On Transport in Europe: The Last 50 Years and the Next 20*

Cesare Marchetti

International Institute for Applied Systems Analysis
A-2361, Laxenburg, Austria

MARCHETTI-051

*Invited paper, *First Forum on Future European Transport*, organized jointly by the Ludwig-Bölkow-Stiftung and Cesta, held at the Universität der Bundeswehr München, September 14-16, 1987.

On Transport in Europe: The Last 50 Years and the Next 20

Cesare Marchetti

Man is a territorial animal, and travel is necessary to explore and exploit territories. Traveling is expensive in terms of time and energy (money) and has to be performed under the constraints of budgets. According to the UMOT model by Zahavi (1979), which I prefer to any other, the costs add up to an average of one hour per day and 15% of disposable income per person in the developed countries. Allocation of time and money over the available transportation modes is made so as to *maximize distance*.

A hierarchy of territories exists. The poor man, walking, has a mean circle of 5 km diameter – his village; a man with a car ordinarily travels within 50 km – his region; and a man using planes can easily travel 500 km. With incomes going up, and the cost/km of transportation going down in real terms, the result is a continuous increase in passenger-km, because people allocate increasing shares of their travel time to the faster transport modes. Demand builds up, too, for still faster modes of transport. When any place on the whole earth becomes reachable within an hour, the process will be complete.

This model helps us to understand the development of the transportation system and to define its twin goals: *as fast as possible, as cheap as possible.*

Another conceptual frame we are developing at IIASA will help us view all transport systems in quantitative terms. Actions express ideas; and ideas are informational packets generated, selected, and diffused in our culture according to mechanisms that resemble those found in DNA genetic pools, i.e., in biological systems. As a consequence, biological models of competition as coded, e.g., in the Volterra-Lotka equations, are very efficient descriptors of the dynamics of change in our society.

The basic intuitive concept ist that of a population growing into a resource niche and/or territory, and of *displacing* another population inside a niche. In the last configuration we may see various populations at the same time, in the same niche, elbowing each other. To take one specific example, we can look at population of ships, identified by their propulsion system – sail, steam, or internal combustion power plants – and express their population dynamic as a fraction (F), e.g., of the UK fleet during the last 200 years (Figure 1). The wriggling lines represent actual statistical data, and the smooth lines are the special solutions of the Volterra-Lotka equations of competition. Each equation has only two parameters to be fitted: a time shift and a rate parameter. Consequently, the close fit between the mathematically generated solutions and reality derives from the conceptual soundness of the analogy, and is not a mathematical illusion.

The same approach applies to the growth of organisms, such as trees – why not to the growth of railway tracks? After all, we speak of trunk lines and branches, so the analogy is already incorporated into our language. Figure 2 shows the growth of railway track length in Europe, since the introduction of railways in 1825. We see two "seasons" of growth. Two great pulses bringing the total length of the network to 400,000 km (Russia included), toward the end of the 1930s. The two growth pulses were followed by a season of stability. We still have (1987) 4×10^5 km of track in operation. By analogy with many other cases, a season of decay and death will follow. The world is on the same track so to speak (Figure 3).

The "seasons" are periods of about 50 years, started by waves of technological innovations, ended by saturated markets, then revived by a new wave of technological innovation. I have analyzed them in terms of *physical* activity by Western societies, and they also neatly match the economic cycles first spotted by Kondratiev. These cycles are very important because they constitute a central clock in the evolution of all sort of systems, including the transportation system, in terms of technologies, traffic, and infrastructures.

One can see this chronological pattern in the development of the infrastructure for transport in the USA (Figure 4) with the sequence of canals → railways → paved roads → air networks. The pulsation and its timing are very evident. We can also observe this pattern, analyzing the "starts", i.e., the opening of the first line, for metro networks around the world. These openings are not scattered at random. They come in bunches. One can look at the growth of a certain bunch as if it were a population filling a niche, and analyze it subsequently. The result, reported in Figure 5, shows the crisp precision of the mathematical description on top of a very clear 55-year pulsation. These concepts are very important because the future I will try to describe is shaped accordingly. They are also important because they show that the basic allocations for the next cycle will be made in the next ten years.

The first message to be extracted from Figure 5 is that *we are in season for metros*. Once the first line is opened, the network must grow in order to acquire its functionality. According to Figure 5, there are about 70 metros in the exponential growth period that initiate logistic development and saturation.

Coming back to the evolution of transport infrastructures in the USA, we may see it as a functionally interconnecting net, in the sense a traveler or a ton of goods can make a trip partly by road, partly by rail, and partly by air. In this perspective the network can be seen as a single object, and its (logistic) growth mapped as we have done in Figure 6. The fit is not perfectly smooth, but considering that so many things are packed into the same bag, it is quite satisfactory. We can now analyze the construction of new transport infrastructures as a competitive process. Let us look at the fraction of total US infrastructure represented by each mode since 1800 (Figure 7).

We have now seen two examples of multiple competition inside a niche: ship propulsion technology in Figure 1, and transport infrastructures. A third example, very pertinent for our transportation problem, is reported in Figure 8. Primary energies can be seen as technologies competing in their economic niche, the global energy market.

The three cases show a remarkable long-term stability, and the solutions of the Volterra-Lotka equations that fit them require only two parameters for each competitor. These parameters may change interactively, but no external information is needed after they have been introduced. The temptation to use the model for forecasting is hard to resist. Because the dynamics of these substitutions is quite slow, this may mean forecasting 50 years ahead.

The showpiece of the process is reported in Figures 9a-c. Here we take the market shares of primary energies, at world level, for a 20-year period (1900-1920) as a data base (Figure 9a). Using *only* the information contained in these data, we can fit the appropriate set of equations (Figure 9b). The segments of equation protruding from the data base can be considered a forecast of energy market shares. To see how good they are, we can superpose *actual* statistical data (Figure 9c). We see then that, if we had applied this technique in 1920, we could have forecast coal and oil market shares in 1970 with a precision of a few percentage points. Gas does not come out so well (+ 7%) because, at the end of the data base period, it had only a 2% market share and the parameters of market penetration usually do not "freeze" until the level is a little higher.

The most remarkable thing in my opinion is that the structure went unmodified through the Great Depression of the 1930s, and World War II. One could say the same about the substitutions in the merchant fleet of Figure 1. And I can state from hundreds of case histories, spanning wars and other violent "surprises", that this is true in general. This capacity of a system to absorb the shocks that come from drastic changes in external conditions is called *homeostasis* biological systems. Homeostasis appears to protect our forecasts from the effects of surprises in human affairs, as well.

My favorite example, which is very pertinent to our discussion, is that of air transport. Its growth at world level is reported in Figure 10. The smoothness of the logistic fit is remarkable, noting especially the fact that no dent is shown around 1974 and 1979, when two sudden and stiff increases in the price of jet fuel created havoc *inside* air transport companies. These firms performed miracles at the organizational and technical levels to compensate for the shocks. And the homeostatic effect was so prompt and efficient that not even a blip shows up at the functional level, in terms of the ton-km performance.

This stability cannot be explained by the behavior of the large fly wheels, the USA and USSR, alone. The statistics of AEA, the group of the most important European air companies, shows a similar stability (Figures 11a-b), although altogether the evolution of traffic here is somehow "noisier" than at the world level. However, even this anomaly cannot be attributed to different levels of aggregations. A single company, e.g., Lufthansa (Figures 12a-c), enjoyed a more regular development of its traffic, passenger, and freight loads than AEA companies taken together.

As I said at the beginning, the individual traveler's allocation of time and money to different modes of transport tends toward the maximization of range, i.e., of mean speed. The airplane being the fastest means of transport, the increase in disposable income, and a slow decrease in real terms of the cost of air transport makes air transport the fast-growing branch of the business. Very poor men walk, very rich men fly, and the in-betweeners drive. The long-term evolution of this process in shown in Figure 13, where the modal split for *intercity* pass-km is given for the USA.

Figure 13 is very interesting, as the USA tends to lead Europe in technological applications and use trends. It says that for intercity transport, trains and buses are almost extinct species. Contrary to current intuition, the car reached its maximum share in 1960, progressively losing pass-km to air transport which hold now almost 20% of the traffic. The logic of such substitutions is that they keep going, business as usual, unless a new competitor pops up, as shown for energy substitution in Figure 8. The only competitor to airplanes I see on the horizon is Magnetic Levitation Trains (Maglev) in a fast configuration (> 500 km/h). Later on I will discuss the logic behind their introduction. From a formal point of view, as every innovation wave yielded a new primary energy (Figure 8) and a new transport mode (Figure 7), we should expect the start of the Maglev mode before the year 2000. Japan may open the race.

The gist of Figure 13 is that, in *relative* terms, passenger air traffic will increase by at least a factor of five in the USA during the next Kondratiev cycle. Allocating more time to the fastest mode will increase total pass-km, i.e., the traffic. So we may count on an order of magnitude, at least, in absolute terms. At present, of the 60 minutes per day each adult devotes to traveling, Americans spend roughly 30 minutes for intercity and less than half a minute on a plane. Just to give a reference point, if not a ceiling, for the evolution of demand, I myself lead an active and healthy life, spending a mean of about 30 minutes per day on airplanes.

The analysis of Figure 13 can be applied to Western Europe, although the scattered data and their inhomogeneity make the curves less crisp and significant (Figure 14). In relative terms, the modal split of intercity transport shows cars in a dominant position now, 30 years after the USA peak, with air transport growing robustly and railways and buses creeping off the stage. Although one should not take any single data point too seriously, the fact that air traffic level in 1985 fell below that allocated by the competition equations could mean the "system" is overdue for some action – e.g., a substantial revision of air tariffs. Certainly, the system is sending out signals in that direction.

Air traffic has increased by a factor of about 50 during the present Kondratiev cycle; for the next cycle, due to start in the middle of the next decade, an increase of a factor of 10 is the rock-bottom forecast. Most of the world lags the USA, meaning the global saturation point is much farther away. Such an increase in traffic will create very tough problems for aircraft designers, and out of these difficulties will emerge a niche for the Maglev and a spatial reorganization of transport system nodes.

On the question of aircraft characteristics, productivity (pass-km/hr) of first-level planes grew logistically with the saturation point at 1.2×10^6 (Figure 15). In the same figure a dashed line reports the evolution of passenger traffic at world level. The two lines are parallel, meaning that aircraft productivity is basically proportional to world traffic when a certain (*successful*) model is introduced on the market. Concorde *does not* fit this pattern.

I do not know precisely why operators optimize their fleet that way, but it is a fact that planes in service by the core of commercial operators, the IIATA firms, have been constant in number at about the 4000 level during the last 40 years. Obviously, the operators applied sufficient pressure on manufacturers, in order to bend them to the unpleasant task of developing and making few very large planes, such as 747s, instead of swarms of very small ones, such as DC-3s. I predict that the reasons for that will remain strong in the future.

Larger planes required larger power plants, whose evolution is reported in Figure 16. The power of the largest piston engines developed along a crisp logistic and saturated in the 1950s around 2.5 MW. The analysis shows they were out of breath, and crossing the Atlantic at that time – with a Constellation, one could certainly feel it. The introduction of deep- breathing engines, the jets, came out of a demand for power, as all people in business know, and Figure 15 shows their great progress to a saturation around 25 MW per engine.

Super fans and prop fans may increase thrust for the same core engine, but that will not certainly provide an order of magnitude increase. On the other side, the chart of Figure 15 shows a saturation point for airplanes of about 1300 passengers at Mach 0.9. A superstretched 747 may do that, but here also a growth factor of 10 is hardly to be expected around this evolutionary line.

As I said, I will stick to the hypothesis that the airlines will zealously protect their freedom to choose the productivity best adapted to their needs, insensitive to the tears of the manufacturers.

Conceptually, a "very simple" way out of the stalemate is given by an *hypersonic airplane* flying, e.g., at Mach 7. For the same physical size of the machine, productivity would go up by an order of magnitude. Second, the engines would inhale larger masses of air and increase their power for the same physical size. They could also be physically larger, having few moving parts at cruise speed. I am sure engineers would shudder at this beastly systems analytic view of their supremely sophisticated problems. But the systems perspective worked well in grasping the significance of the change in the past and in other fields too.

Going fast may solve the problem for airplanes operating at the first level, but what about the lower ones? Hypersonic flight is not obviously the answer, e.g., for short stretches inside Europe. Looking at productivity of second and third level planes, we can observe them neatly clustered around golden means, i.e., each level has about 62% of productivity of the one above it. Just to give an example from a single company with homogeneous seating criteria, Alitalia (1987) has an inventory of aircraft with mean seating for 433 – 272 – 165 – 115 – 48 passengers. Inside this logic, with an increase in traffic by a factor of 10, the still subsonic equivalent of an airbus should have 2500 plus passengers. Apart from the problems of building flying apartment houses, with the power limitations I have just quoted, the handling problems of such a large highly viscous slug of passengers is mind-boggling. I see here the *historic opportunity for the Maglev*. These trains moving at a mean speed of 500 km (better 1000) are perfectly equivalent to an airplane, as the traveler sees basically only speed (and cost!).

The *Maglev* could then become the most attractive *intercity vehicle for core cities*, the very large or very important ones, in order to attract the large traffic that justifies its high capacity and investment costs. Connections between the hubs of core cities and the smaller ones, the third plus levels, *would be handled by airplanes* as is done now. With the Maglev "sandwiched" between planes, the obvious locations of their stations will be at airports, which will become the traffic hubs, akin to the urban railway stations at the end of last century. This configuration can already be seen at an embryonic stage in West Germany, where trains (TRN!) already move between hyperconnected airports, when the small distance can grace the small speed.

Embedded into the air transport system, Maglevs would not need to have their own network system. Because cities grow around their transport systems (viz., the inevitable 60 minutes per day), Maglev will physically condense the functional hypercity "corridors", presumably beginning with the Tokyo-to-Osaka one with its 70 million people. In these configurations, it will have great importance the oft-cited and rarely addressed problem of the airport-to-city connection by extending fast legs of the Metro System. Fortunately, as I said before, Metro Systems are in season. Thinking of European corridors, it is perhaps still time to conceive a *Channel Tunnel that may host Maglevs* running at 1000 km/h.

Coming one notch down to the second-best transportation techniques, *cars* now provide the backbone of passenger transport in developed countries in general and Europe in particular. Although invented in Europe, the car as a means of personal transport first exploded in the USA. Our inevitable logistic analysis of the growth of car populations is shown in Figure 17a for Europe and Figure 17b for the USA. The growth is in two pulses, as usual, owing to the Kondratiev cycle constraints. It reached saturation levels of 7.5 M and 26 M cars, respectively, for the first pulse; 150 and 125 M cars, respectively, for the second pulse, leading to very similar car populations in the two continents.

Coming back to our basic model of allocating transport modes, in a zero approximation a car is a personal transport mode dedicated to one person. As such, it becomes the fastest way of moving and the said person will spend on it much of his 60-minute daily allocation for traveling. A very curious characteristic of cars, whose deep significance I could not decode, is that the mean speed one can get with them, is about 50 km/h, and has remained constant since Ford's time. This means an extraordinary stability in the km/yr traveled by the average car (Figure 18) and finally also in the pass-km it contributes to the traffic volume.

My best forecast, concerning *cars in Europe, is that they are saturated for good*. I am saying that for many intuitive reasons, but formally by analogy with many other technologies that fit the 54-year Kondratiev cycle, one could define the technology lifecycles as two up, one steady, one down. Two examples are reported in Figures 19 and 20, coal and steel in the UK, and others will come when discussing railways (which, by the way, have already gone through the two up and the steady cycles).

Contrary to current wisdom, cars were born in the womb of paved roads, as an analysis of relative penetrations show, but they themselves littered auto routes. Auto routes' length in Europe is saturating, at the level of single countries and obviously as a whole (Figures 21a-b). Much of the road work we see around in Europe nowadays is in fact directed much more toward improving the capacity of existing auto routes than to extending them.

One reason for car saturation is that they are not really suitable for densely populated cities. On the other hand, everywhere, including developing countries, populations implode into cities (Figures 22 and 23), and cities become larger and larger with the progress (speed!) of their public transport. This basic and growing incompatibility expresses itself in the expanding areas where cars are off-limits around the centers of cities. If the the American market is any clue to the future European scene, once *cars* are excluded from the city centers, functionally and legally, they may *become small trucks* carrying voluminous adult toys around the country side.

I have not delved into the problem of intercity bus transportation. Buses seem to fare well in Europe (Figure 24), although their share of pass-km is very slowly eroding (Figure 14). Just from visual clues, they seem to be the transport mode choice for wandering tourists. Some substitution for services that one normally would associate with trains is also visible. The fact that buses can compete with subsidized railways, reducing government interference, may help seal the railways' fate. From a general point of view, buses have the same speed limitations of cars, and consequently they will follow a parallel course.

Coming down one rung on the speed ladder, we find *trains*. Railways were the breakthrough in transportation at the beginning of last century and constituted the core of transport systems until World War II. Their success can be well measured by their expansion, which occurred in two Kondratiev pulses, in Europe and the world (Figures 2 and 3). All major networks were started in the first pulse, following the mathematics of a population filling a niche (Figure 25). During the second Kondratiev pulse, the existing networks grew. The third pulse, which formally began in 1940, registered no growth globally; although some networks grew somewhat (the USSR), most started to wear away (Figures 26 and 27). The same shrinkage happened to their personnel, albeit too slowly (Figures 28a-b).

In common with other technologies on their way out, railways held stable traffic in expanding markets, but consistently lost market share. Their productivity grew at a glacier's speed, when compared with that of competing industries, who had a 2% or 3% per year. Without any exceptions known to me, they survive on subsidies. An extreme case is the Italian railway system, which accounts for less than 5% of the pass-km traffic and less than 8% of the goods traffic, yet keeps increasing its staff, and has deficits larger than its total payroll. If trains are kept for cultural, folkloric reasons, the personnel should wear glorious uniforms, and the trains should run again on steam. They should also *stop* at rural road crossings, as did the early trains.

