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Time for a Change: Rates of Diffusion of Ideas, Technologies and Social Behaviors

Arnulf Grübler

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IIASA International Institute for Applied Systems Analysis ▫ A-2361 Laxenburg ▫ Austria
Telephone: +43 2236 807 ▫ Fax: +43 2236 71313 ▫ E-Mail: info@iiasa.ac.at

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Arnulf Grübler
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Unlike resources found in nature, technology is a manmade resource whose abundance can be continuously increased, and whose importance in determining the world's future is also increasing. [C. Starr and R. Rudman, 1973]

Abstract

Diffusion phenomena are identified to be at the heart of processes of technological, economic and social change. Patterns, regularities and timing of diffusion processes are illustrated on basis of selected examples. A metaanalysis of a larger sample of diffusion processes for the USA identifies rates of change and their historical discontinuities. The paper concludes in emphasizing the interlinkages within whole families of technologies and forms of social *techniques* (technology clusters). Historically, these have been instrumental in raising productivity and also alleviating many adverse environmental impacts. The emergence of a new cluster could hold promise for an environmentally more compatible technological trajectory leading to further dematerialization and decarbonization of our economies.

[1]Paper presented at the Workshop on Technological Trajectories and the Environment, Rockefeller University, New York, October 28–29, 1993.

Introduction

The purpose of this paper is to discuss dynamics of processes of social, economic and technological change taking an inductive and empirical approach.

Technology is seen as the principal dynamic force mediating between human activities and the environment. Technology however, is interpreted in a larger sense, referring to whole *socio-technical systems of production and use*, enabling humans to extend their capabilities and to accomplish tasks which they could not perform otherwise.

In the most narrow terms, technology is represented by man-made objects, referred to by engineers as "hardware" and by anthropologists as "artifacts". But technology does not end here. Artifacts have to be produced, i.e., invented, designed, and manufactured. This requires a larger system: hardware (machinery, a manufacturing plant), factor inputs (labor, energy, raw materials) and finally "software" (know-how, human knowledge and skills). The latter (for which the French use the term *technique*) represents the disembodied nature of technology (its knowledge base). Finally, *technique* is not only required for the production of given artifacts but also for their *use* (e.g., the technique of driving a car or using a bank account), both at the level of the individual, as well as at the level of society. Forms of organization (like the existence of markets), institutions, social norms and attitudes are important to understand how particular systems of production and use of artifacts emerge and function. They are also important determinants for the origin and choice (selection) mechanisms of particular (combinations of) artifacts, and the rate by which they become incorporated (or not incorporated) into a given socio-economic setting. A process referred to as *technology diffusion*.

What then, is technological change? First, it is important to emphasize that technology evolution is *cumulative*, i.e., changes build on previous experiences and developments. Artifacts become obsolescent, however, the knowledge base developed for their production and use persists, being available for both the reproduction of existing and for the development of new solutions (innovations). But changes are not instantaneous. They require considerable time between development, first implementation, and widespread replication. Following Schumpeter we can distinguish between invention, innovation, and finally, diffusion. Invention is the first demonstration of the principal feasibility of a proposed new solution. Fermi's Chicago reactor demonstrated the feasibility of a controlled nuclear fission reaction (invention). 1957, 15 years later to the day after the inauguration of Fermi's pile, the Shipping Port reactor went into operation (innovation). And it took over 30 years after that date for nuclear reactors to account for some 20 percent of the electricity generated in the USA, with the prospects of further diffusion highly uncertain. Earl Pemberton in his classic 1936 article on "the curve of culture diffusion rate" provides other examples. The first country to introduce postage stamps was England in 1840 (innovation), and it took close to 50 years for a sample of 37 independent European and (North and South) American countries to follow suit. The first compulsory school law at the state level in the USA was enacted in 1847. However, it took until 1927 for the last (southern) state to adopt a similar legislation. These illustrative examples already indicate that changes in technologies and *social techniques* are not one-time discrete events, but rather a process characterized by time lags and considerable time involved in diffusion.

Inventive and innovative activities can provide *potentials* for change. However, it is only through *diffusion* that these potentials become actually translated into changes of social practices, artifacts and infrastructures in use. As such diffusion phenomena are at the heart of changes in society and the material structures (infrastructures and artifacts) it manifests itself. That is why in the subsequent discussion diffusion analysis provides the central metric to analyze the dynamics of processes of social and technological change.

