring and transformations in social relations is captured in the Schumpeter (1939) notion of long waves in economic development, i.e., a sea-saw like pattern of Kondratieff pulses of expansionary and recessionary (restructuring) periods experienced in market economies during the last two centuries (Kondratieff, 1926 and 1928). Rather than a process of continuous growth, long-wave theory supports the idea that

growth itself comes in pulses stimulated by the appearance and widespread diffusion of social, institutional, and technological innovations, leading to new forms of organization of production, new products, new infrastructures, and even whole new industries. In the works of Freeman (1983), Mensch (1975), Marchetti (1985), Nakićenović (1984), and many others, conceptual and empirical descriptions of long waves, diffusion, invention, and innovation processes have been laid, albeit from different methodological and theoretical perspectives. For a comprehensive review of this line of research see van Duijn (1983), Vasko (1987), or Goldstein (1988).

[4] The theoretical foundation for the use of this particular model is derived from the theory of product life cycles as well as from extensive research into the temporal and spatial patterns of the diffusion of innovations carried out in the fields of cultural anthropology, sociology, geography, and economics. Social learning theory and more recently also evolutionary economics confirm the logistic pattern of the spread and replacement of ideas and artifacts and the self-organizational nature of the process. The growth model considered is in its linear (logit) transform $log\ (y/K - y) = b(t - t_0)$ where K represents the asymptote (saturation level) of the growth process, b a growth parameter (for clarity defined as Δt, i.e., the time to grow from 10 to 90 percent of K) and the third parameter t_0, the inflection point (at $K/2$, where the growth rates reach their maximum in order to level off thereafter until saturation) locates the process in time. Ordinary nonlinear least squares algorithms are used to estimate the model parameters from historical data. Uncertainty ranges, particularly for the saturation parameter K are obtained by using Monte-Carlo type simulation techniques, as standard statistical assumptions on parameter correlation and distribution do not hold for this particular statistical problem. Hence, uncertainty values are not necessarily distributed normally around the mean value of the estimate. Details of the estimation algorithms are given in Grübler, Nakićenović, and Posch (1987).

[5] The model describes the evolution of the fractional shares, f, an infrastructure accounts for in the total length of all infrastructures by a set of coupled logistic market share equations. The fractions f are again not plotted directly but as the linear transformation of the logistic curve $log\ f/(1-f)$, i.e., as the ratio of the market share held by a given transport infrastructure over the sum of the market shares of all other competing infrastructures. Thus, the presence of linear trends in *Figure 4* indicates where the fractional substitution of transport infrastructures follows a logistic curve. A finding of a large number of studies is that the relative market share of competing technologies usually follows a logistic trajectory. A simple model for two competing technologies was first proposed by Fisher and Pry (1971) and analyzes of hundreds of cases at IIASA and elsewhere have since demonstrated the conceptual and empirical power of the model. In dealing with more than two competing technologies, we must generalize, however, the two variate Fisher-Pry model, since in such

cases logistic trajectories cannot be preserved in all phases of the substitution process. Every competitor undergoes three distinct substitution phases: growth, saturation, and decline. This is illustrated by the substitution path of rail tracks in *Figure 4*, which curves through a maximum from increasing to declining market shares. In the model of the substitution process, we assume that only one competitor is in the saturation phase at any given time, that declining technologies fade away steadily at logistic rates, and that new competitors enter the market and grow at logistic rates. As a result, the saturating technology is left with the residual market shares (i.e., the difference between one and the sum of fractional market shares of all other competitors) and is forced to follow a nonlogistic path that joins its period of growth to its subsequent period of decline. After the current, saturating competitor has reached a logistic rate of decline, the next oldest competitor enters its saturation phase and the process is repeated until all but the most recent competitor are in decline. A more comprehensive description of the model and its assumptions is given in Nakićenović (1979).

[6] The quasi capital stock (excluding depreciation) is measured in constant 1980 Canadian dollars, derived from cumulative investment data given in Haritos (1987) and Urquhart and Buckley (1965). Railway investment data prior to 1850 were based on marginal railway construction cost estimates calculated from data from Urquhart (1986).