From whatever side I analyzed railways, I could not draw any hint of a future revival. In my opinion, they are lost as networks, and they will inevitably decline during the next cycle, due to start around 1995. Some experiments in fast connections, such as the Paris–Lyon route, may contradict the gloomy outlook. I must say first, from a systems point of view, I do not consider these fast links to be railroads in the traditional sense, although they use railroad technology. When a passenger arrives at the terminal city, he finds the old, slow trains to move him to his local destination. So the system amounts to a weak version of the fast interconnection between core cities that I predict for Maglev, *but* with airplanes providing the networking higher *and* lower in the transport hierarchy.

Because of time constraints, I can give only brief consideration to the transport of goods. The general rules of competition hold here, too, which make the treatment quite similar to that for passengers. Trains were the backbone of transport from 1840–1940, but road transport has taken over since then. The theoretical arguments that railways consume less energy and are less polluting than trucks, while certainly true, do not offset the fact that for internal reasons the system can be inefficient (read Italy) and stubbornly resistant to any change (read Italy). The situation is reminiscent of the case of coal extraction in the UK (Figure 19). Figures 29-35 try to give a quantitative historical picture of the evolution and devolution of these systems. Incidentally, transport by internal waterways follows similar patterns, with some exceptions due to massive transport of oil on barges.

A final consideration concerns pipelines. On land they monopolized the transport of oil and gas, the bulkiest stuff we have to carry. Only final products are trucked around for short distances. As Figure 7 shows, we are moving to an economy based on natural gas as *the* fuel, and the need for carting most oil products should disappear, around the end of the next Kondratiev cycle (2050) (Figure 36). Gas pipelines are developing briskly both in Europe (Figure 37) and at the world level (Figures 38a-b).

Conclusions

Although this analysis has been done by envelopes and cores, in the best exploratory tradition of the oil industry, some firm conclusions can be drawn.

1. *Rail transport* is at the end of its "product life cycle". Much would be gained by facing the facts and taking the obvious measures.

2. *Passenger transport by car*, intercity, reached its maximum modal share 30 years ago in the USA and it is reaching it now in Europe, where the number of vehicles will remain basically stable during the next Kondratiev cycle. The modal share will keep decreasing.

3. *Passenger air traffic* is the fast growing branch of the system, under the stimulus of the speed it can provide. A factor of 10 increase, and the long lead time needed to modify the infrastructures, will require intensive research to make the right policy choice in this development. As the air system becomes the workhorse of passenger transport, its interface with cities and its networking will require rethinking. *Maglevs* should be considered a high-flux branch of such a system, much like optical fibers in the city telephone system.

4. *Road transport of goods* will take away all freight traffic from railways, which have already lost all but a small share of it.

REFERENCES

Blackman, Jr, W. A. (1972), A mathematical model for trend forecasts, *Technological Forecasting and Social Change, 3*:441-452).

Bossert, R.W. (1977), The logistic curve revived, programmed, and applied to electric utility forecasting, *Technological Forecasting and Social Change, 10*:357.

Debecker, A. and T. Modis (1986), *Determination of the Uncertainties in S-Curve Logistic Fits*. Geneva: Digital Equipment Corporation.

Fisher, J.C. and R.H. Pry (1970), A simple substitution model of technological change. *Technological Forecasting and Social Change 3*:75-88.

Grübler, A. (1987a), Aufstieg und Fall von Infrastrukturen. *Technikergeschichte* (forthcoming).

Grübler, A. (1987b), Der Kampf ums Dasein, in *Verkehr 2001 – Perspektiven*. Vienna: Osterreichische Gesellschaft für das Verkehrs– und Strassenwesen (forthcoming).

Haldane, J.B.S. (1924), The mathematical theory of natural and artificial selection, *Transactions, Cambridge Philosophical Society, 23*:19-41.

Historical Statistics on the U.S. Colonial Times to 1970. Washington, DC: U.S. Department of Commerce (1975).

Internationale Eisenbahnstatistik (1927). Internationaler Eisenbahnverband, Paris.

Lotka, A.J. (1956), *Elements of Mathematical Biology*. New York: Dover Publications, Inc.

Marchetti, C. and N. Nakicenovic (1979), *The Dynamics of Energy Systems and the Logistic Substitution Model*. Research Report RR-79-13. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Mitchell, B.R. (1981), *European Historical Statistics, 1750-1975*. New York: Facts on File.

Montroll, E.W. and N.S. Goel (1971), On the Volterra and other nonlinear models of interacting populations, *Rev. Mod. Phys., 43*(2):231.

Nakicenovic, N. (1979), *Software Package for the Logistic Substitution Model*. Research Report RR-79-12. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Nakicenovic, N. (1984), *Growth to Limits: Long Waves and the Dynamics of Technology*. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Nakicenovic, N. (1986), *Patterns of Change: Technological Substitution and Long Waves in the United States*. Working Paper WP-86-13. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Nakicenovic, N. (1987), *Transportation and Energy Systems in the U.S.* Working Paper WP-87-01. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Oliver, F.R. (1964), Methods of estimating the logistic growth function, *Applied Statistics, 13*:57-66.

Pearl, R. (1924), *Studies in Human Biology*. Baltimore: Williams and Wilkins Co.

Peschel, M. and W. Mende (1986), *The Predator-Prey Model*. Springer Verlag: Berlin-Heidelberg-New York.

Peterka, V. (1977), *Macrodynamics of Technological Change – Market Penetration by New Technologies*. Research Report RR-77-22. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Pollins, H. (1971), *Britain's Railways: An Industrial History*. Newton Abbot: David and Charles Ltd.

Statistical Trends in Transport, 1965-1983 (1986), European Conference of Ministers of Transport. Paris: Organisation for Economic Co-operation and Development.

Stürmer, G. (1872), *Geschicht der Eisenbahnen. Teil 1: Entwicklung und jetzige Gestaltung sämtlicher Eisenbahnnetze der Erde*. Bromberg: Verlag Mittler.

Transport Statistical Series, 1982 (1985), European Conference of Ministers of Transport. Paris: Organisation for Economic Co-operation and Development.

Verhulst, P.F. (1845), in *Nouveaux Memoires de l'Academie Royale des Sciences, des Lettres et des Beaux-Arts de Belgique 18*:1-38.

Verkehr in Zahlen (1983). Bonn: Der Bundesminister für Verkehr.

Volterra, V. (1931), *Lecon sur la Theorie Mathematique de la Lutte Pour la Vie*. Paris: Gauthier-Villars.

Woytinsky, Wl. (1927), *Die Welt in Zahlen. Fünftes Buch: Handel und Verkehr*. Berlin: Rudolf Mosse Buchverlag.

Zahavi, Y. (1979), *The "UMOT" Project*. Report No. DOT-RSPA-DPB-2-79-3, U.S. Department of Transport, Washington, D.C.

MATHEMATICAL APPENDIX

The equations for dealing with different cases are reducible to the general Volterra–Lotka equations

$$\frac{dN_i}{dt} = K_i N_i + \beta_i^{-1} \sum_{n}^{j\neq 1} \alpha_{ij} N_i N_j \quad , \tag{1}$$

where N_i is the number of individuals in species i, and α, β, and K are constants. The equation says a species grows (or decays) exponentially, but for the interactions with other species. A general treatment of these equations can be found in Montroll and Goel (1971) and Peschel and Mende (1986). Since closed solutions exist only for the case of one or two competitors, these treatments mainly deal with the general properties of the solutions.

In order to keep the analysis at a physically intuitive level, I use the original treatment of Verhulst (1845) for the population in a *niche* (Malthusian) and that of Haldane (1924) for the competition between two genes of different fitness. For the multiple competition, we have developed a computer package which works perfectly for actual cases (Marchetti and Nakicenovic, 1979), but whose identity with the Volterra equations is not fully proven (Nakicenovic, 1979).

Most of the results are presented using the coordinates for the linear transform of a logistic equation originally introduced by Fisher and Pry (1970).

The Malthusian Case

This modeling of the dynamics of population systems started with Verhulst in 1845, who quantified the Malthusian case. A physically very intuitive example is given by a population of bacteria growing in a bottle of broth. Bacteria can be seen as machinery to transform a set of chemicals in the broth into bacteria. The rate of this transformation, *coeteris paribus* (e.g., temperature), can be seen as proportional to the number of bacteria (the transforming machinery) and the concentration of the transformable chemicals.

Since all transformable chemicals will be transformed finally into bacterial bodies, to use homogeneous units one can measure broth chemicals in terms of bacterial bodies. So $N(t)$ is the number of bacteria at time t, and $\overline{N}$ is the amount of transformable chemicals at time 0, before multiplication starts. The Verhulst equation can then be written

$$\frac{dN}{dt} = aN(\bar{N} - N) \quad , \tag{2}$$

whose solution is

$$N(t) = \frac{\bar{N}}{1-e^{-(at+b)}} \quad , \tag{3}$$

with b an integration constant, sometimes written as t_0, i.e., time at time 0; a is a rate constant which we assume to be independent of the size of the population. This means that there is no "proximity feedback". If we normalize to the final size of the system, $\bar{N}$, and explicate the linear expression, we can write equation (2) in the form suggested by Fisher and Pry (1970).

$$\log\frac{F}{1-F} = at + b \quad , \quad \text{where } F = \frac{N}{\bar{N}} \quad . \tag{4}$$

Most of the charts are presented in this form. $\bar{N}$ is often called the *niche*, and the growth of a population is given as the fraction of the niche it fills. It is obvious that this analysis has been made with the assumption that *there are no competitors*. A single species grows to match the resources ($\bar{N}$) in a Malthusian fashion.

The fitting of empirical data requires calculation of the three parameters $\bar{N}$, a, and b, for which there are various recipes (Oliver, 1964; Blackman, 1972; Bossert, 1977). The problem is to choose the physically more significant representation and procedure.

I personally prefer to work with the Fisher and Pry transform, because it operates on *ratios* (e.g., of the size of two populations), and ratios seem to me more important than absolute values, both in biology and in social systems.

The calculation of $\bar{N}$ is usually of great interest, especially in economics. However, the value of $\bar{N}$ is very sensitive to the value of the data, i.e., to their errors, especially at the beginning of the growth. The problem of assessing the error on $\bar{N}$ has been studied by Debecker and Modis (1986), using numerical simulation.

The Malthusian logistic must be used with great precaution because it contains implicitly some important hypothesis:

- That there are no competitors in sight.
- That the size of a niche remains constant.
- That the species and its boundary conditions (e.g., temperature for the bacteria) stay the same.

The fact that in multiple competition the starts are always logistic may lead to the presumption that the system is Malthusian. When the transition period starts there is no way of patching up the logistic fit.

The fact that the niches keep changing, due to the introduction of new technologies, makes this treatment, generally speaking, unfit for dealing with the growth of human populations, a subject where Pearl (1924) first applied logistics. Since the treatment sometimes works and sometimes not, one can find much faith and disillusionment among demographers.

One-to-One Competition

The case was studied by Haldane for the penetration of a mutant or of a variety having some advantage in respect to the preexisting ones. These cases can be described quantitatively by saying that variety (1) has a reproductive advantage of k, over variety (2). Thus, for every generation the ratio of the number of individuals in the two varieties will be changed by $\frac{1}{(1-k)}$. If n is the number of generations, starting from $n = 0$, then we can write

$$\frac{N_1}{N_2} = \frac{R_0}{(1-k)^n} \quad , \quad \text{where } R_0 = \frac{N_1}{N_2} \text{ at } t = 0 \quad . \tag{5}$$

If k is small, as it usually is in biology (typically 10^{-3}), we can write

$$\frac{N_1}{N_2} = \frac{R_0}{e^{kn}} \quad . \tag{6}$$

We are then formally back to square one, i.e., to the Malthusian case, except for the very favorable fact that we have an initial condition (R_0) instead of a final condition ($\bar{N}$). This means that in *relative terms* the evolution of the system is not sensitive to the size of the niche, a property that is extremely useful for forecasting in multiple competition cases. Since the generations can be assumed equally spaced, n is actually equivalent to time.

As for the biological case, it is difficult to prove that the "reproductive advantage" remains constant in time, especially when competition lasts for tens of years and the technology of the competitors keeps changing, not to speak of the social and organizational context. But the analysis of hundreds of cases shows that systems behave exactly *as if*.

Multiple Competition

Multiple competition is dealt using a computer package originally developed by Nakicenovic (1979). A simplified description says that all the competitors start in a logistic mode and phase out in a logistic mode. They undergo a transition from a logistic-in to a logistic-out during which they are calculated as "residuals", i.e., as the difference between the size of the niche and the sum of all the *ins* and *outs*. The details of the rules are be found in (Nakicenovic, 1979). This package has been used to treat about one hundred empirical cases, all of which always showed an excellent match with reality.

An attempt to link this kind of treatment to current views in economics has been made by Peterka (1977).

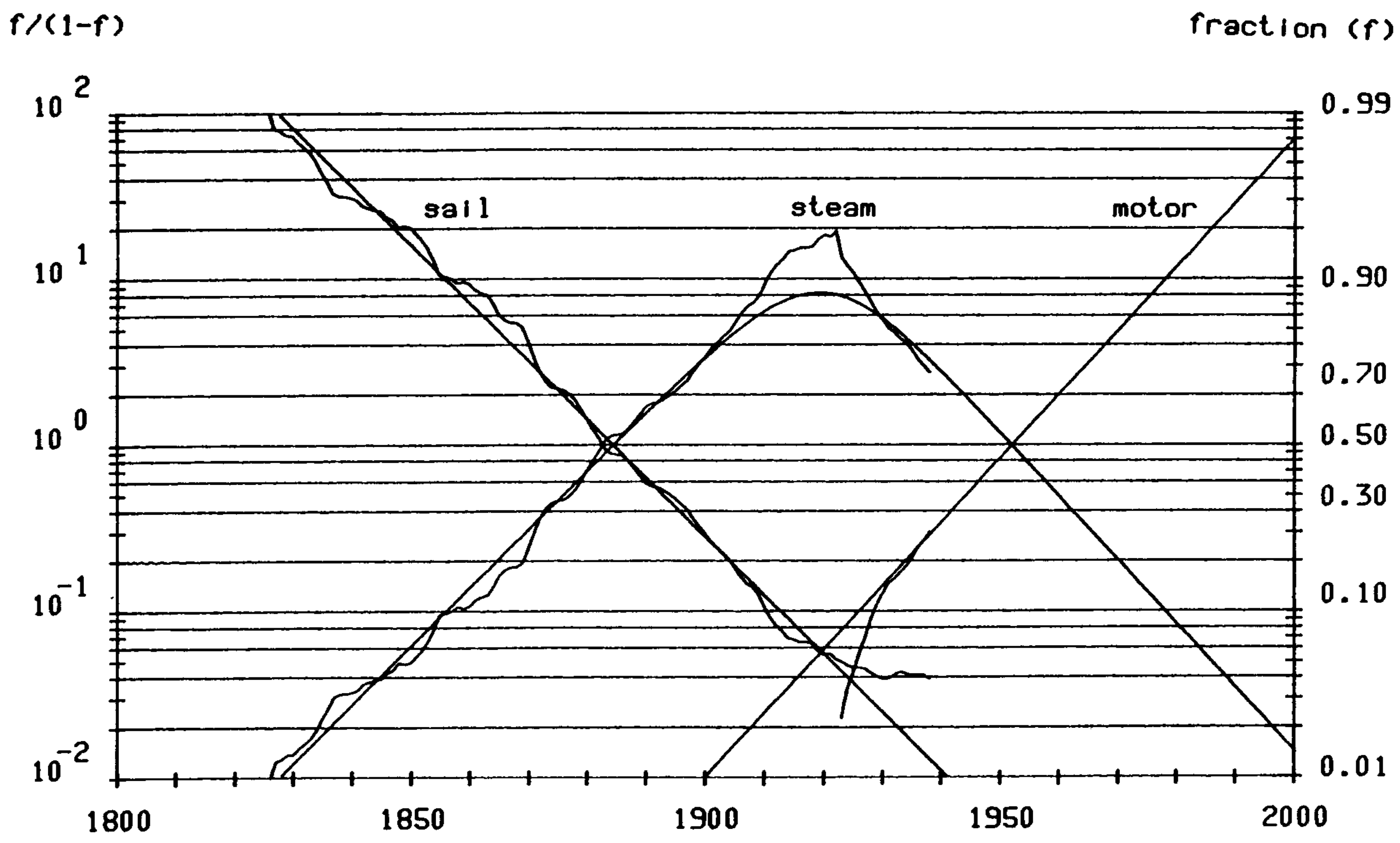
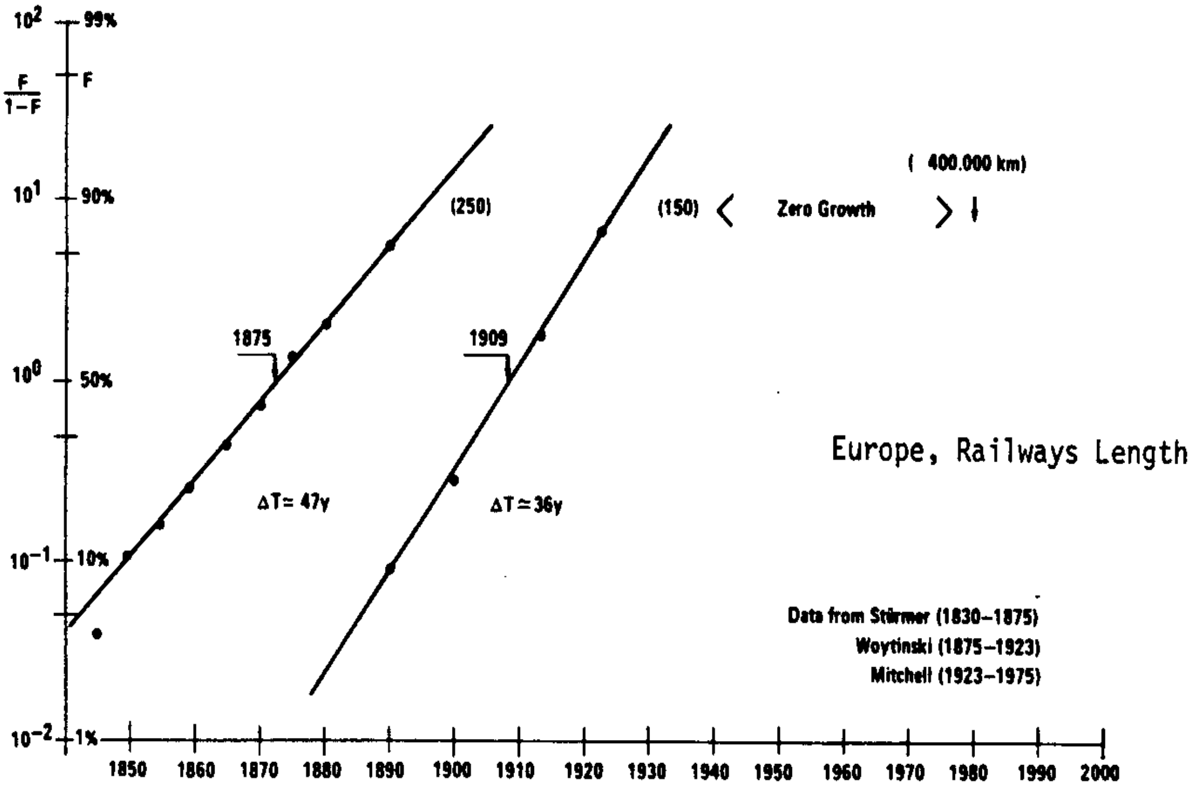
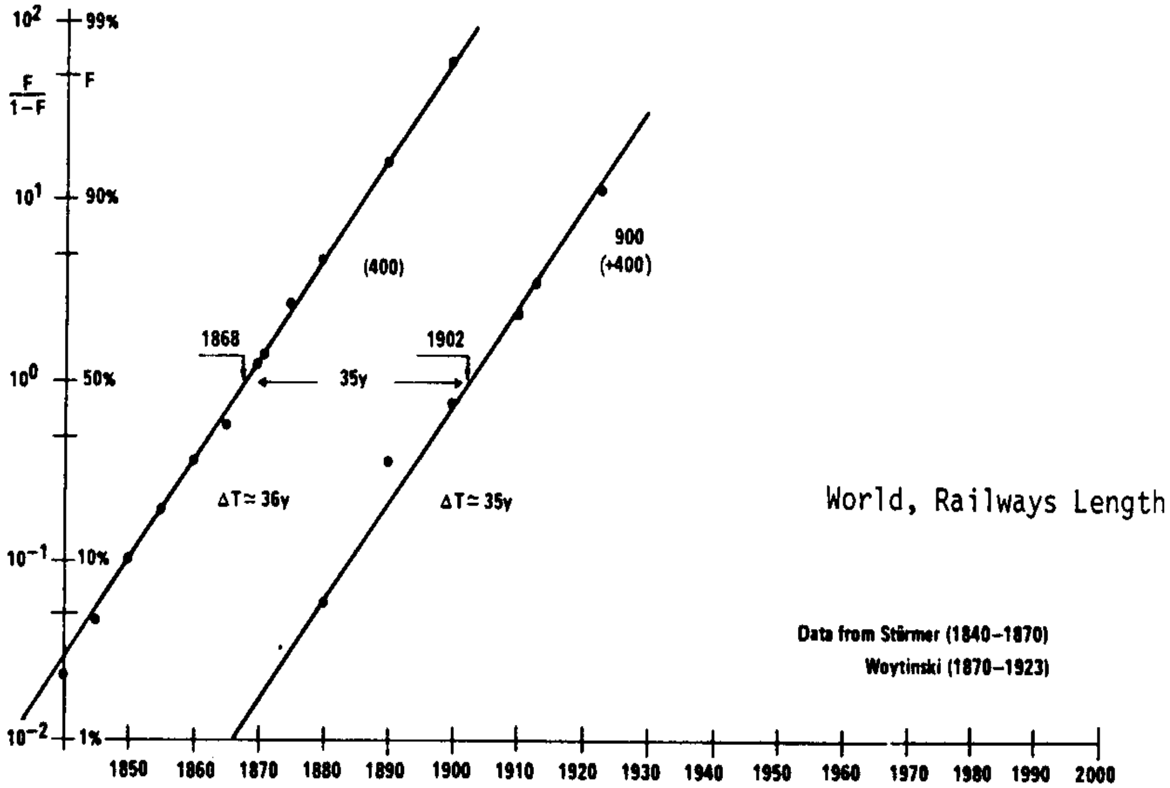