Diffusion: Social Actors and Networks

To discuss some of the salient features of diffusion let us leave the field of technology and return to the 11th century A.D. The reform movement of Benedictian rule by St. Bernard led in 1098 to the foundation of Citeaux (Cluny), which was to become the mother house of some 740 Cistercian monasteries. About eighty percent of them were founded in the first 100 years of the Cistercian movement and close to half of the total foundations occurring between 1125 and 1155 (*Figure 1*). The time path of the spread of Cistercian rule is non-linear and not unlike the diffusion patterns we observe for technological systems (cf. examples below). The temporal diffusion pattern is almost invariant across cultures, across cultural traits, or artifacts: slow growth at the beginning, followed by accelerating and then decelerating growth, leading into saturation (and eventual decline).

The role of social networks, and diversity is exemplified by the differentiation into different "sub-families" (named after their respective motherhouses, each of whom follows their own pattern of settlements,[2] regional specialization, and implementation of Cistercian rule. Some of the additions to Cistercian rule were not genuine new settlements, but "takeovers", as yet another illustration of the social interactions involved in diffusion: Savigny (with all its daughterhouses) submitted to Clairvaux rule in 1147, in turn to become the motherhouse of all Cistercian settlements on the British Isles. Despite differentiation and regional specialization, close communication existed between all of the monasteries, representing an important channel for the spread of innovations like the watermill or new agricultural practices introduced in the 13th and 14th century.

Diffusion is both a temporal and spatial phenomenon. The topology of the Cistercian network clearly reveals a hierarchy of centers of creation and structured channels of spread (cf. *Figure 2* illustrating the spread of two Cistercian "sub-families"). The patterns bear witness to the existence of *networks*. In fact, there is a growing literature[3] emphasizing in particular the role social and spatial networks and the interactions they support, play in the diffusion process. Another feature emerging from *Figure 2* are the significant differences in the spatial density of settlements. The innovation origin, Burgundy was home to all of the four mother houses and hosted the highest spatial concentration of settlements. From there daughterhouses were founded (regional sub-innovation centers in the terminology of spatial diffusion), from where Cistercians spread out further to the respective hinterlands (neighborhood effect in spatial diffusion) and to other sub-regional centers, being in turn origin of further settlements. However, the density of settlements decreases further out to the periphery, i.e., away from innovation centers, implying persistent regional differences and disparities. This is not a unique feature of the diffusion process discussed here, but also applies

[2]According to Cistercian rule, settlements were to be located in remote, undeveloped areas. Thus, Cistercian monasteries were important local nodes for internal colonization (and of deforestation) in 13th and 14th century Europe.

[3]Cf. Hägerstrand, 1968, and Rogers, 1983 for an overview of spatial and temporal diffusion. For a more recent overview of diffusion theory cf. Nakićenović and Grübler, 1991. On the role of networks, cf. e.g., Kamann and Nijkamp, 1991.

to the spread of technological artifacts and infrastructure networks as illustrated in *Figure 3* for the development of the railway network in the USA.

Some Regularities of Diffusion

The above example, deliberately chosen from a field outside technology, illustrates some regularities of diffusion processes which can be derived from both theoretical and empirical streams of diffusion research (summarized in *Figure 4*).

(1) No innovation spreads instantaneously. Instead, a typical S-shaped temporal pattern seems to be the rule. This basic pattern appears invariant, although the regularity and timing of diffusion processes vary greatly.

(2) Diffusion is both a temporal and spatial phenomenon. Originating from innovation centers, a particular idea, practice, or artifact, spreads out further to their respective hinterlands (core area) and via a hierarchy of sub-innovation centers into the periphery (defined either spatially or functionally/socially).

(3) The periphery, while starting adoption later, profits from external learning and the experience gained in the core and generally has faster adoption rates, i.e., is "catching-up". As the development time is shorter, however, the absolute adoption intensity is lower than in innovation centers or in core areas in (spatial or functional) proximity to them.

(4) As a result, despite that, diffusion is essentially a process of homogenization, application densities, (spatial and intensity of use) and timing of diffusion remain heterogeneous, in space, among the population of potential adopters, across different social strata. Thus, there is little theoretical or empirical evidence to assume that adoption intensities of early diffusion starters are any guide to the adoption levels of late followers.

Diffusion: Spread in a Turbulent and Changing Environment

Before discussing further diffusion examples, let us return to the process prior to diffusion: innovation generation and selection. In fact, a realistic history of social and technological innovations would consist mostly of "non-starters", i.e., examples of no diffusion rather than diffusion. Thus, the existence of one (or a range) of possible innovations in itself is no guarantee for subsequent diffusion.