[7] While the canal network of Tzarist Russia extended only over 800 km prior to the Revolution (connecting however an extensive system of natural waterways) the USSR has constructed over 20,000 km of canals since 1920. Remarkably enough, this expansion process can be described by an extremely regular logistic growth pattern (see Grübler, 1990) that is presently approaching saturation, indicating that no further expansion should be expected. This becomes more plausible considering the increasing (environmental) opposition to large-scale river improvement and canal construction inside the USSR.

[8] The remarkably constant output of rail transportation, slightly above 10 billion passenger-miles/year since 1970, should not come as a surprise. It is a typical situation for a transport mode at the end of its technology life cycle, preserving its last niche (commuting) and being kept alive by public subsidies.

[9] This particular example provides a good *ex post* test of the forecasting capabilities of the competitive evolutionary model used here for organization of our empirical data base. The estimates as reported in Nakićenović (1986) based on data up to 1980 turned out to be excellent forecasts. No market share level of any technology forecast for 1986 deviates more than four percent from the final actual data.

[10] Based on a logistic growth model with an estimated saturation level of 1.3 10^{12} passenger-km, t_0 in 1972, and a Δt of 39 years. We estimate a 90 percent probability that the saturation level of the present growth pulse will be between 1.1 and 1.4 10^{12} passenger-km.

[11] About ten percent of all passenger-km in France in 1900 were traveled by bicycles and motorcycles, also for longer, intercity distances. Automobiles were entirely negligible (around 3,000 registered cars) in this early phase of growth of road transport. The data for bicycles and motorcycles are of course only first order magnitude estimates, but are rather on the low than on the high side.

[12] This corresponds to around 135 passenger-km traveled and to around 47 kg-km transported (per unit of GDP in constant 1985 Francs) respectively. Assuming 90 kg per passenger, passenger transport corresponds to around 12 kg-km (per unit of GDP in constant 1985 Francs), and total traffic thus to around 60 kg-km (per unit of GDP in constant 1985 Francs). Transport and communication accounted for around six percent of GDP in 1985.

[13] The prevalence of passenger over goods transport elasticities is indicated by the shaded area in *Figure 15*. Note that due to the high uncertainty involved in the estimates of GDP during wartime periods, we have omitted these in *Figure 15*. Historically we may conclude, that as a rule passenger transport growth reacted more sensitively to business cycle variations (with the exception of the post-1973 period). This emphasizes once more the noteworthy bifurcation in the behavior of the two elasticities in France in the 1970s and early 1980s.

[14] It is indicative that software already constitutes a major fraction (over 80 percent) in military investments. Similar tendencies are also to be expected for the manufacturing sector, as demonstrated by Ayres (1988).

[15] The spatial diffusion of railways again proceeds along a S-shaped trajectory, spreading out first through a hierarchy of innovation centers and from there further out to the hinterland, as analyzed in detail in Godlund (1952), Marchetti (1987), and Grübler (1990).

[16] Later increases are again a result of territorial changes, including the *Anschluß* of Austria in 1938, and do not represent a railway construction effort. For the decline process of the railway network of the FRG after World War II, the share of the FRG territory in the maximum railway network of the German Reich was taken as an initial condition for the model estimation.

[17] As in the case of the FRG, Austria's share (Cisleithania) in the peak railway network of the Empire is taken as an initial value to calculate the decline process. The decline process proceeds at an extremely slow pace compared to other industrialized countries, i.e., with a Δt of some 200 years; this is probably due to the strong influence of railway trade unions in the Austrian political system.

[18] Because of the strong population dynamics of these countries, per capita densities show even larger disparities with industrialized countries and are also decreasing for most developing countries.

[19] This does not imply that developing countries should not construct any new railway lines. For the transport of low-value goods, say soya beans or iron ore, railways are an efficient and cost-effective transport mode for these countries. Our conclusion just refers to the fact that we do not consider the successful

catching-up by these countries to rely in any way on the development of an infrastructure, which was so essential for the growth of industrialized countries in the 19th century.

[20] In the absence of statistics on total car registrations in OECD countries, we use a proxy sample of 12 countries: Australia, Austria, Canada, France, FRG, Italy, Japan, Spain, Sweden, New Zealand, UK, and USA.

[21] COMECON – Council for Mutual Economic Assistance. Since 1989, because of the changes in Eastern Europe, COMECON as an institution is of less significance for the European members. Other members include Cuba, Vietnam, Mongolia, and the USSR.