FIGURE 1. The competition between propulsion technologies inside a certain commercial fleet (the "niche") is analyzed here for the UK, in terms of shares of the total tonnage in use. The statistical data are fitted with a solution of the Volterra-Lotka equations of competition for biological systems. SOURCE: Nakicenovic (1986).





FIGURES 2 and 3. "Growth in a niche" analysis of European and world railways in terms of length of track. Railways were the backbone and the revolution of modern transport. Track length did grow at fantastic speed during the middle half of the last century as the figures show for Europe and the world. A second growth pulse, centered at the turn of the century, brought them to their final configurations. The previous Kondratiev cycles ended in 1985 and 1940, and the saturation points of all four pulses match these dates. During the present Kondratiev cycle, ending in 1995, track length did remain basically constant worldwide at 1.3 million km and also in Europe at 400,000 km. Following the logic of Figures 19 and 20, railways will functionally disappear during the next 50 years. SOURCE: Stürmer (1872), Mitchell (1981), Woytinksy (1927).

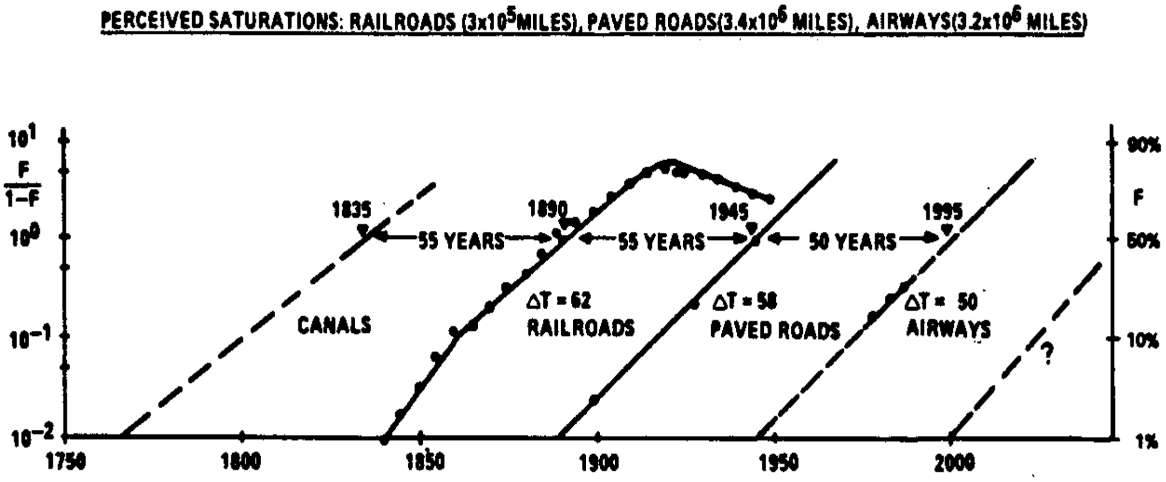


FIGURE 4. Development of transport infrastructures in the USA. Each mode is monitored by its length. The "niche" or virtual final lengths, are calculated by best fit. The 55 years of the Kondratiev cycles are apparent from the time constants and the spacing of the growth pulses.

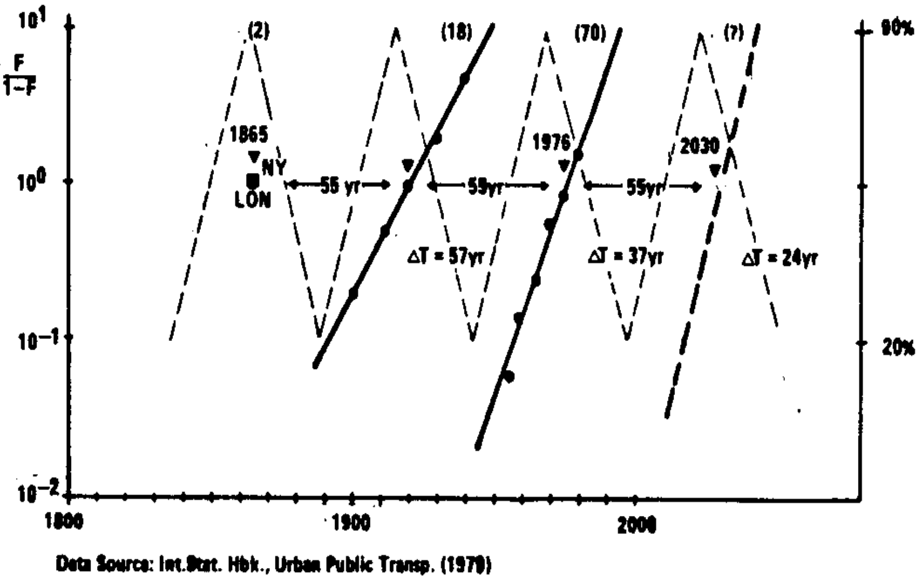


FIGURE 5. The dates of opening of "first lines" for a Metro in world cities, cluster into three groups. Each group can be considered as a population growing into a niche and treated accordingly (see mathematical appendix). The chart can be read as the number of Metro networks having gone through three pulses of growth, the third still extending. These first lines will naturally expand into grids in the following years. The 55 years cycle is evident in the structure.

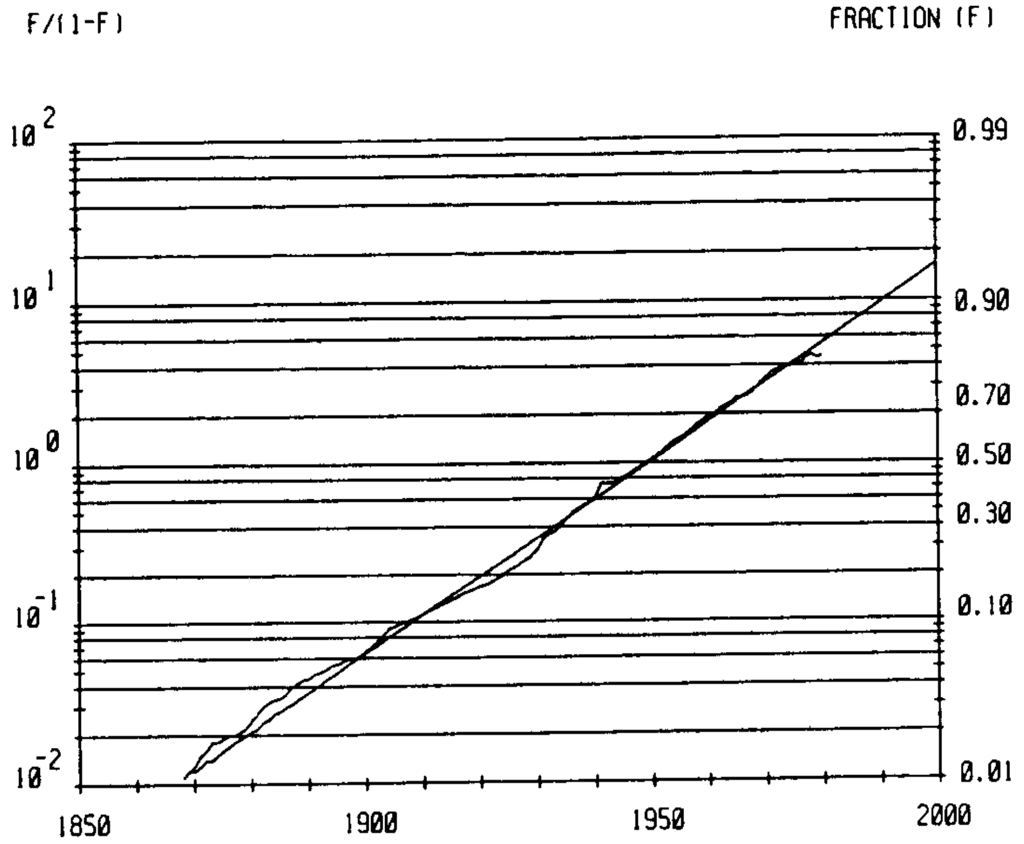


FIGURE 6. The sum of the lengths of transport infrastructures of Figure 4 is here reported. The total network length is again fitted with a logistic equation. SOURCE: Grübler (1987a).

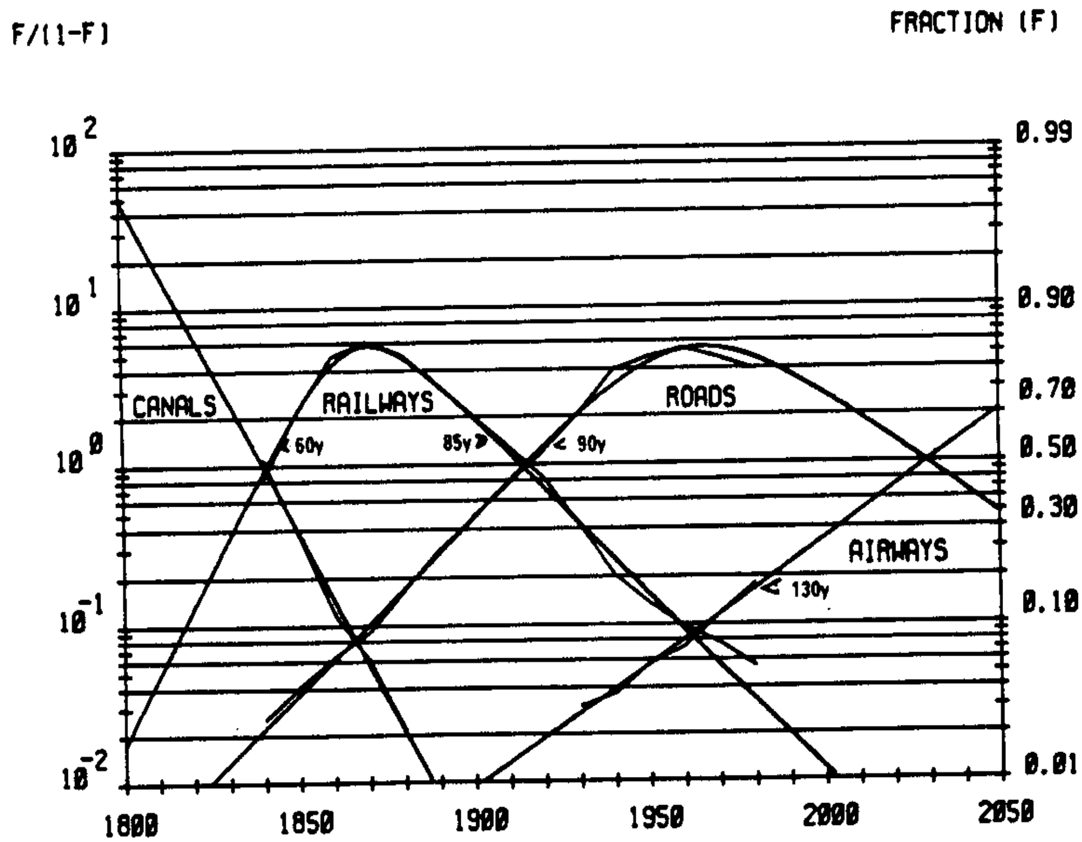


FIGURE 7. The competition between the "modes" of Figure 4 can be seen now in relative terms, taking the envelope of Figure 6 as their dynamic niche. The analogy of technology substitution in Figure 1 is evident. SOURCE: Nakicenovic