To appreciate the uncertainty in the early phases of technology development let us look at a historical problem of technological hazard and environmental pollution from steam railways. Smoke sparks from woodburning steam locomotives in the USA represented a considerable fire hazard to both human settlements and forests. Over 1000 patents on "smoke-spark arresters" were registered in the 19th century (some illustrated in *Figure 5*) in a futile search of a solution (to be solved finally not via an "add-on" technology, but by the replacement of steam by diesel and electric locomotives). This large variety of possible alternatives illustrates that diversity and experimentation are precursors to diffusion. "Many are called, but few are chosen."[4]

An additional factor that can influence diffusion is resistance and opposition to change. Opposition to new proposed technologies is a recurrent historical phenomenon from the early railways to the opposition to the introduction of mechanical threshing machines in rural England in the 1830s (in fact again a diffusion process as shown in *Figure 6*, the speed of which [two weeks], illustrates that social interaction and communication have been quite effective even in absence of modern transport and communication technologies). While possible opposition is source of uncertainty, it fulfills two important roles in the context of technology evolution: first it can operate as effective selection mechanism against socially unsustainable solutions, rejecting technologies, or, second, it is an important driving force for qualifying technologies to respond to societal concerns, improving its performance and thus enabling further diffusion.

Even in a case of successful diffusion, the driving forces and factors determining speed and extent of diffusion[5] are very heterogeneous, and in addition change over time. It is important however to emphasize that ordered structured transition paths at the macro level appear driven rather than dissipated

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[4]The choice (selection) of a particular alternative may not conform to *ex ante* or *ex post* defined optimality criteria. Sometimes selection of a particular alternative results from an accumulation of small random events, eventually leading into a "lock-in" into a particular configuration. Thereafter, positive feedback mechanisms yield increasing returns to adoption of the standardized alternative (for a model cf. Arthur, 1988).

[5]For an overview from the fields of sociology and anthropology cf. Rogers, 1983. From economics, cf. Mansfield, 1961 and 1968. For industrial innovations, cf. Nasbeth and Ray, 1974, and Ray, 1989.

by diversity and complex interactions at the micro level. Such diversity, according to recent theoretical findings[6], appears almost as a prerequisite for diffusion. In addition to micro-sociological and economic factors there appear also more generic systemic factors at work influencing speed of change: like level of aggregation, or size of the system (cf. Grübler, 1991), or whether diffusion entails creating an entirely new context or supplants already existing techniques and artifacts.

Three Levels of Diffusion

A taxonomy of diffusion processes can be developed by differentiating the environment in which diffusion processes operate. In the most "pure" case an idea, practice, or artifact represents such a radical departure from existing solutions that it creates so to speak its own niche through diffusion. More frequently however, a new solution does not evolve in a vacuum but *interacts* with existing practices, technologies, etc. This case is referred to as (technological) substitution, with varying degrees of interaction (one to one competition, or multiple substitution). This interaction is usually most visible by looking at relative (e.g., market) shares of competing alternatives rather than on absolute volumes.[7]

Figure 7 illustrates a diffusion case proper, showing the growth of the canal network in the 19th century USA. The empirical data are approximated by a symmetrical growth cure (a three parameter logistic[8] in this case). The

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[6]Cf. Dosi *et al.*, 1986, Silverberg *et al.*, 1988, and Silverberg, 1991.

[7]A frequent impact of diffusion is a "demand pull", i.e. the market volume grows significantly during the diffusion process.

[8]In the form of

$$y = f(t) = K/(1 + e^{-b(t-t_0)})$$

where K denotes the asymptote (the saturation level), b denotes the growth or diffusion rate (the speed to the diffusion process), and t_0 denotes the inflection point (at K/2 where the growth rates are at their maximum) and which serves to position the growth curve in time. A convenient notation for the diffusion speed (rate) is

$$\Delta t = \frac{1}{b} \log 81 = \frac{1}{b} 4.3944915 \quad ,$$

indicating the time for the process to grow between 10 and 90 percent of the ultimate K. Another interpretation of Δt is the time required to grow from one to 50 percent of the saturation level. Because of the symmetry condition 2 Δt denotes the time required to grow from 1 to 99 percent of K.

estimated asymptote of the diffusion processes is with some 4000 miles in good agreement with the historical maximum of canal length operated of some 4053 miles in 1851. The speed of diffusion, or the diffusion rate, has a Δt of 31 years, i.e the entire diffusion cycle spans some 60 years. The year of maximum growth occurred in the mid-1830s (t_0 = 1835). Thus, it took more than half a century to develop the canal network in the USA, with most of canal construction occurring within a period of 30 years. The canal network declined rapidly after having reached its maximum size, due to vicious competition from railways (cf. the discussion of technological substitution below). As *Figure 8* (Nakićenović, 1991) illustrates, also subsequent transport infrastructures evolved along a similar dynamic pattern as in the case of canals. For better comparability, the different sizes of individual networks have been renormalized, although in absolute extension railways and surfaced road networks were one and two orders of magnitude larger respectively than canals at their maximum network length. Consequently the dynamics of growth of railway and surfaced road networks are also somewhat slower (Δt's of 55 and 64 years respectively). The importance of the successive development of transport infrastructures for the USA economy, even for nearly aspect of daily life, cannot be addressed here.[9] Here we just point to the close relationship between different infrastructures: railways and the telegraph evolved together as did road networks and the oil pipelines delivering the energy required for the cars on the roads. This illustrates the importance of *technological interdependence and cross-enhancing*, which requires to look at the diffusion of particular technologies/techniques not in isolation, but in a larger context (cf. discussion on "technology clusters" below).