[22] We estimate that there is a 90 percent probability that the saturation level of the diffusion process will be between 404 and 524 million passenger cars. For comparison, in 1984 world passenger car registrations are estimated to amount to 364.8 million passenger cars (MVMA, 1987). The estimate includes the intercept (saturation level of previous growth pulse with 34.6 million cars). R^2 of the estimate is 0.9998.

[23] As the diffusion process has presently progressed to only 50 percent of the estimated final saturation level, the statistical uncertainty involved in parameter estimation is substantial. We estimate a 90 percent probability that the saturation level K will be between 207 and 516 million road vehicles (1986: 176.5 million). R^2 of estimate is 0.9966.

[24] This points to the fact that the replacement rate of the "rolling stock" of the road transport fleet is much the same whether we deal with horses or cars. The average useful life of horses and cars is about ten years.

[25] *Figure 32* also includes the diffusion of total road vehicles in the USA (i.e., riding horses and mules and later automobiles) because of the high density of individual road transport means in the USA prior to the advent of the automobile. The high car density of the USA at present and the high ultimate saturation level can be better understood when considered on the basis of *Figure 32*.

References

Abernathy, W.J., 1978, *The Productivity Dilemma, Roadblock to Innovation in the Automobile Industry*, The Johns Hopkins University Press, Baltimore and London.

Ayres, R.U., 1988, Technology forecast for CIM, *Manufacturing Review* **2**(1):43–52.

Barker, T.C. and Robbins, M., 1975, *A History of London Transport*, Vols. 1 & 2, Allen and Unwin, London, UK.

Borderon, D., 1989, *The Potential for Increased Efficiency of Energy Use; Masterminding Tomorrow's Technologies*, Group Planning, Shell International Petroleum Co. Ltd., London, UK.

Cerwenka, P., 1986, *Wechselwirkungen zwischen Telekommunikation und Personenverkehr*, Öffentlicher Sektor–Forschungsmemoranden, 12. Jg., Heft 2, June 1986, pp. 38–56.

van Duijn, J.J., 1983, *The Long Wave in Economic Life*, Allen and Unwin, London, UK.

Fisher, J.C., and Pry, R.H., 1971, A simple substitution model of technological change, *Technological Forecasting and Social Change* **3**:75–88.

Freeman, C., ed., 1983, *Long Waves in the World Economy*, Butterworths, London, UK.

Godlund, S., 1952, *Ein Innovationsverlauf in Europa, dargestellt in einer vorläufigen Untersuchung über die Ausbreitung der Eisenbahninnovation*, Lund Studies in Geography, Ser. B. Human Geography No. 6., C.W.K. Gleerup Publishers, Lund, Sweden.

Goldstein, J.S., 1988, *Long Cycles: Prosperity and War in the Modern Age*, Yale University Press, New Haven and London.

Grübler, A., 1990, *The Rise and Fall of Infrastructures: Dynamics of Evolution and Technological Change in Transport*, Physica Verlag, Heidelberg, FRG.

Grübler, A. and Nakićenović, N., 1987, *The Dynamic Evolution of Methane Technologies*, WP-87-2, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Grübler, A., Nakićenović, N., and Posch, M., 1987, *Methods of Estimating S-shaped Growth Functions: Algorithms and Computer Programs*, Unpublished document, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Haritos, Z.J., 1987, *The Economic Long Wave and Transportation*, University of Toronto/York University, Toronto, Ontario, Canada.

International Air Transport Association (IATA), 1961 to 1987, *World Air Transport Statistics* IATA, Cointrin-Geneva, Switzerland.

International Road Federation (IRF), 1970 to 1986, *World Road Statistics*, Geneva and Washington.

Kondratieff, N.D., 1926, Die langen Wellen in der Konjunktur, *Archiv für Sozialwissenschaft und Sozialpolitik* 56:573–609.

Kondratieff, N.D., 1928, Die Preisdynamik der industriellen und landwirtschaftlichen Waren, *Archiv für Sozialwissenschaft und Sozialpolitik* **60**:1–85.

Marchetti, C., 1983, The Automobile in a Systems Context, the Past 80 Years and the Next 20 Years, *Technological Forecasting and Social Change* **23**:3–23.