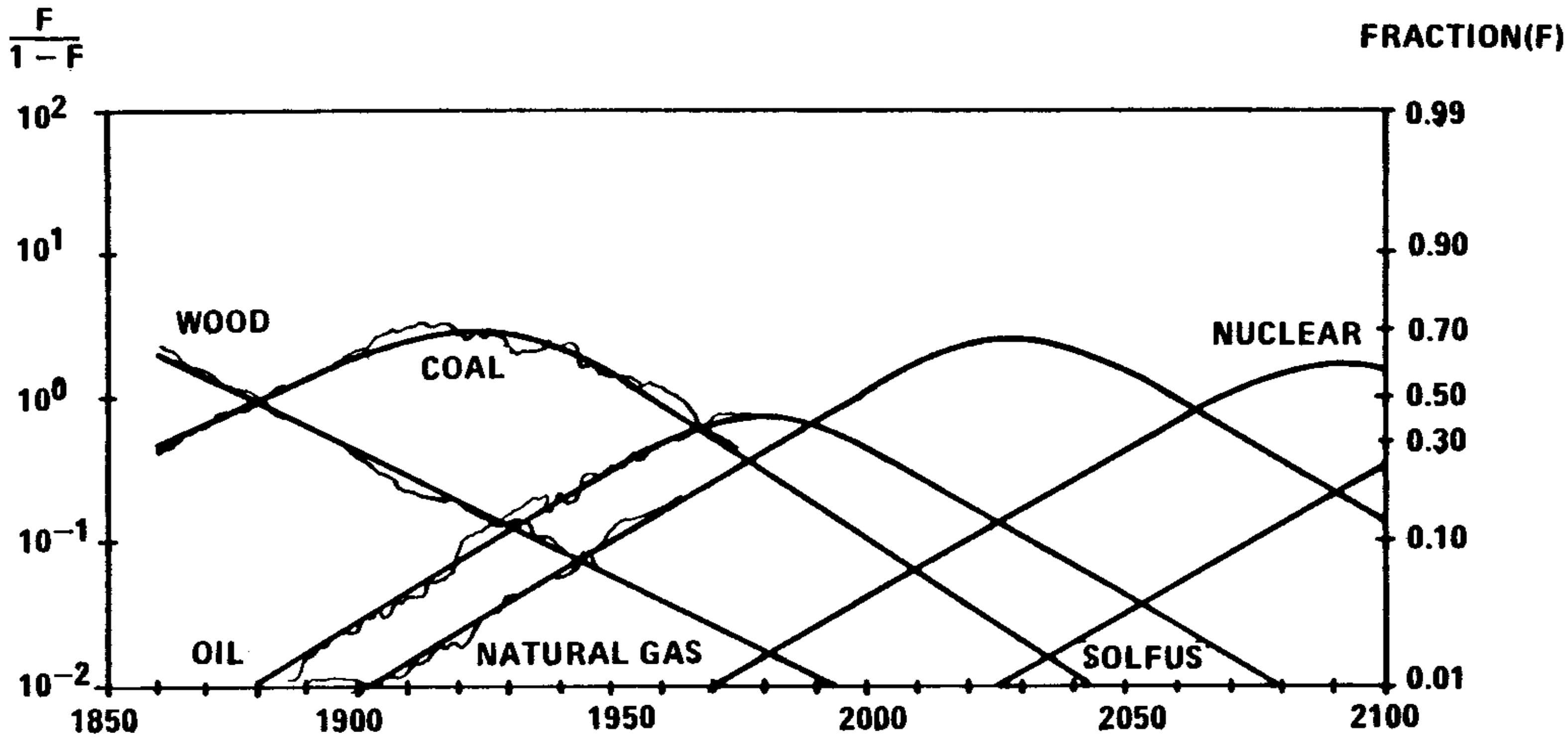
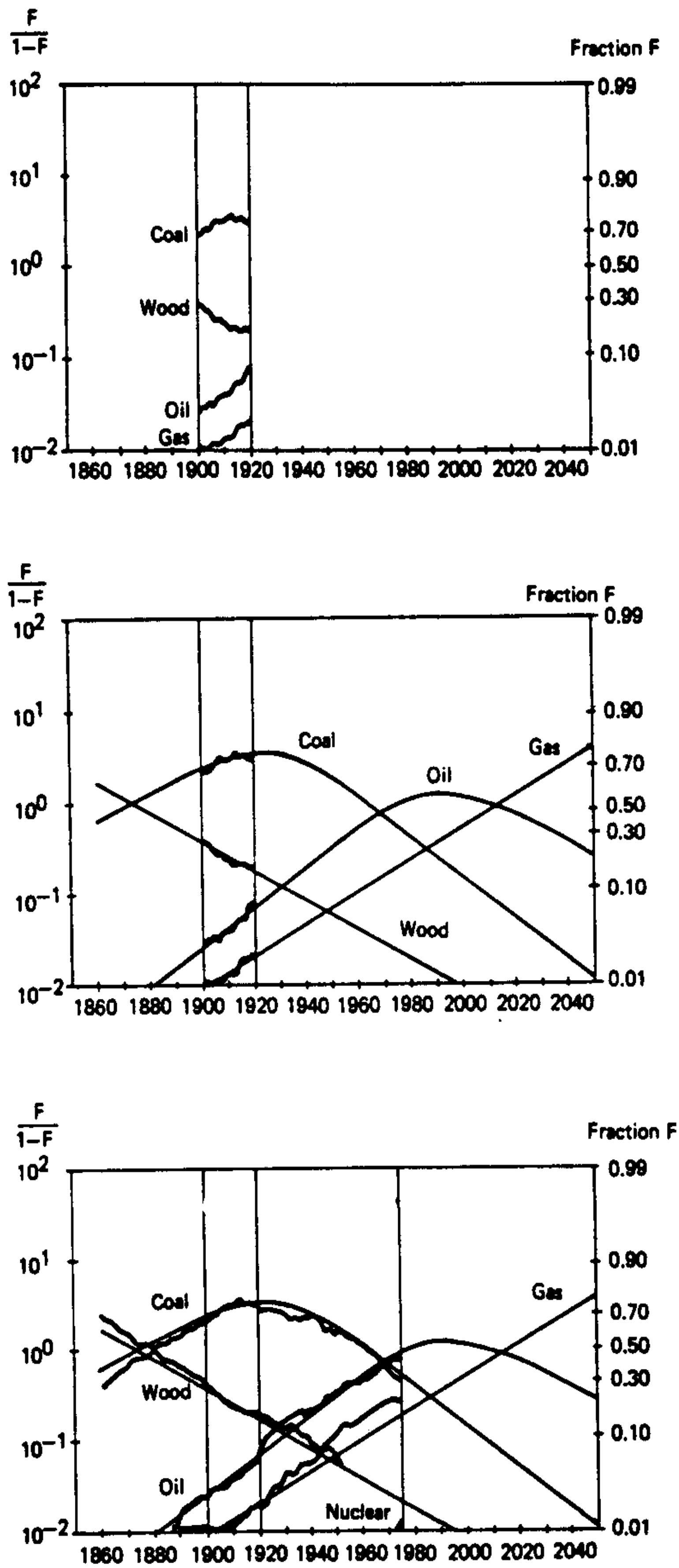


FIGURE 8. Inside the envelope of total energy consumption at world level, we examine here the competition between primary energies in terms of market shares (in tons of coal equivalent). SOURCE: Marchetti and Nakicenovic (1979).



FIGURES 9a–c. An exercise in forecasting, grounded on the high long term stability of the systems. Data bases are the market shares for primary energies in the period 1900-1920 (Figure 9a). The competition equations are fitted in Figure 9b. Their quality as predictions is tested in Figure 9c, by superposing actual statistical data.

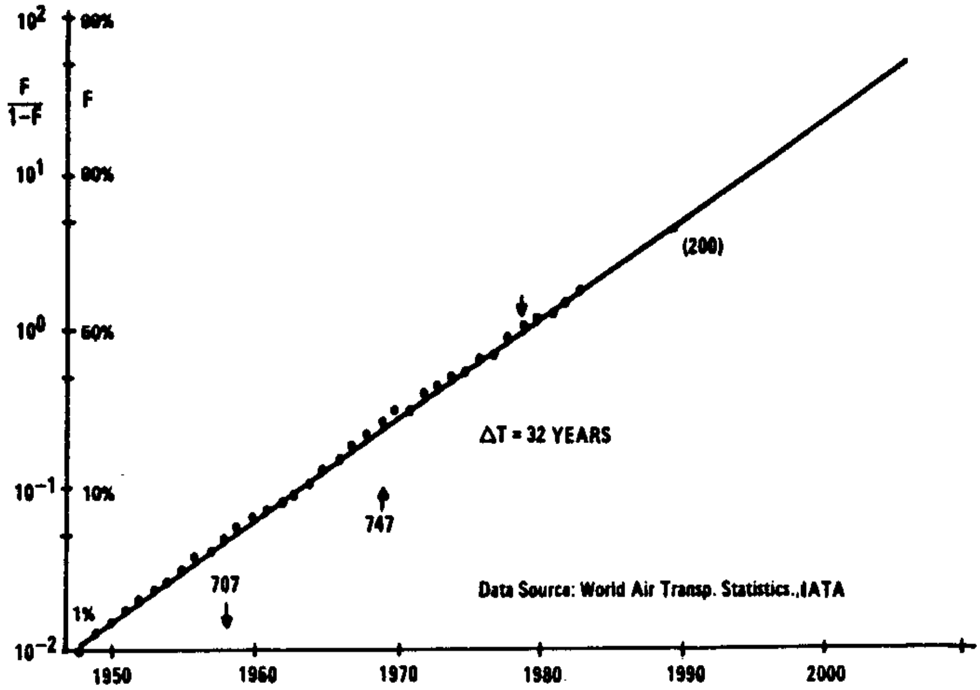


FIGURE 10. The ton-km performed by the air traffic system at world level can be very snugly fitted by a simple logistic equation. Saturation toward 1995 does not mean the end of the growth of air transport, but the end of a Kondratiev cycle of growth. The next pulse of growth will start in 1995. The remarkable absence of fluctuations as reactions to important changes in context, like the stiff increase in fuel prices, reveals powerful homeostatic correction inside the system.

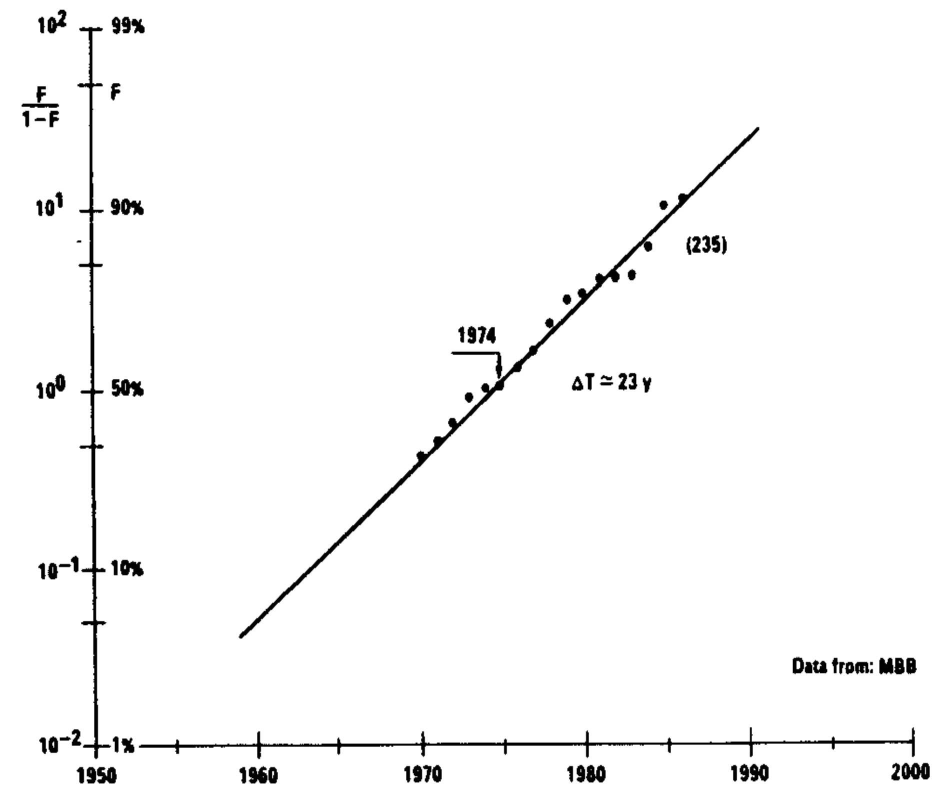
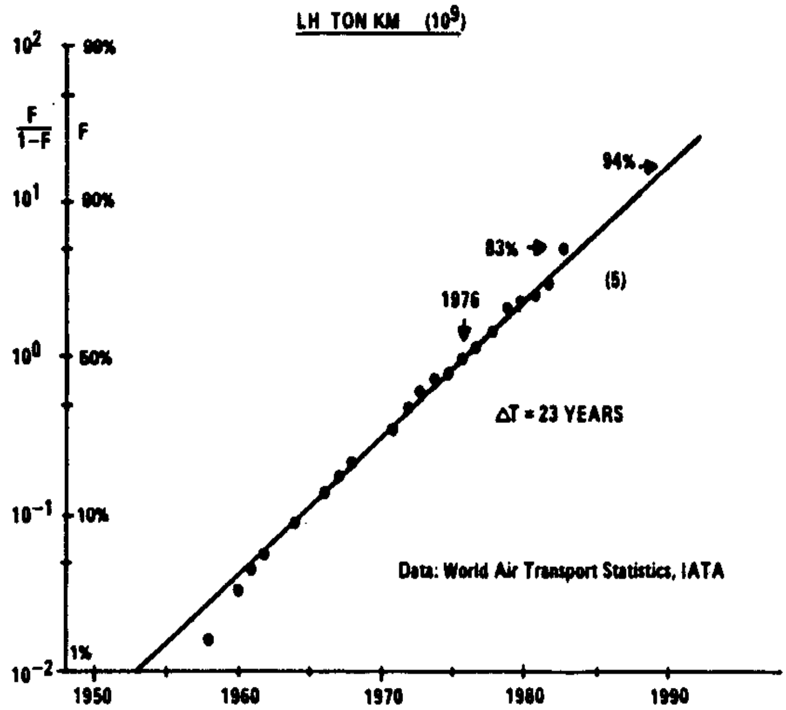
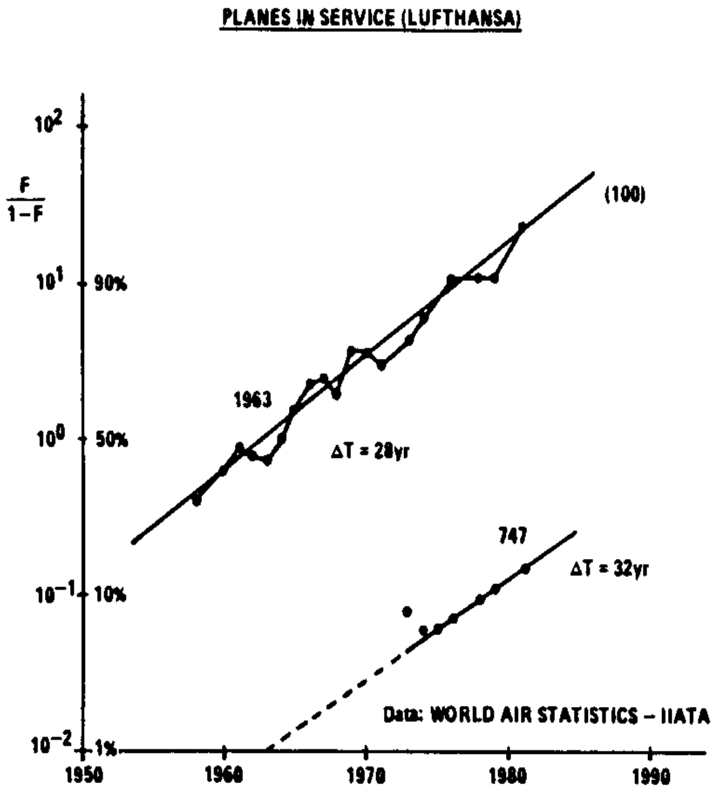


FIGURE 11. The same analysis of Figure 10 is here reported for passengers in the AEA area, basically Europe.





FIGURES 12a-b. To show that the fluctuations of Figure 11 are not due to lower level aggregation by respect to world case, a single company is here analyzed, for its development in terms of traffic and size of fleet, Lufthansa 747 expressed as fraction of fleet.

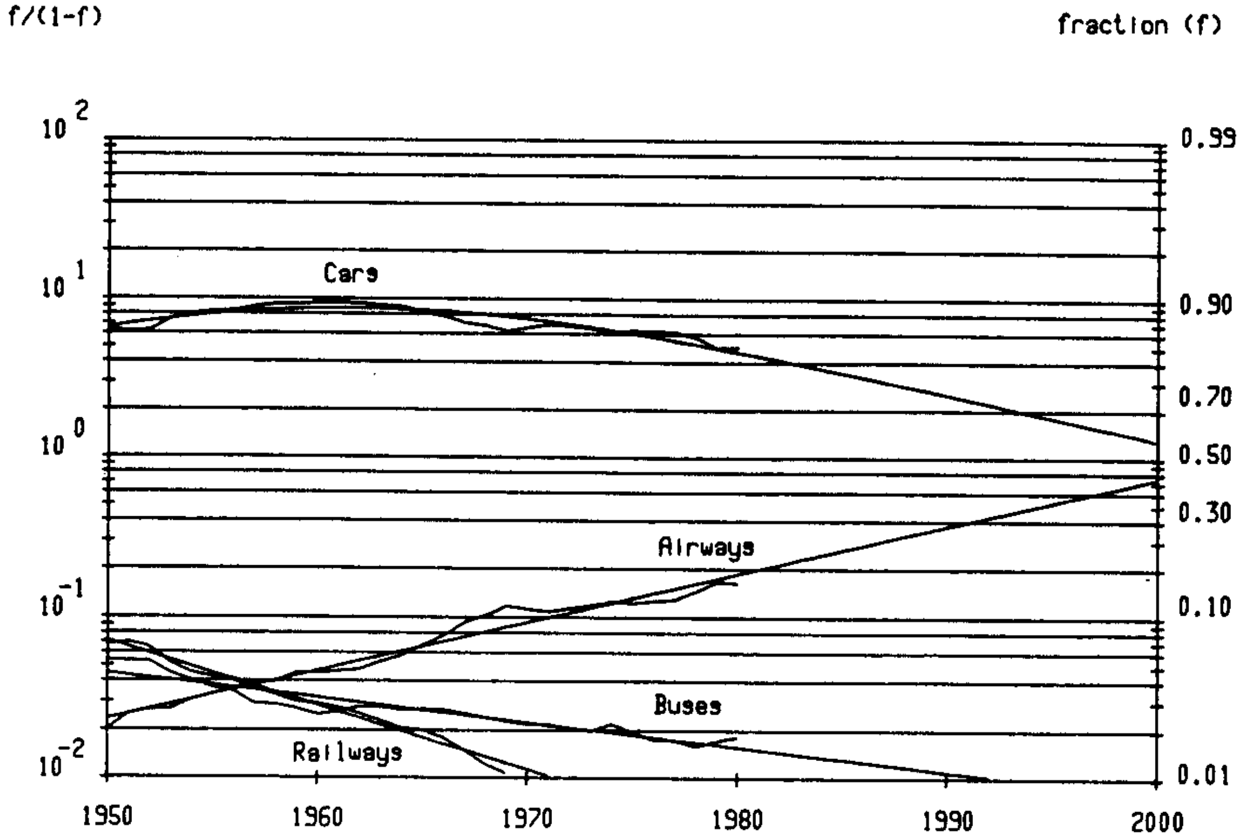


FIGURE 13. Intercity passenger-mile traffic in the USA is here analyzed in terms of modal competition. Cars reached their maximum traffic share already in 1958. The winning mode is air transport, but the time constant of penetration is not short, about 60 years. SOURCE: Nakicenovic (1987).