Figure 9 illustrates another dimension of diffusion processes: the case of technological substitution. This case illustrates the diffusion of a technological artifact (the passenger car), which grew by replacing another artifact (the riding horse and the carriage). *Figure 9* shows the absolute numbers of draft animals and cars in the USA, illustrating that the 20 million horses used for transport purposes practically disappeared from the roads within less than three decades. The model estimates shown in figure are derived from a (logistic) substitution curve fit indicating a dynamic of this replacement process with a Δt of 12 years

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[9]For an account of the dynamic interactions in US transport infrastructure development, cf. Nakićenović, 1988. For a discussion of the impacts of transport infrastructure development on economic growth and discontinuities in economic development cf. Isard, 1942, Grübler, 1990, and Berry, 1993 (who also provides a good account of their impact on urbanization, cf. Berry, 1990).

(cf. Nakićenović, 1986). *Figure 10*, reporting on the diffusion of catalytic converter cars (Δt of 12 years) in the USA, illustrates[10] that the dynamics of the replacement of the road vehicle fleet have not changed since the horse area. The example given in *Figure 9* above illustrates yet another dynamic feature of technology evolution: growth beyond the initial field of application (i.e., a combination of substitution and diffusion proper). The car grew initially by replacing horses. However, after completion of that process in the 1930s, new markets opened, viz. were created: long-distance travel (competition to railways) and short-distance commuting that enabled the development of concomitant settlement patterns (suburbanization). Currently, some 143 million passenger cars are registered in the USA, or close to 0.6 cars per capita. Is this a likely guide for future mass-motorization globally? We do not think it is. Instead, the high density of cars in the USA is rather seen as result of specific initial conditions of high individual mobility even before the advent of the automobile and a long sustained period of diffusion, which created precisely those conditions in lifestyles, spatial division of labor, settlement patterns, of an "automobile society".

Returning to the stylized exposition of the diffusion phenomenon (*Figure 4* above), let us analyze whether the diffusion of cars at a global scale is consistent with the theoretical propositions. As *Figure 11* indicates, it is. Both the acceleration of diffusion rate of late adopters, as well as the declining adoption density as a function of introduction date (and shorter diffusion time) appear corroborated by empirical data. A conclusion supported also by an analysis of the declining adoption densities of "late-starters" in the railway development of the 19th century (Grübler, 1990). Thus, heterogeneity in adoption levels are likely to persist, the more as with the possible development of new transport systems corresponding better to evolving concerns over functionality and environmental impacts, alternatives to the internal engine powered car would become available. Adopting this perspective leads to considerable lower transport energy demand scenarios than frequently assumed (Grübler *et al.*, 1992).

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[10]Measuring market shares. The asymptote of the process (no technology can hold more than 100 percent market share) is known in this case. In addition, the non-linear diffusion function is presented in linear form. Hence,

$$\log \left(y/(1 - y)\right) = b(t - t_0)$$

a transformation especially suited for a more detailed inspection of the (turbulent) introduction and saturation phases in technological diffusion/substitution.

Finally, and in most cases also most realistic process of technological change, let us consider the case of multiple competing technologies,[11] as done in *Figure 12* for the process technology change in USA steel manufacture. Here as many as four technologies (with decreasing and increasing market shares) compete simultaneously on the market. The diffusion trajectories of all processes show also a high degree of diversity in their dynamics, ranging with Δt's below two decades (replacement of the crucible process) to nearly seven decades (diffusion of electric arc steel). These changes in process technology not only enabled significant expansion of production but were also highly significant from an environmental perspective. They went along with structural changes in the energy supply mix in direction of higher (exergetic) quality and cleaner energy carriers (*Figure 13*), a trend consistent with the overall evolution of energy supply, as illustrated in Nakićenović's contribution to this conference. As a result of these combined changes the energy intensity per ton of steel produced in the USA has declined by over a factor 10 over the last 100 years (cf. Grübler, 1990b/Vasko). This particular example clearly indicates the scale of historical trends towards **dematerialization** of energy use. A further result was a significant decline in the carbon intensity of USA steel manufacture (*Figure 14*), a **decarbonization** trend which follows a typical learning curve, despite minimizing carbon emissions were up to today not on the agenda of the industry. It is important to stress that these improvements were not result from isolated technological changes, but rather of a combination of both gradual, cumulative technology improvements and more radical structural changes in both fields of steel process technology *and* energy supply. These two structural change processes, operating *in tandem* are an illustration of the importance of interlinkages and interdependencies between different technological systems, a point discussed in the following chapter.