Marchetti, C., 1985, Swings, cycles and the global economy, *New Scientist* **1454**:12–15.

Marchetti, C., 1987, Infrastructures for movement, *Technological Forecasting and Social Change* **32**(4):373–393.

Mensch, G., 1975, *Das technologische Patt, Innovationen überwinden die Depression*, Umschau Verlag, Frankfurt, FRG.

Motor Vehicle Manufacturers Association of the United States (MVMA), 1987, *World Motor Vehicle Data*, MVMA, Detroit and Washington, DC, USA.

Mitchell, B.R., 1980, *European Historical Statistics 1750–1975*, Second revised edition, Macmillan Press, London, UK.

Montroll, E.W. and Badger, W.W., 1974, *Introduction to Quantitative Aspects of Social Phenomena*, Gordon and Breach, New York, NY, USA.

Mothes, F., 1950, Das Wachstum der Eisenbahnen, *Zeitschrift für Ökonometrie* **1**:85–104.

Nakićenović, N., 1979, *Software Package for the Logistic Substitution Model*, RR-79-12, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Nakićenović, N., 1984, *Growth to Limits, Long Waves and the Dynamics of Technology*, University of Vienna, Vienna, Austria.

Nakićenović, N., 1986, The automobile road to technological change, diffusion of the automobile as a process of technological substitution, *Technological Forecasting and Social Change* **29**:309–340.

Nakićenović, N., 1988, Dynamics and replacement of U.S. transport infrastructures, in J.H. Ausubel and R. Herman, eds., *Cities and their Vital Systems, Infrastructure Past, Present and Future*, National Academy Press, Washington, DC, USA.

Nakićenović, N., 1989, *Expanding Territories*, Unpublished document, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Schmidt, E., 1983, *op cit.* Marchetti, 1983.

Schumpeter, J.A., 1935, The analysis of economic change, *Review of Economic Statistics* **17**:2–10.

Schumpeter, J.A., 1939, *Business Cycles, a Theoretical, Historical and Statistical Analysis of the Capitalist Process*, Volumes I & II, McGraw-Hill, New York, NY, USA.

Schumpeter, J.A., 1942, *Capitalism, Socialism and Democracy*, 6th Edition, 1987, Unwin Paperbacks, London, UK.

Szalai, A., 1972, *The Use of Time, Daily Activities of Urban and Suburban Populations in Twelve Countries*, Mouton, The Hague and Paris.

UN, 1977, *U.N. Yearbook of Industrial Statistics 1977, Vol. 1: General Industrial Statistics*, United Nations, New York, NY, USA.

UN, 1987, *U.N. Yearbook of Industrial Statistics 1987, Vol. 1: General Industrial Statistics*, United Nations, New York, NY, USA.

U.S. Department of Commerce (US DOC), 1975, *Historical Statistics of the United States, Colonial Times to 1970*, Volumes 1 & 2, Bureau of the Census, Washington, DC, USA.

U.S. Department of Commerce (US DOC), 1976 to 1987, *Statistical Abstract of the United States 1976 to 1987*, 97th to 108th editions, Bureau of the Census, Washington, DC, USA.

Urquhart, M.C., 1986, New estimates of gross national product, Canada 1870–1926: Some implications for Canadian development, in S. Engerman, and R. Gallman, eds., *Long-term Factors in American Economic Growth*, University of Chicago Press, Chicago, IL, USA.

Urquhart, M.C., and Buckley, K.A.H., 1965, *Historical Statistics of Canada*, Cambridge University Press, Cambridge, UK.

Vasko, T., ed., 1987, *The Long-wave Debate*, Springer-Verlag, Berlin, Heidelberg, New York.

Voigt, F., 1965, *Verkehr*, Dunker & Humblot, Berlin.

Woytinsky, W., 1927, Die Welt in Zahlen, fünftes Buch: *Handel und Verkehr*, Rudolf Mosse Buchverlag, Berlin, Germany.

Zahavi, Y., 1979, *The "UMOT" Project*, Report DOT-RSPA-DPB-20-79-3, Prepared for U.S. Department of Transportation and FRG Ministry of Transport, NTIS, Springfield, VA, USA.

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