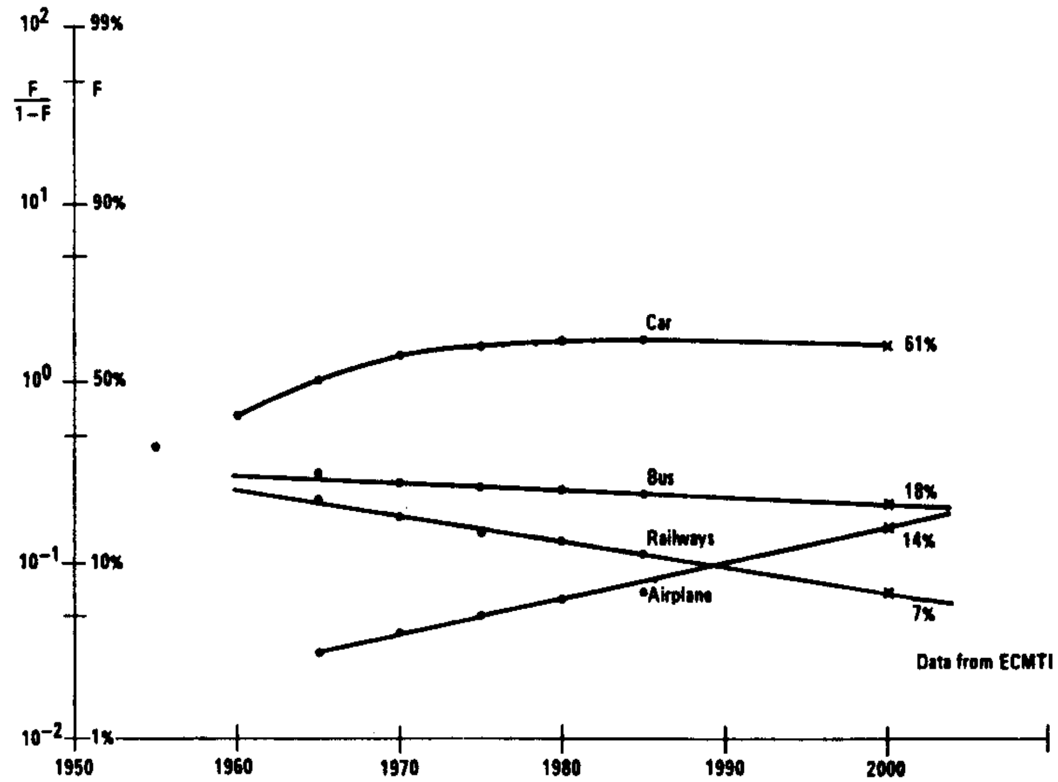


FIGURE 14. Homogeneous time series over long periods are difficult to assemble for Europe where data of different quality are scattered between different statistics. In spite of methodological weakness, the analysis shows a clear trend in mode substitution, analogous to that of the US and retarted at least 30 years. Also here

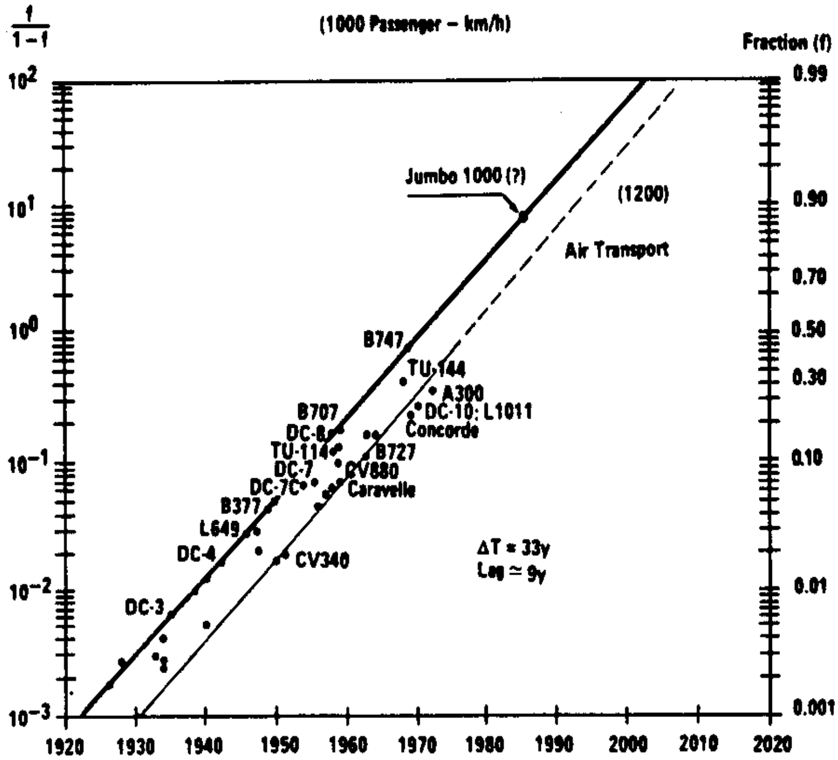


FIGURE 15. The meshing of planes productivity and volume of traffic reveals very simple rules, which may help understand the lines of future developments in the characteristics of aircraft and organization of traffic flows. SOURCE: Nakicenovic (1987).

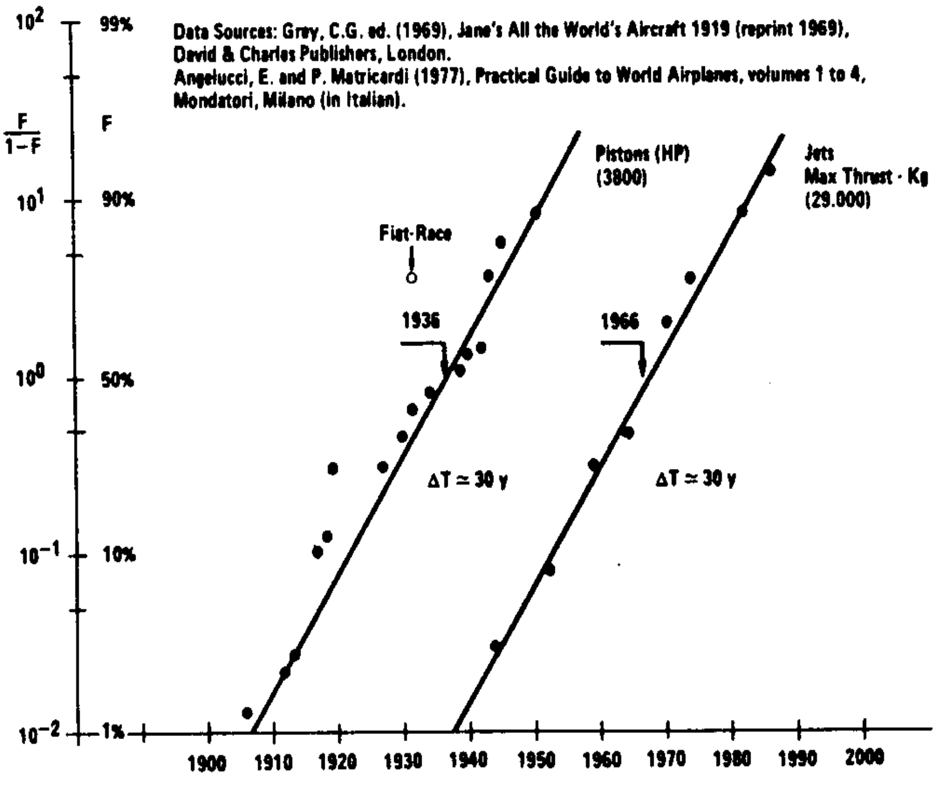
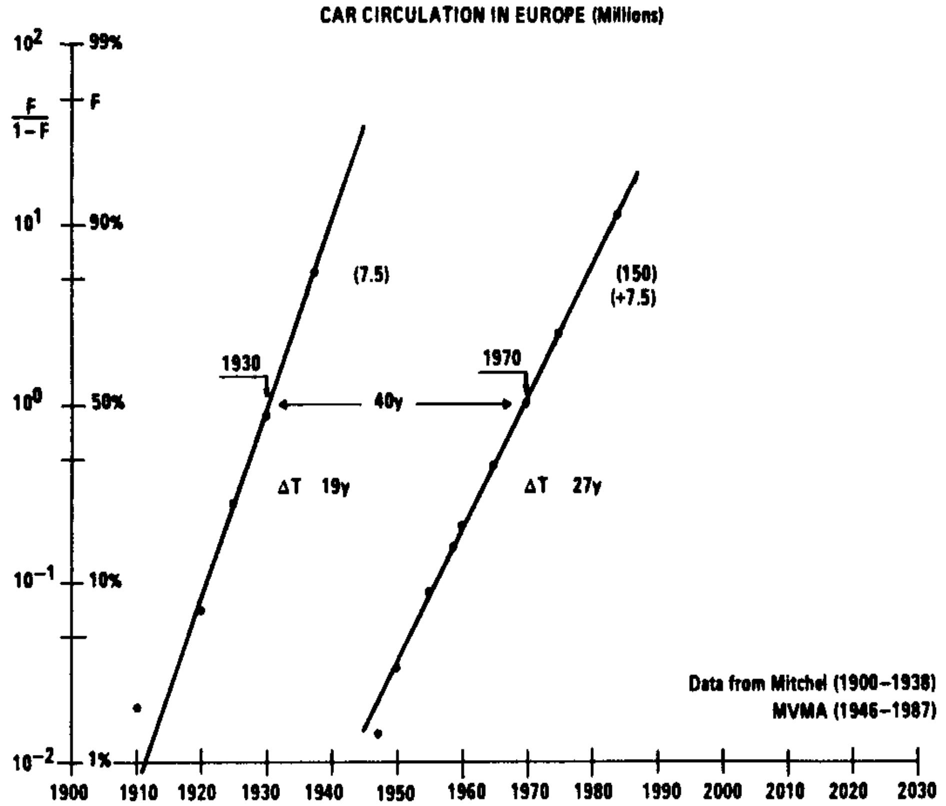
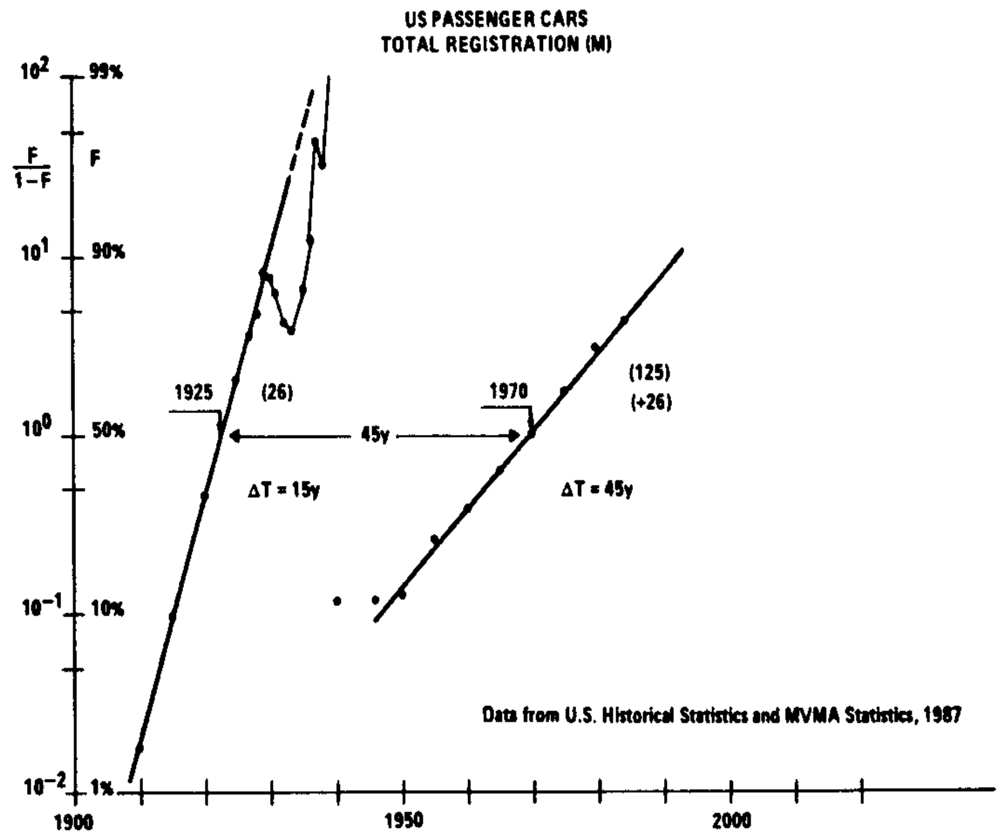


FIGURE 16. Development of power plants for airplanes show a possible shortcoming in the capacity of engine manufacturers to provide more powerful subsonic machines. This may open an opportunity window for very fast machines, possibly in the Mach 7 range. SOURCE: Grübler (1987b).





FIGURES 17a-b. The number of registered cars did grow in Europe and the USA along similar lines. A first pulse ending in 1940 and a second one ending in 1995 well in tune with Kondratiev cycles. The first pulse was larger in the USA, bringing total number of cars in circulation to 25 million in the 1930s. In Europe they were about 7 million at the beginning of World War II. Europe did catch up after the war, with a larger pulse, and the two car populations are going soon to be almost equal.

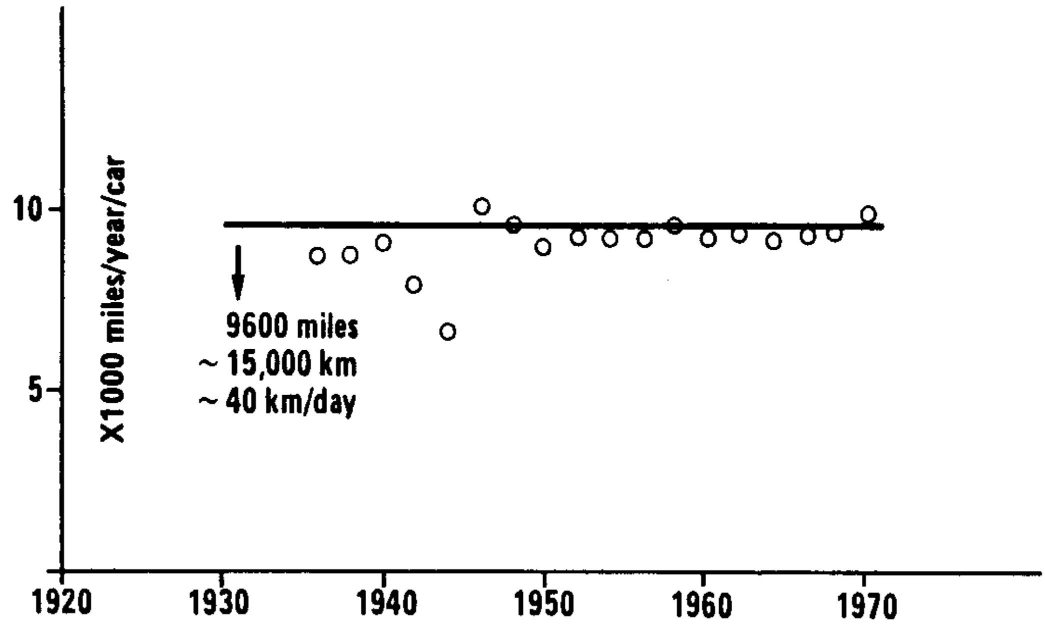
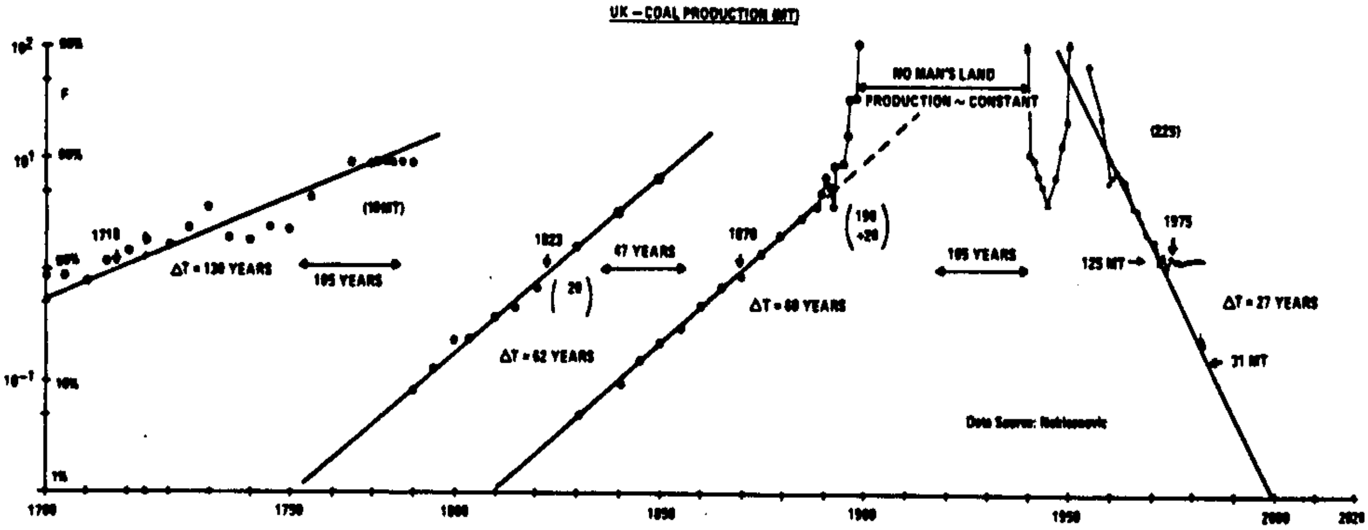
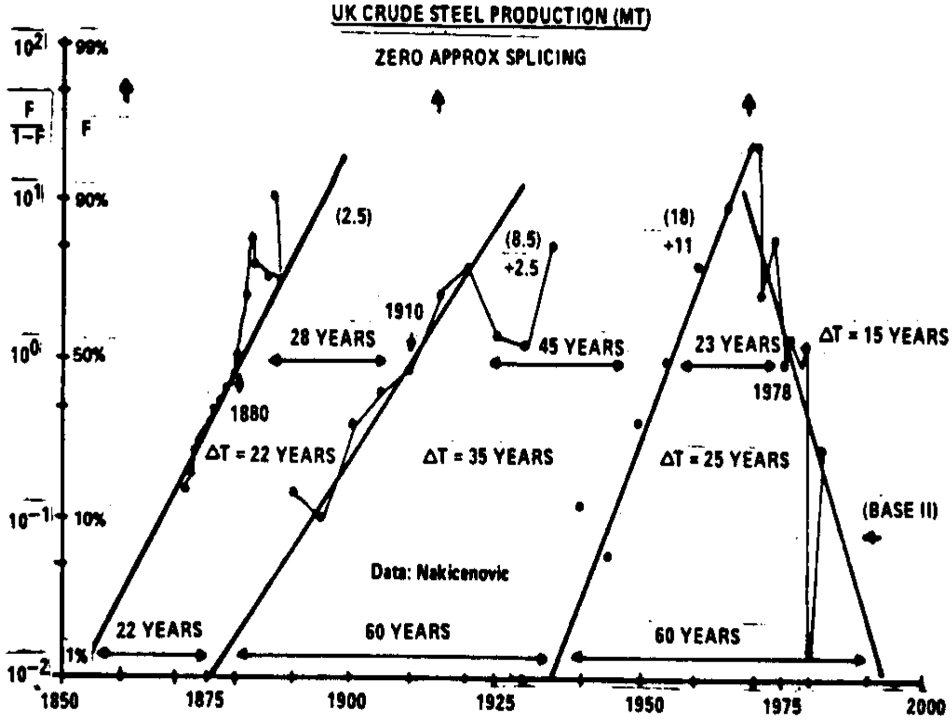
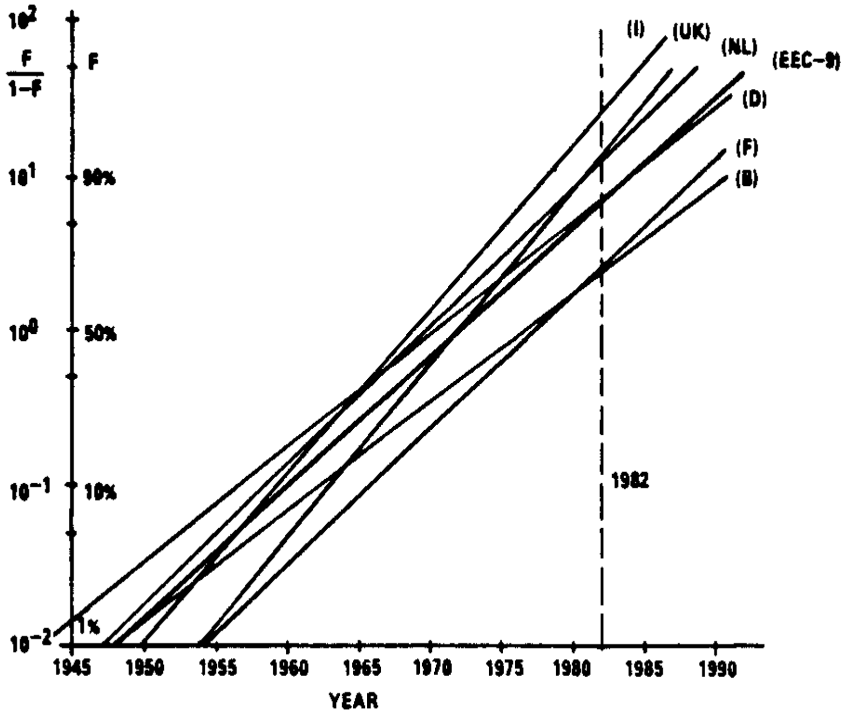