Clusters and Families

Technologies cannot be looked at in isolation, nor can they be separated from techniques for their production and use, and the overall socio-economic framework they are embedded in. We can distinguish four levels of changes in the technology base:[12] (1) incremental improvements, (2) radical changes in

[11]For a model cf. Marchetti and Nakićenović, 1979.

[12]For a more detailed discussion cf. Freeman and Perez, 1988, and Grübler, 1992.

(individual) technologies and artifacts, (3) changes in technology systems (combinations of radical changes in technologies combined with organizational and managerial changes), and finally, (4) changes in whole clusters and families of technologies and in associated organizational and institutional settings. It is these technology clusters, which in our interpretation represent the technological "trajectories", subject of this conference. As an example consider the development of the automotive industries which was contingent *inter alia* on developments in materials (high quality steel sheets), the chemical industries (oil refining, in particular catalytic cracking), production and supply infrastructures (exploration and oil production, pipelines and gasoline stations), development of public infrastructures (roads), and a host of other technological innovations. The growth of the industry was based on a new production organization (Fordist type of mass production combined with Tayloristic scientific management principles), yielding significant real-term cost reductions, which made the car affordable to a wider social strata, thus changing settlement patterns, consumption habits of the population, leisure activities, etc. In turn, the automobile is just one artifact among many consumer durables which now belongs as a "standard package" to every household in industrialized countries. Clusters of radical innovations and technology systems, interdependent and mutually cross-enhancing, give rise to whole "families" of technological innovations with associated new institutional and organizational settings. Interlinkages and multiplier effects are responsible for the pervasive impacts of such techno-institutional "clusters" on the economy and society.

From a historical perspective we can identify four such "technology clusters" (and a speculative emerging fifth one). *Figure 15* tabulates various phases of industrial and economic development through the concept of technology clusters. It lists the dominant cluster in the top row, and the emerging (dominating in the successive phase) below. Examples of key technologies in the areas of energy and transport systems, materials and industry, as well as in the final consumer sphere are listed. Finally, we summarize the dominant "organizational style", i.e., the predominant mode regulating industrial, economic and social relations, and give a geographical taxonomy of centers of industrialization (core) and regions catching-up (newly industrializing or "rim" countries).

The four historical and the prospective fifth technology cluster sketched out in *Figure 15* are nick-named after their most important carrier branches or functioning principles. These are: the *textile* cluster, extending to the 1820s, the *steam* cluster until about the 1870s, *heavy engineering,* lasting until the eve of WW II, and *mass production/consumption* until the 1970s and 1980s. Currently we appear in the transition to a new age of industrial and economic development. Both its characterization as "total quality" (i.e., control of both the internal and external [environmental] quality of industrial production) cluster as well as the technological examples listed are necessarily speculative.

Rates of Change

In order to quantify the emergence of above discussed "technology clusters" an empirical analysis into the diffusion history of a larger sample of technologies and *social techniques* was performed for the USA (cf. Grübler, 1990, and 1991). This empirical analysis also serves as a data base to perform a "metaanalysis" of processes of change with respect to their dynamics.

Consistent with the larger definition of "technology" adopted here, the examples used in the analysis were not only taken from the technological field alone. The empirical cases considered include the areas of energy, transport, manufacturing, agriculture, consumer durables, communication, military, and finally, economic and social diffusion and structural change processes such as the diffusion of literacy, reduction of infant mortality, structural changes in employment, etc. Two samples were analyzed. The first sample consists of 117 diffusion cases analyzed at IIASA[13]. This sample is augmented by all the additional cases we were able to find in the literature with a quantification of diffusion parameters, bringing the sample size to a total of 265 innovation cases.

Figure 16 shows the histogram of the diffusion rates as measured by their Δt's for the two samples. They range in duration from very short-term processes of only a few years to decades, even centuries. The mean value ranges between 40 and 60 years with a standard deviation of about equal magnitude. The largest number of diffusion processes have Δ's in the order of between 15 to 30

[13] cf. Marchetti and Nakićenović, 1979; Marchetti, 1980; Nakićenović, 1986; Grübler, 1990.

years,[14] some of which we have given for illustrative purposes above (e.g., vehicle fleets or steel production methods). In general, Δt's appear to have a rank-size distribution.

The histogram gives one kind of summary about the distribution of diffusion processes: at any period of time, change in a society can be decomposed into a large number of diffusion/substitution processes with a great variety in their Δ's. Another possible aggregate measure is the average diffusion rate over time for the whole socio-economic system. For this measure we calculate the average diffusion rates of our innovation samples i.e. the sum of the first derivatives of the diffusion/substitution trajectories[15] at any given point in time divided by the number of diffusion processes occurring at that moment. This indicator is the diffusion equivalent to the annual GNP growth rate. The resulting average diffusion rate measures the changing average rate of technical, economic and social change at the country level: in our case the USA since 1800.

Figure 17 shows the average diffusion rate of 117 diffusion processes. It portrays clear peaks and troughs, indicating that the process of change is not gradual and linear but is instead characterized by pronounced discontinuities. The general increase in the average rate of change is not necessarily indicative because the closer we approach the present simply more shorter-term diffusion processes are documented. The increasing average rate of change could therefore a statistical artifact stemming from the bias in the sample in this direction. Although we take averages, the higher number of overlapping short-term processes in one interval could result in a higher aggregate diffusion rate. On the other hand, the rising average rates of change could also result from the cumulative nature of the process of technological change. Even though no individual diffusion process may proceed faster compared to the past, the number and variety of artifacts (particularly those with comparatively faster turnover rates) is much larger today than ever. This could result in an increase in the average rate of change. In other words, while no individual technology or artifact diffuses

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[14] Starr and Ruman 1974, p. 360, suggested a doubling time of the technological component of economic growth of 20 to 30 years. An assumption which appears corroborated by our data sample.

[15] Calculated from the parameters of a logistic diffusion/substitution function. In cases the empirical data did not support their approximation by this particular model, piecewise linear trends of the *log(F/K-F)* transform were used to model the empirical distribution.

faster than in the past (under appropriate *ceteris paribus* conditions), there are much more technologies and objects in use, and thus "more to change".

Figure 17 represents just an aggregate rate of change over all diffusion processes, regardless of their social or economic importance. In a subsequent step we have developed a weighting measure, assuming that the importance of any particular process of diffusion or change is directly related to the time constant of diffusion. Thus, we assume that the longer a process takes, the more pervasive (important)[16] its macro level effects. It is noteworthy that also this weighted average rate of socio-technical change reveals pronounced long-term discontinuities as shown in *Figure 18.*

The discontinuities in the long-term rate of socio-technical change are the result of the complex coupled dynamics of the discontinuous rate innovations are introduced, and of the different rates of absorption (diffusion) of these innovations in the socio-economic system. Periods of accelerating technological and social diffusion rates indicate the emergence of a "technology cluster" under which a large number of interrelated innovations diffuse into the economic and social environment contributing, via backward and forward linkages, to prolonged periods of economic growth. These periods are followed by periods where progressively more and more innovations enter their saturation phase of diffusion. Thus, each peak in the average rate of change in Figures 17 and 18 characterizes the start of saturation of a corresponding cluster or family of diffusion processes. This "season of saturations" results in a significant decline in the average rate of technical and social change and, via market saturation and a decrease in investments, also to a slowdown in economic growth. Presumably many innovations have emerged during the last decades that may turn out to be successful. If they were included they could perhaps lead to a trend reversal in the rate-of-change curve sometime after the mid-1990s, the time when these successful innovations, after a slow initial diffusion, would in turn enter into the exponential part of their diffusion life cycle.

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[16]The weighing measure proposed, links the importance of a particular diffusion process proportionally to its diffusion time constant Δt. Thus, a one percent growth in the railway network of the USA (Δt of 55 years), is assumed to be proportionally (55/12) more important than a one percent growth in the diffusion of diesel/electric locomotives (replacing steam locomotives) proceeding with a Δt of 12 years.

The conclusion on the discontinuous nature of socio-economic change is corroborated by analyzing the average diffusion rates of the second innovation sample comprising 265 innovation cases. Compared to the first sample, the greater preponderance of shorter term diffusion and substitution processes after the World War II period results in a shorter mean Δt of the sample (i.e. of the weighing measure). Therefore, also the weighted aggregate rate of change is higher than for the first sample (*Figure 18*). However, this does not necessarily mean that this larger sample of diffusion processes yields higher rates of overall socio-technical change, but rather that it is an indication of the better documentation of also shorter term diffusion processes the closer we approach the present. Still, pronounced discontinuities remain and also the larger sample confirms the findings that the diffusion rate has been declining since 1970, indicating an increase in (market and diffusion) saturation phenomena ever since.