FIGURE 18. Mileage per car per year in the USA. It is extraordinarily stable in spite of the great advances in car speed and acceleration during the last 50 years. Apparently the user is satisfied with a *mean* speed of 50 km/h and all the advances simply compensate for the cluttering of streets and roads. It is also curious to observe that mean speed on foot is 5 km/h, by car 50 km/h, and by plane 500 km/h. Our hypersonic Orient Express may provide 5000 km/h, *mean*.





FIGURES 19 and 20. The analysis of a thousand case histories show a great homogeneity in the shape of technology life cycles, so that analogy is very meaningful. Here we have reported the life cycles of coal industry and steel industries in the UK to provide a possible scheme for the life cycle of cars as a means of personal transport in Europe. SOURCE: Nakicenovic (1984).



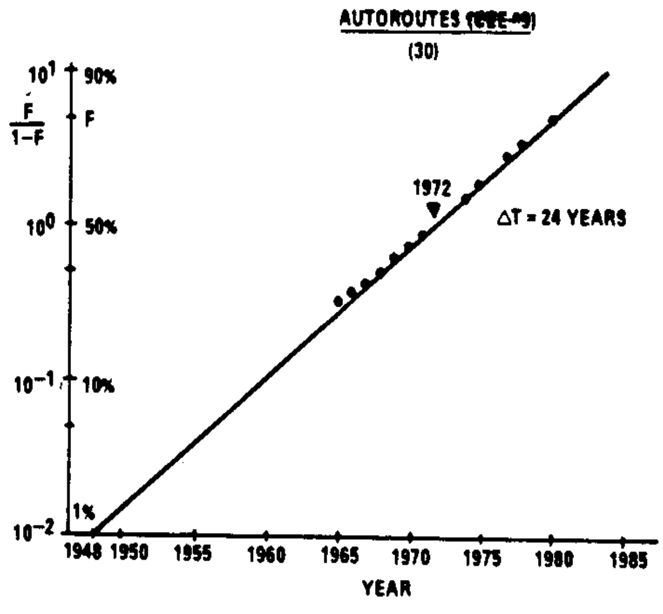
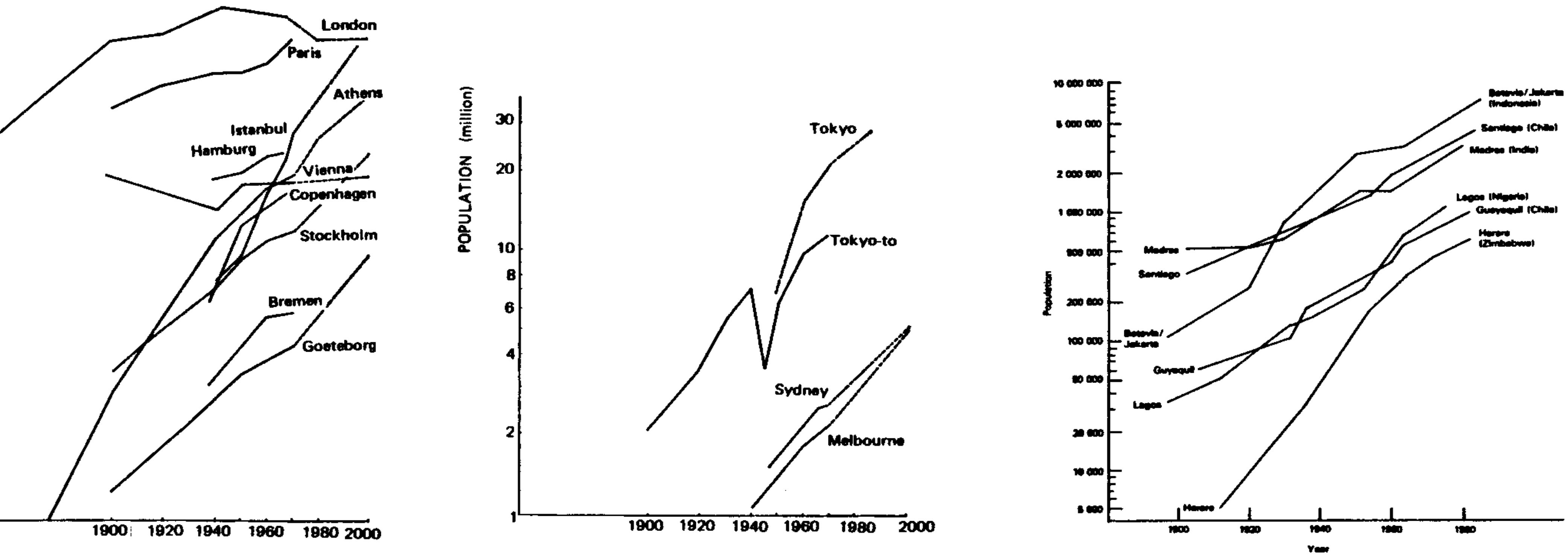


FIGURE 21. The evolution of auto routes length in the EEC, show a very neat progress to saturation for all countries studied and EEC as a whole. It shows weak system demand for new connections. In fact, most of the investments in auto routes are nowadays directed to improve capacity of existing links.



FIGURES 22a–c. The growth of a number of cities around the world is here reported to show their exponential explosion. Large *dense* cities can provide public services that much reduce the usefulness of a personal car. They also generate traffic for intense intercity links that may make Maglev economically interesting. The speed of Maglevs may finally fuse *functionally* such cities, with linear super-cities as "necklaces" of old ones. Maglevs linking the Tokyo-to-Osaka corridor may generate a 100 million city.

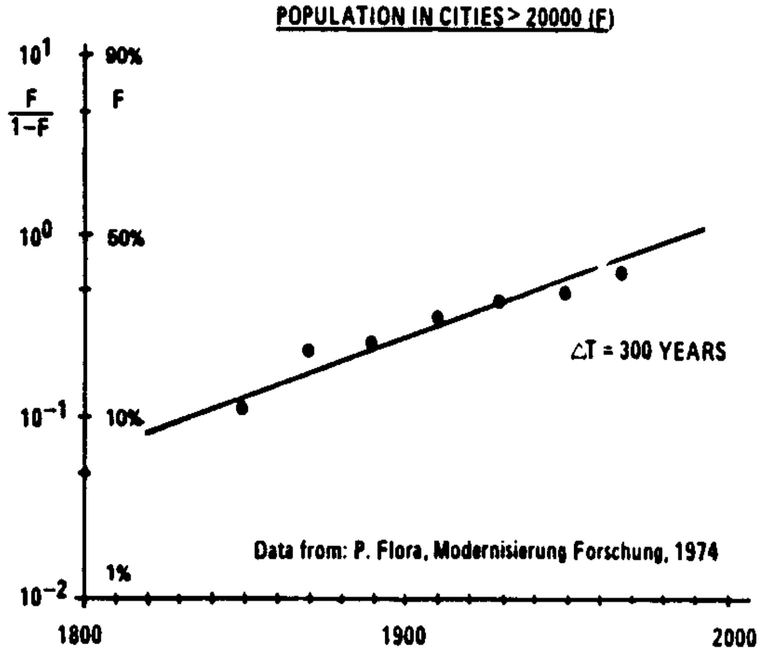


FIGURE 23. Urbanization is not a recent phenomenon. An historical analysis shows it is deeply rooted in the past. The great revolution came when the introduction of the tractor in agriculture removed the necessity for people to live on the land.

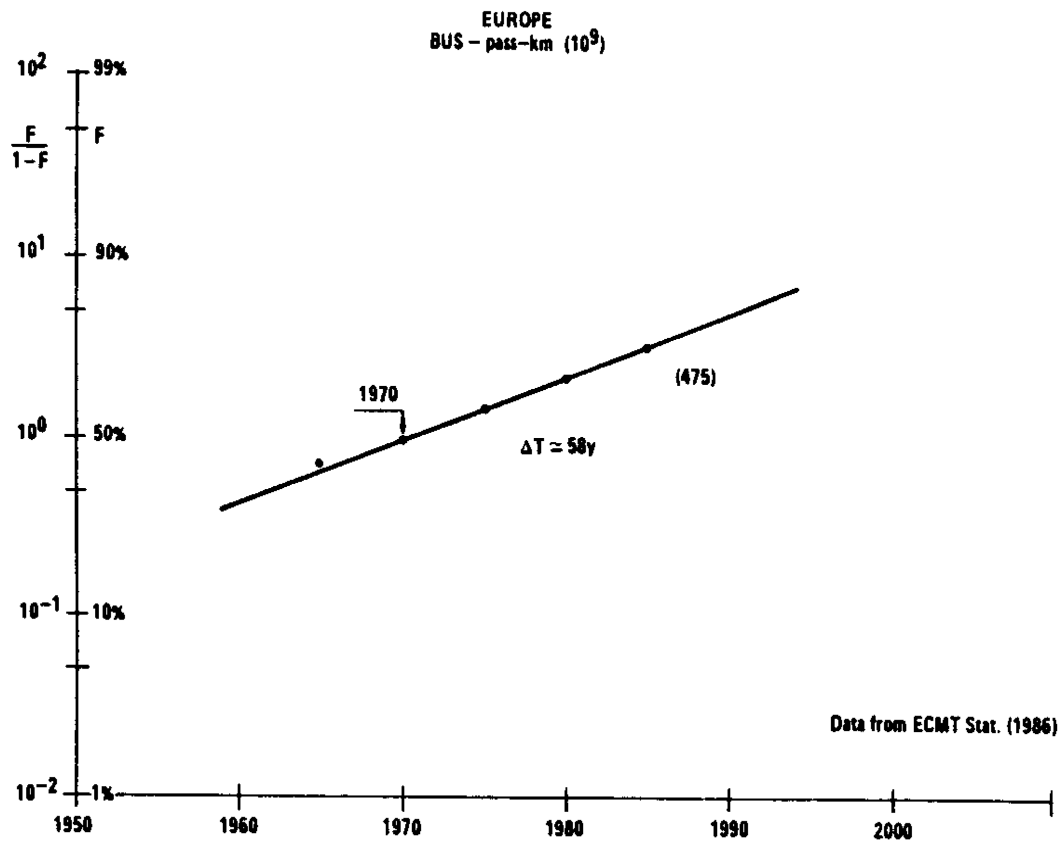


FIGURE 24. Bus traffic is increasing in Europe. These figures, however, include city traffic.

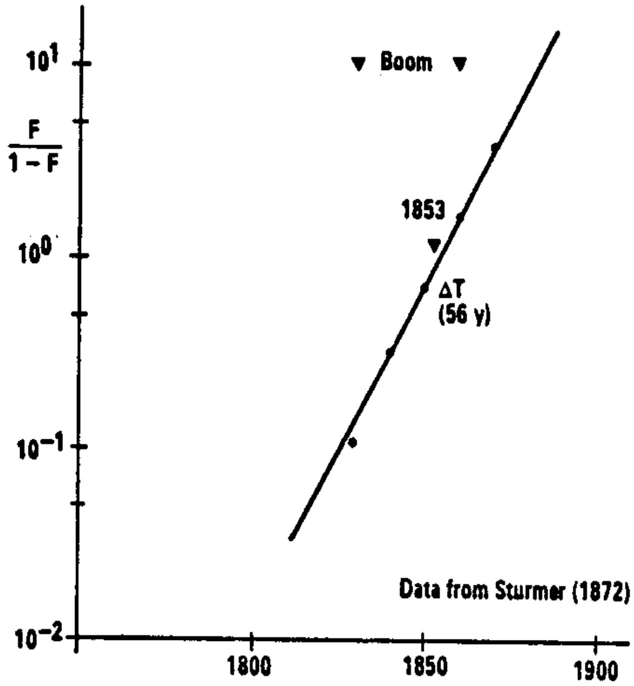


FIGURE 25. If we take the opening dates for the *first line* of each national railway network in the world, and we organize it assuming these are birth dates of a *population* of railway systems, we obtain this chart. Although the conceptual background is quite stiff, the analysis shows the supersystem did behave *as if*.

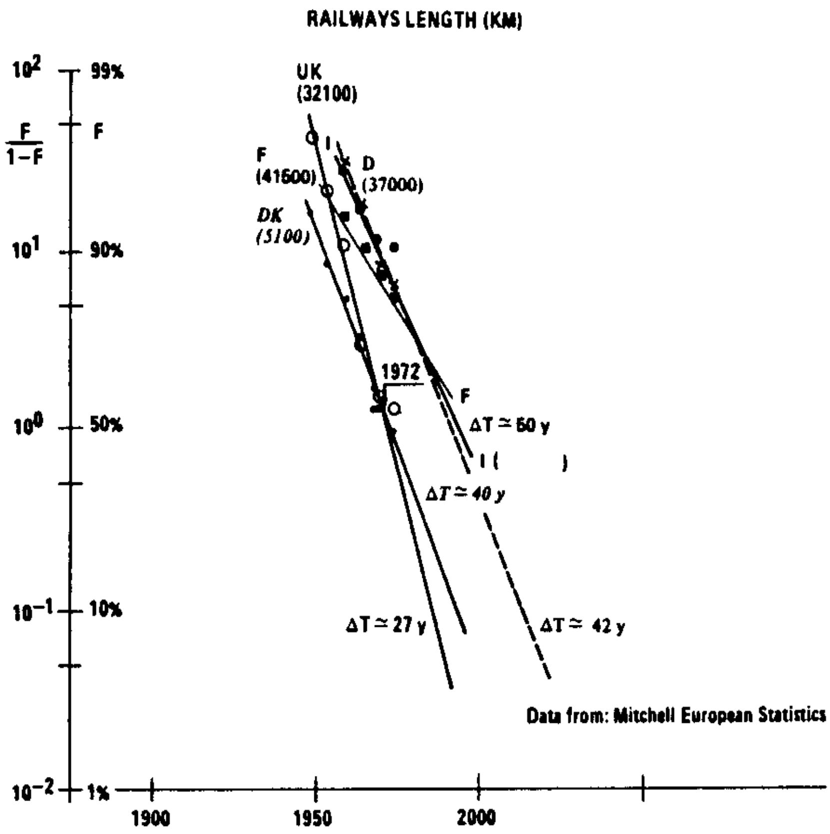


FIGURE 26. In spite of the great formal resistance to close tracks, even when they are wilted wigs, sometimes they fall by their own. Some short range analyses of track length in operation is here reported for some countries.