It should be noted that the turning points (discontinuities) in the diffusion rates of technological and social innovations coincide quite closely with the turning points of long-term "Wechsellagen" of economic growth as identified by a number of long wave researchers (Marchetti, 1980; van Duijn, 1983; Vasko, 1987). The resulting peaks (i.e. the maxima in the rate of socio-technical change and the onset of leveling-off and saturation phenomena) occurred in 1840, 1912 and 1970, respectively. Troughs (maxima of saturation periods and the slow begin of a new phase of accelerated socio-technical change) occurred in 1820, 1875 and 1930. It is certainly not incidental that these troughs coincide with pronounced recession, even depression, periods in the economic development of the USA.

The diffusion history of a larger number of processes of technical, economic and social change presented above points to an essentially Schumpeterian view of long-term development. Major economic expansion periods appear driven by the widespread diffusion of a host of interrelated innovations, a "technology cluster", leading to new products, markets, new industries and infrastructures. These diffusion processes are sustained (in fact contingent) by mediating social and organizational diffusion processes. The growth (diffusion) of a dominant "cluster" can not however be sustained indefinitely. Market saturation, the dwindling improvement possibilities of existing process technologies, managerial and organizational settings, and an increasing awareness of the negative (e.g environmental) externalities involved in the further perusal and extension of the dominant growth regime pave the way to a "season of saturations". During such periods opportunities arise for the introduction of new technological, organizational and social solutions, some of which may have been latently already in existence but were barred from "market entry" due to the dominance of the previous "growth paradigm". Even when such innovations are introduced successfully, their penetration rates in the initial phase of their diffusion life cycle are rather slow and a matching new social and economic mediating context has still to emerge. This perpetuates the period of phase transition where the old is saturating and the new is still embryonic. It is only after such a period of transition, crisis and mismatch that a new prolonged period of widespread diffusion of a new socio-technical "bandwagon" and thus a period of prolonged growth becomes possible.

The picture that emerges from our phenomenological approach is that the overall development trajectory appears punctuated by crises that emerge in the transition from an old saturating cluster to a new but yet uncertain development path. As such, diffusion and its discontinuities may be one of the inherent features of the evolutionary process that governs social behavior.

Conclusion: Technology and the Environment

From a historical perspective, changes in technologies and techniques (forms of organization, institutions, policies) have been instrumental in raising productivity, resulting material output, but also in alleviating many adverse environmental impacts. In a nutshell, "it is technology, above all, that has denied or forestalled the original Malthusian vision of population outrunning subsistence. Mankind has been able to modify and increase the size of its niche and sustain increasing populations at higher levels of economic well-being. That niches keep changing, through the introduction of new technologies, and that we can change them are too commonly overlooked." (Ausubel *et al.*, 1989).

What is then the role of technology in expanding and in creating new niches for human activities and sustenance and addressing environmental problems? We see three principal roles of technology: (1) as source for overcoming resource and environmental limits to human activities on one side and as a resulting (indirect) source of environmental problems on the other, (2) as a possible remedy to environmental problems,[17] and finally, (3) as an (microscopic and macroscopic) instrument of observation, aiding to identify (new) environmental problems.

The dynamics of change identified in this paper give reason to be cautiously optimistic. Provided appropriate incentives and policies are in place to nurture the development of environmentally more benign technologies and their diffusion, many changes could be implemented over a time frame of two to three decades. However, there will also be areas where changes will be much slower, particularly in the fields of long lived structures of our built environment: the housing stock and the infrastructures for transport and energy. Here rates of change and diffusion constants of several decades to up to a century are typical and will be costly to accelerate. Therefore also the efficiency of use of existing systems begs attention.

There are two strategies in response to environmental challenges: the first focusses on incremental changes and environmental "add-on" (end-of-pipe) technologies. Such policies can bring changes comparatively fast, however tend to reinforce the dominant trajectory, blocking more systemic (and radical) changes. A second strategy opts for more radical departures
from existing technologies and practices. However such strategies – although more effective in the long run – require much more time to implement because of the multiplicity of forward and backwards linkages between technologies, infrastructures and forms of organization for their production and use. Policy changes and diffusion of new forms of organizational, particularly to address the increasing importance of diffuse sources of environmental pollution from a myriad of end uses, will be instrumental.

How can the progress on moving towards a new "green" technological trajectory be shepherded and monitored in view of the multitude of changes required at all levels of society and its economy from R&D, production to end-use? Local and regional and global environmental quality needs to be monitored, and technology is certainly a key to improve both scientific understanding and timeliness and policy relevance of information collected.

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[17]On this "paradox of technological development" cf. Gray, 1989.