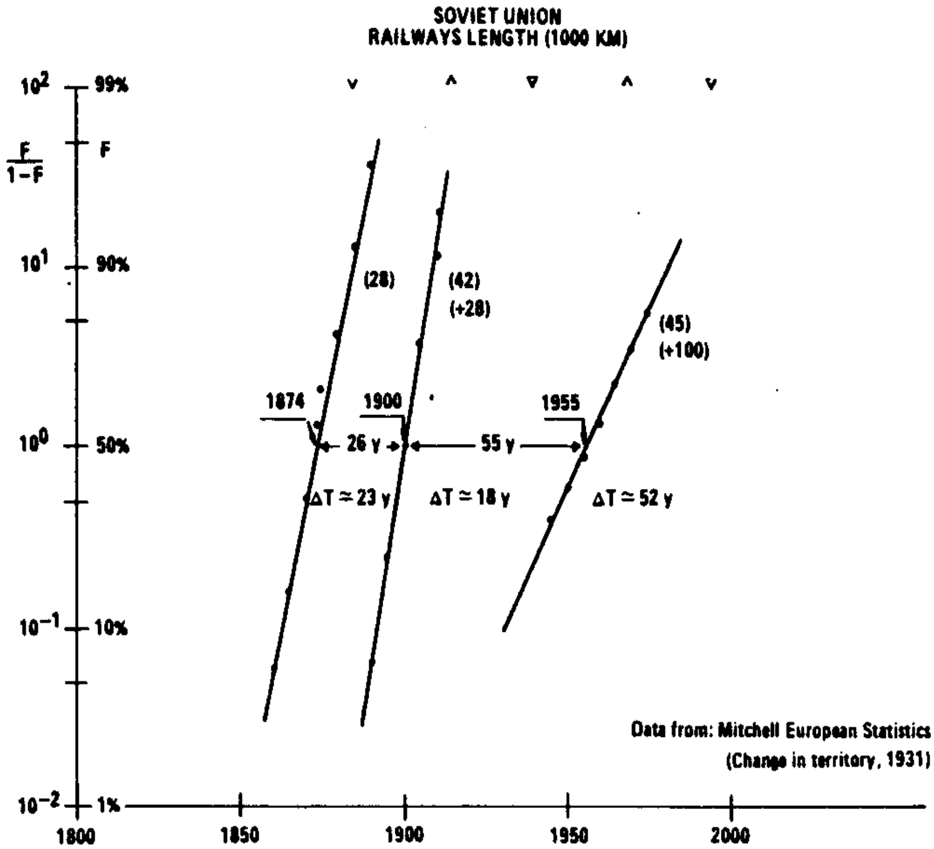
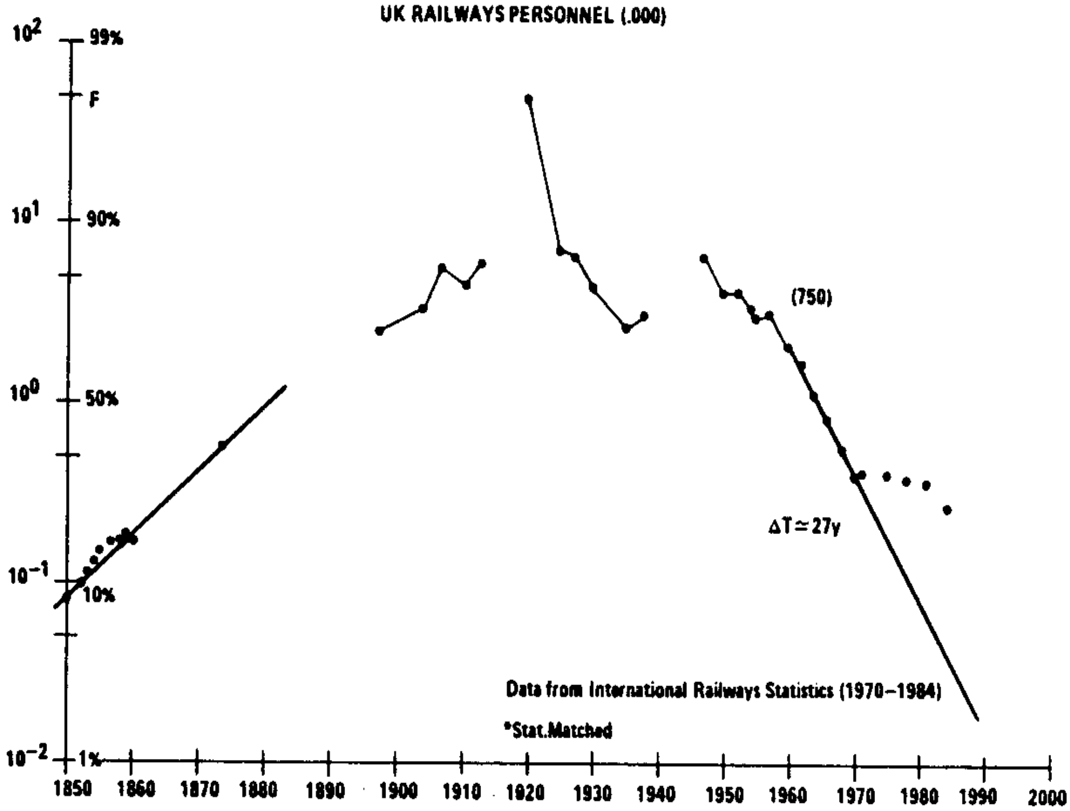
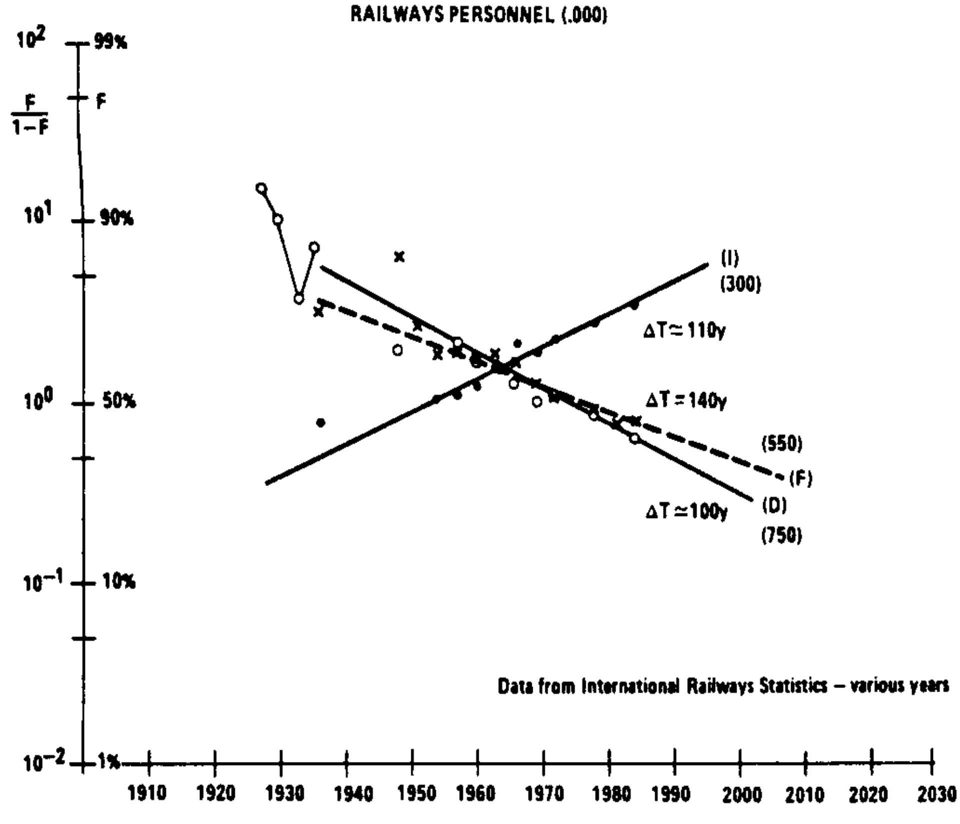


FIGURE 27. Soviet Union is a special case in many ways. Its track length keeps growing, if slowly, basically due to new penetrations in Siberia.





FIGURES 28a-b. The change in staff for some railways is reported here. Because their traffic did not change much since the 1930s, staff number is an indicator of productivity. In no case railways productivity did increase as in competing industry and the general economy. This brought them inevitably into a pension plan at the expense of taxpayers. The case of the UK is reported since the beginning.

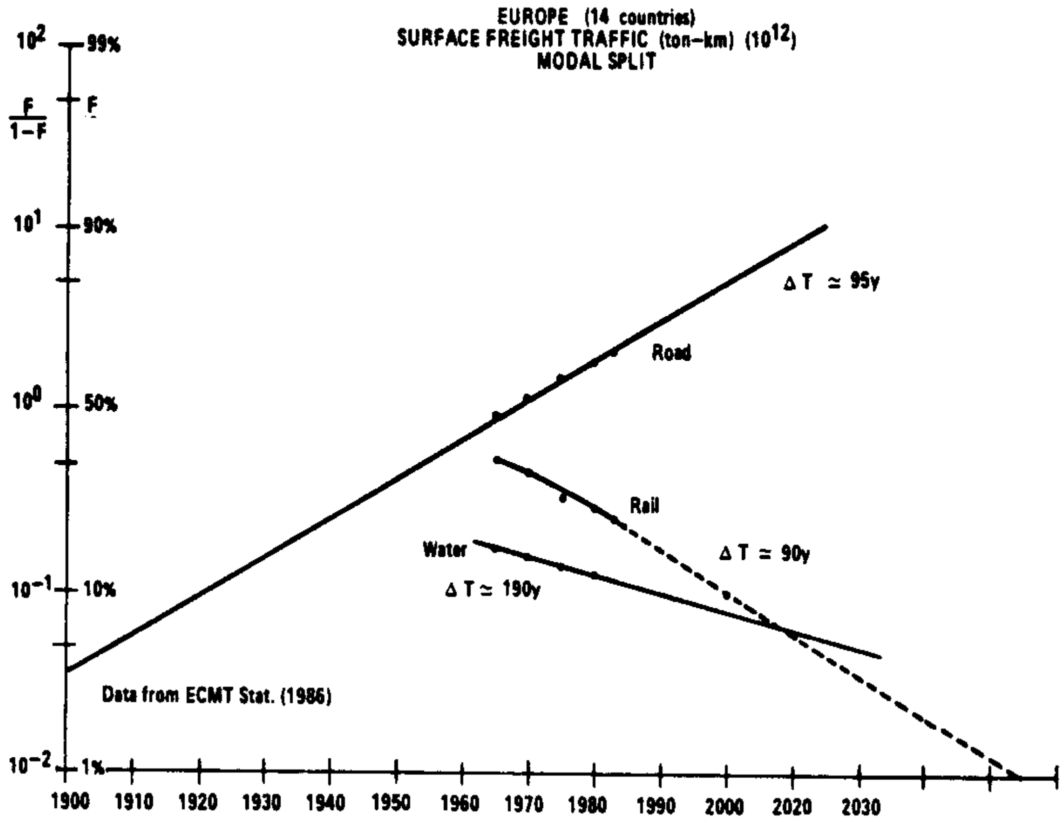


FIGURE 29

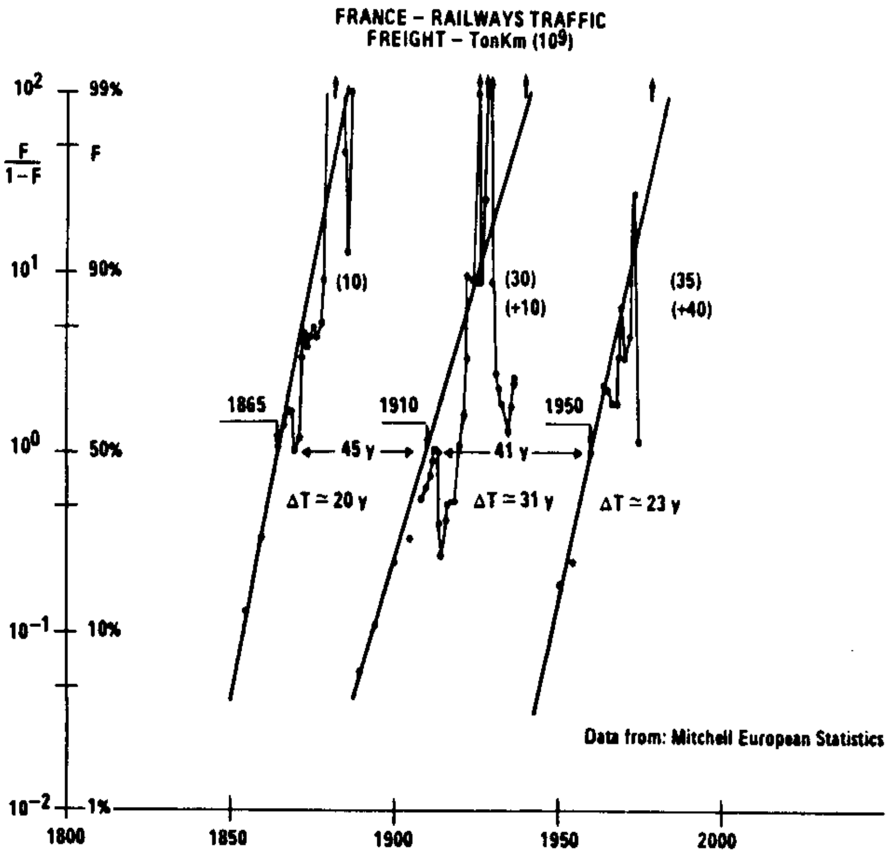


FIGURE 30

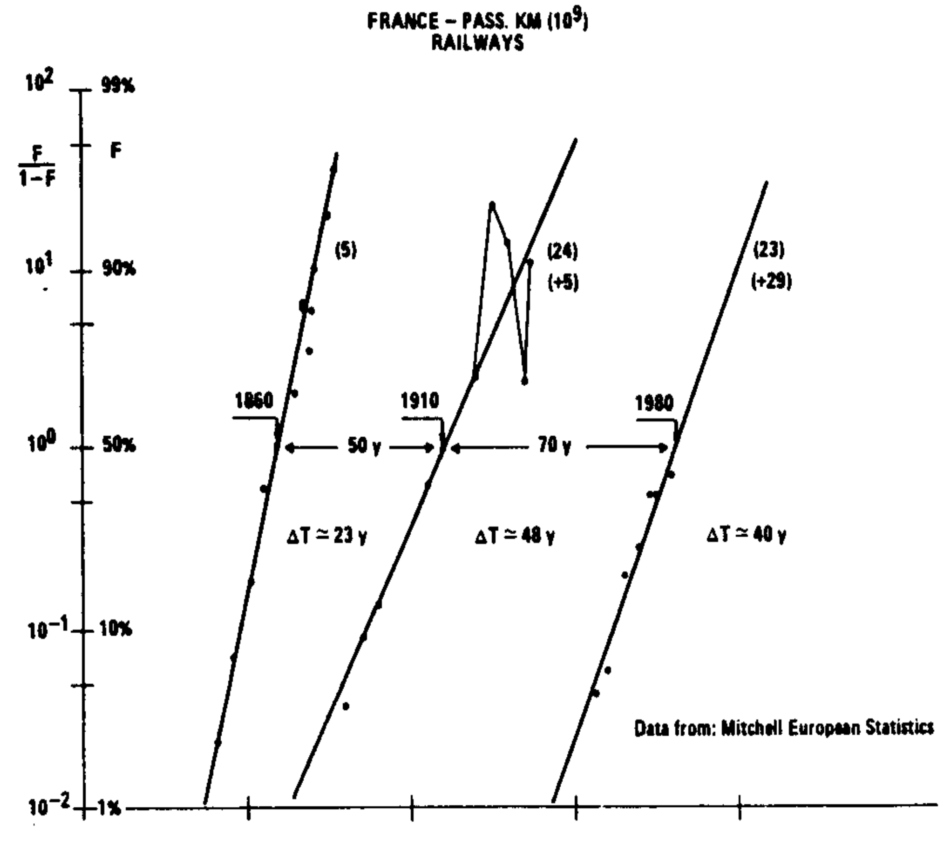


FIGURE 31

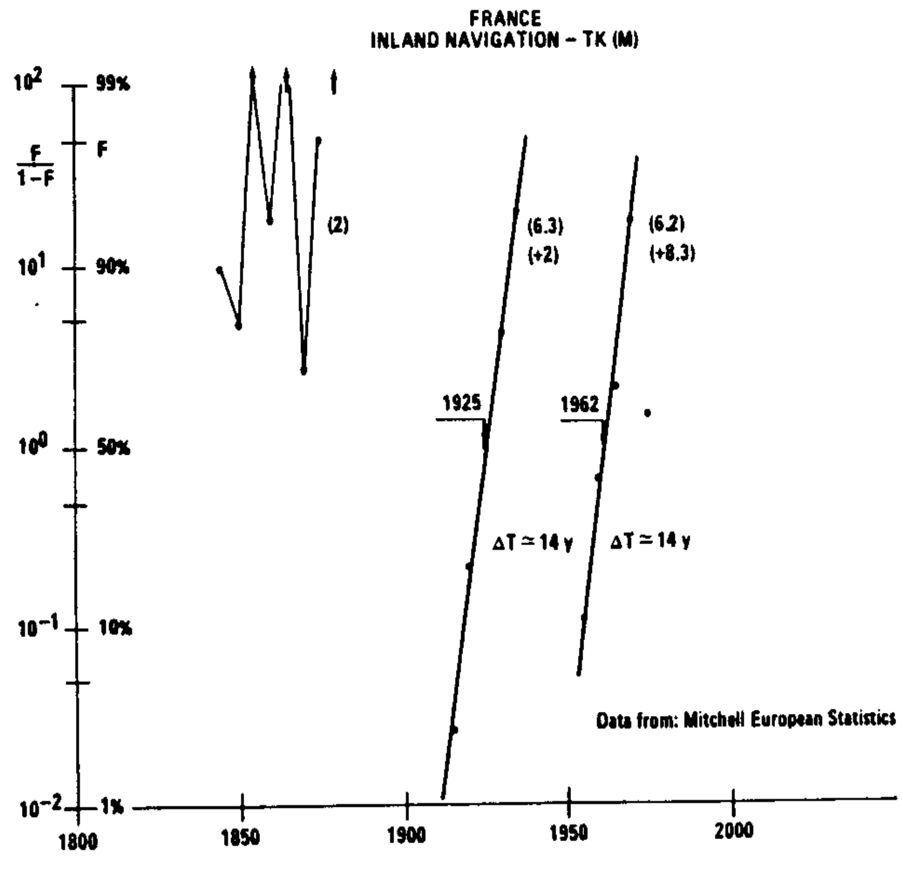


FIGURE 32

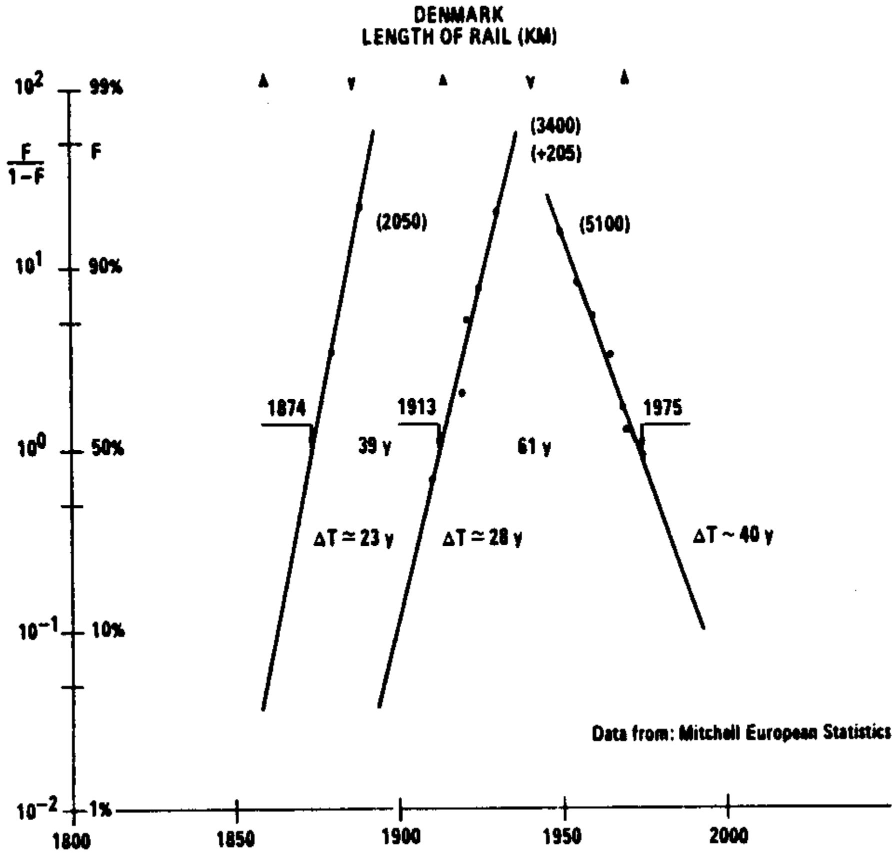


FIGURE 33

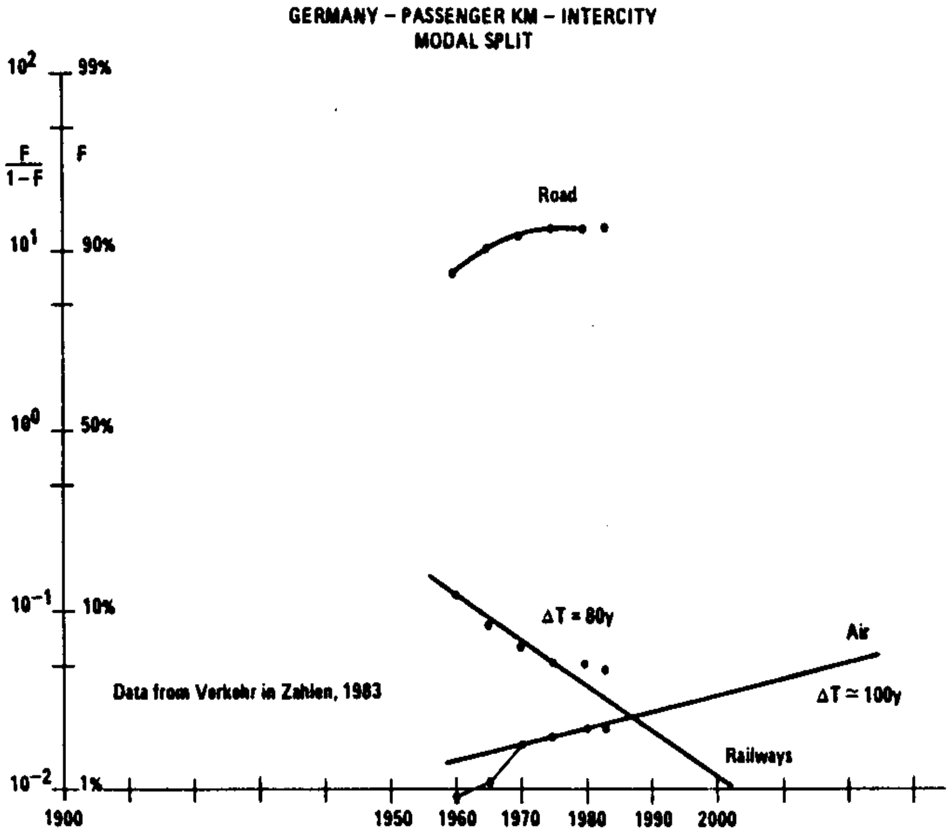


FIGURE 34

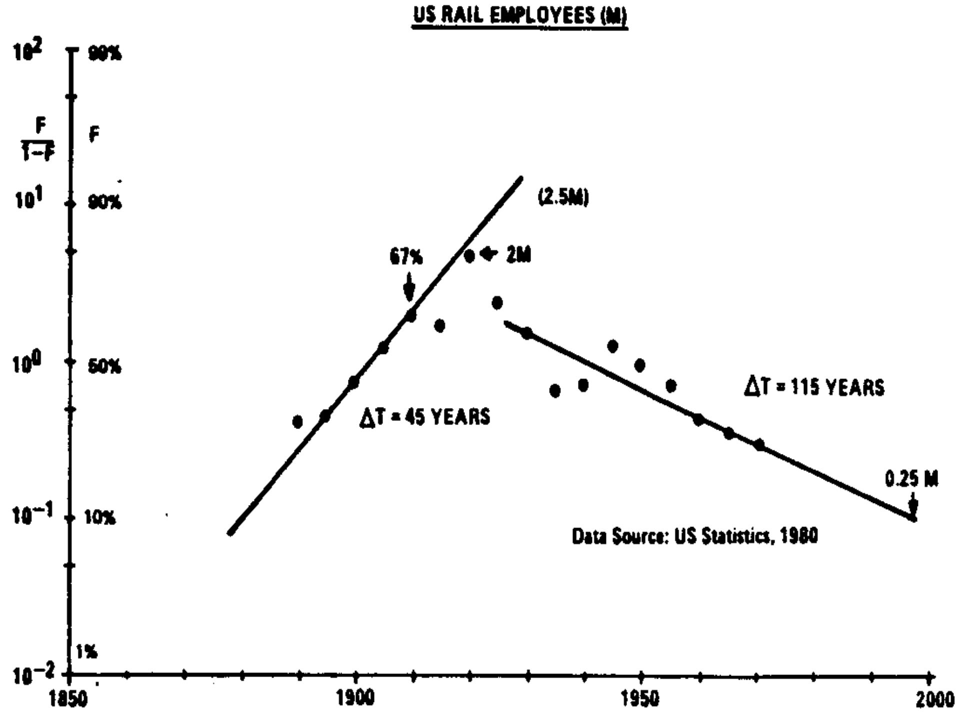


FIGURE 35

FIGURES 29-35. Some hints on the evolution of freight traffic is given here. The data base is too small to show many conclusions, but the trends are clear.

A set of national cases have been examined here to give depth and variety to the analysis. The general trends are visible everywhere, and even when growth is still present, instead of stagnation, this growth is small. It remembers the famous sea captain's order to the engineer: ***dead slow, almost backward.***

WORLD OIL CONSUMPTION 10^9 tons

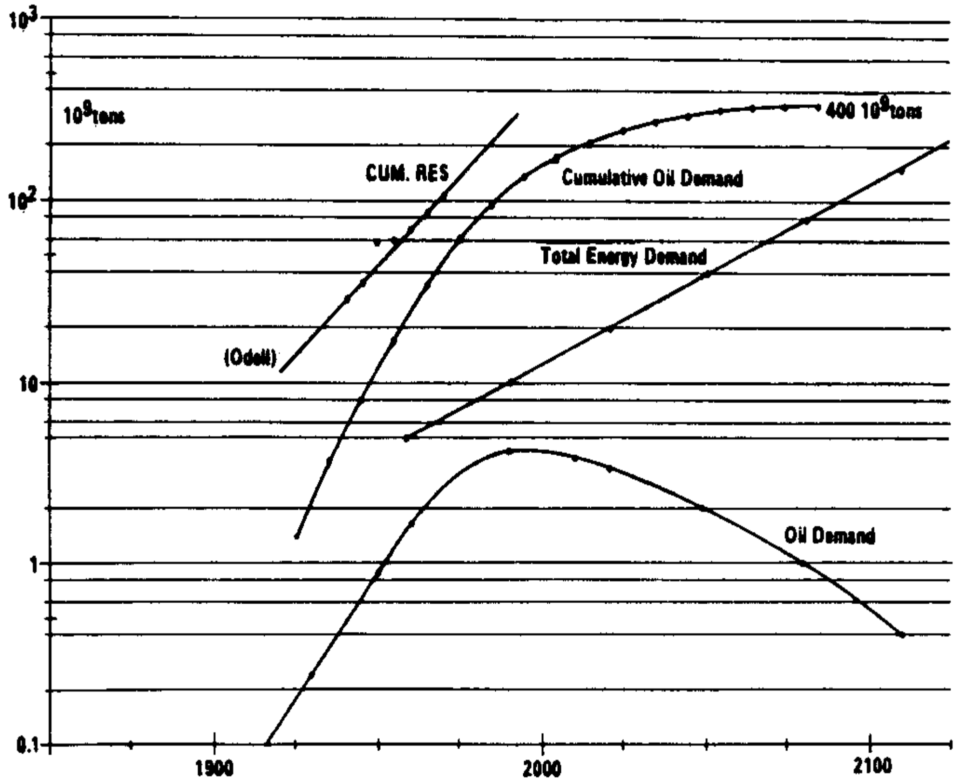
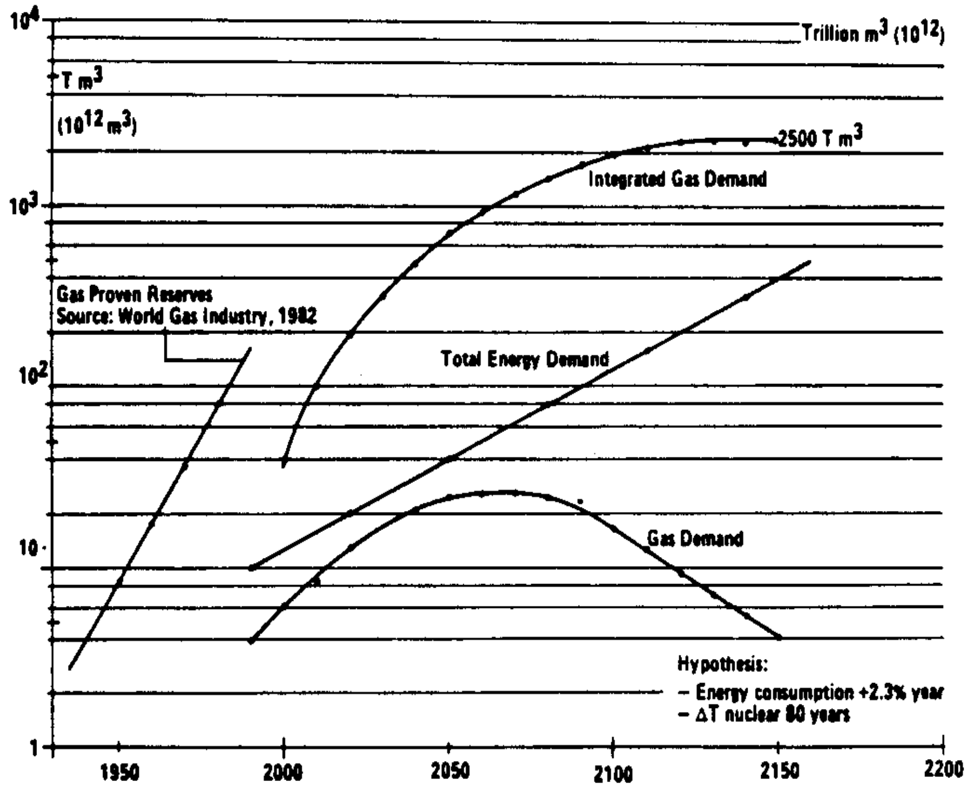
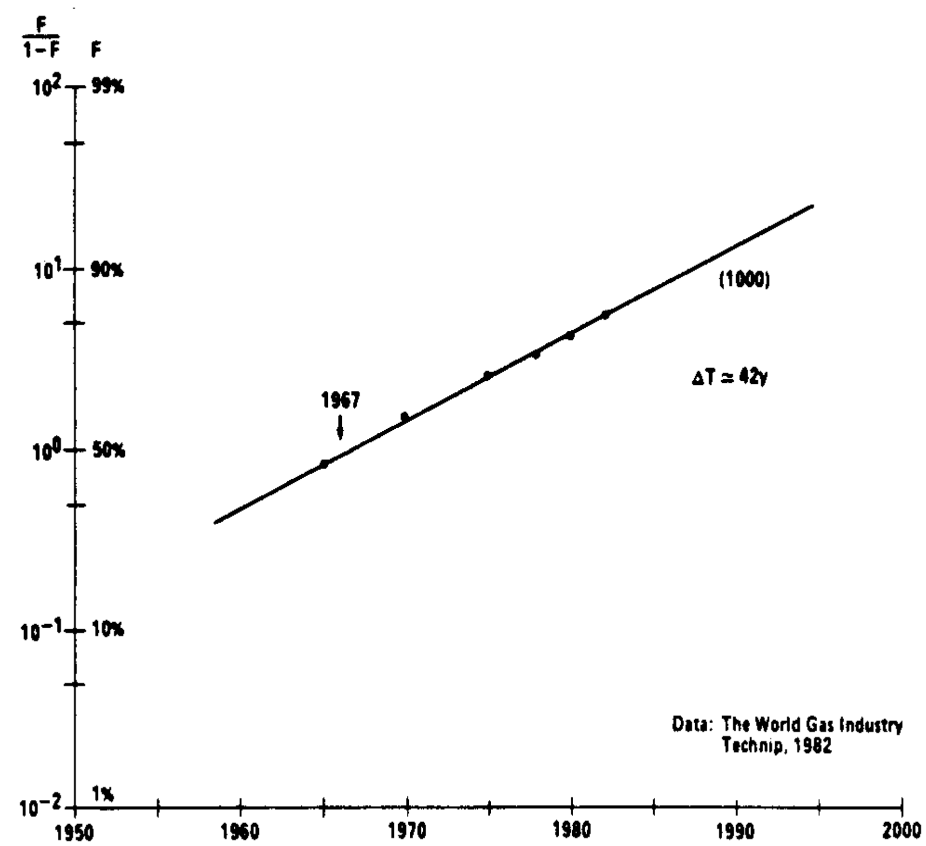


FIGURE 36. Oil consumption is presented here at world level, using the shares of Figure 7 and total energy consumption growing at the historical (150 years) rate of 2.3%. Europe is somehow anticipated by respect to this scheme shown for the world.

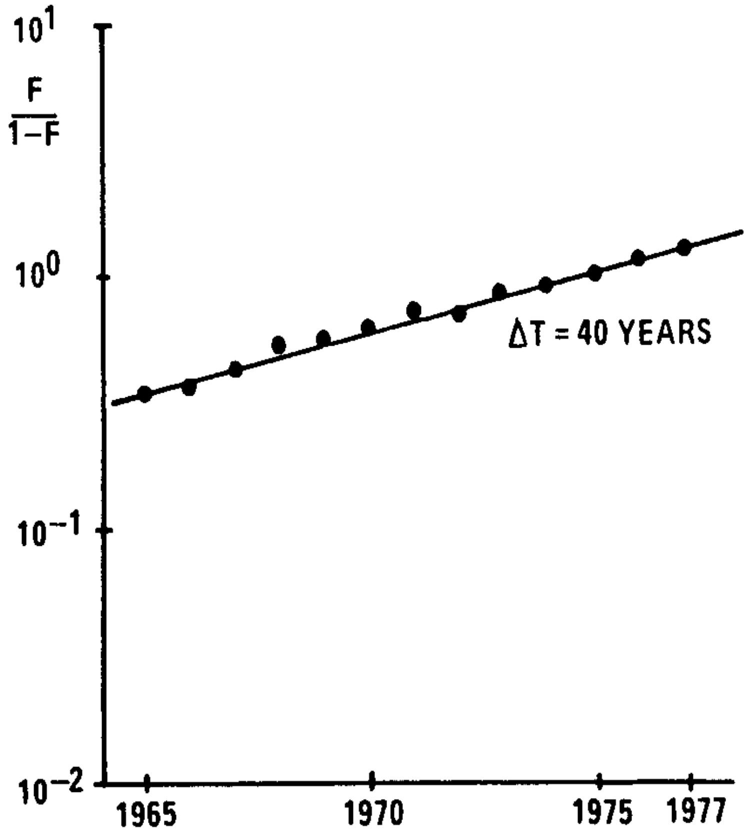
WORLD GAS CONSUMPTION (Trillion m^3 (10^{12})
INTEGRATED FROM 1990 UP TO YEAR 2150





MAJOR GAS PIPELINES IN THE EUROPEAN COMMUNITY (160)

(x1000km)



FIGURES 38a-b. Analysis of gas pipelines growth for Europe and the world. It is