As regards technology policy, this paper has illustrated the importance of interlinkages and interdependencies forming whole families and clusters of technologies. Thus, technology policy will have to try to enhance synergies and interlinkages between individual technologies that eventually might yield similar cluster effects as the marriage of coal with the steam engine or of oil with the internal combustion engine. As long as these interlinkages are not in place, even ambitious diffusion oriented policies for the promotion of individual technologies are unlikely to work. As a simple illustration consider just the recurrent interest into electric cars, the diffusion of which however, is constrained by bottlenecks from the energy storage media like battery technology.

However, as illustrated in Nakicenovic's contribution to this conference, there are also useful macro-indicators that can serve as metric to assess in a more generic way the progress towards an environmentally more compatible future. Indicators of material, energy and emission intensities for the economy as a whole and for different economic and human activities (including end-uses) can help to guide further progress in dematerialization and decarbonization of human activities.

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Figures

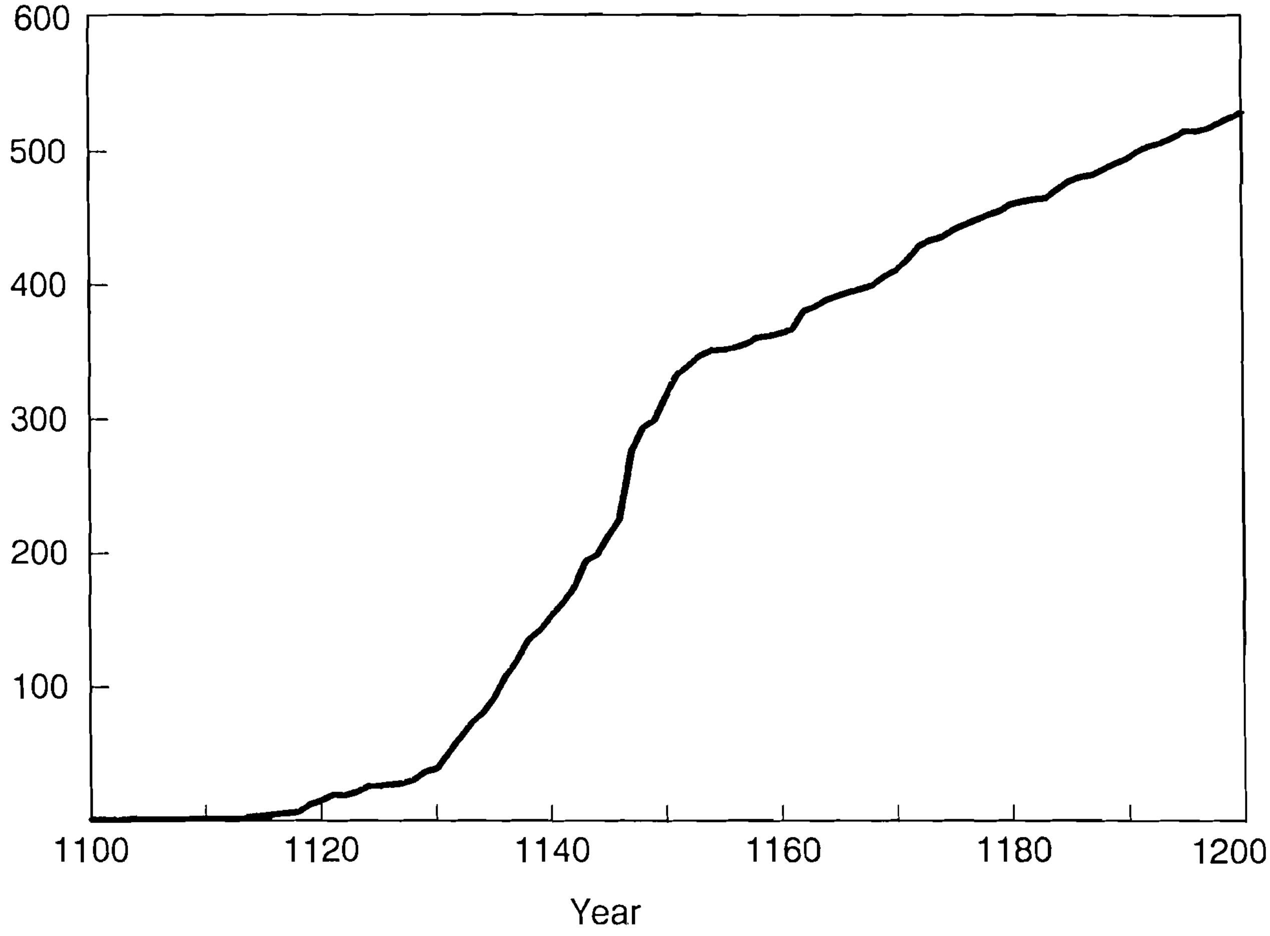

Figure 1. Diffusion of Cistercian monasteries in Europe: the first 100 years. Data source: Janauschek, 1877.

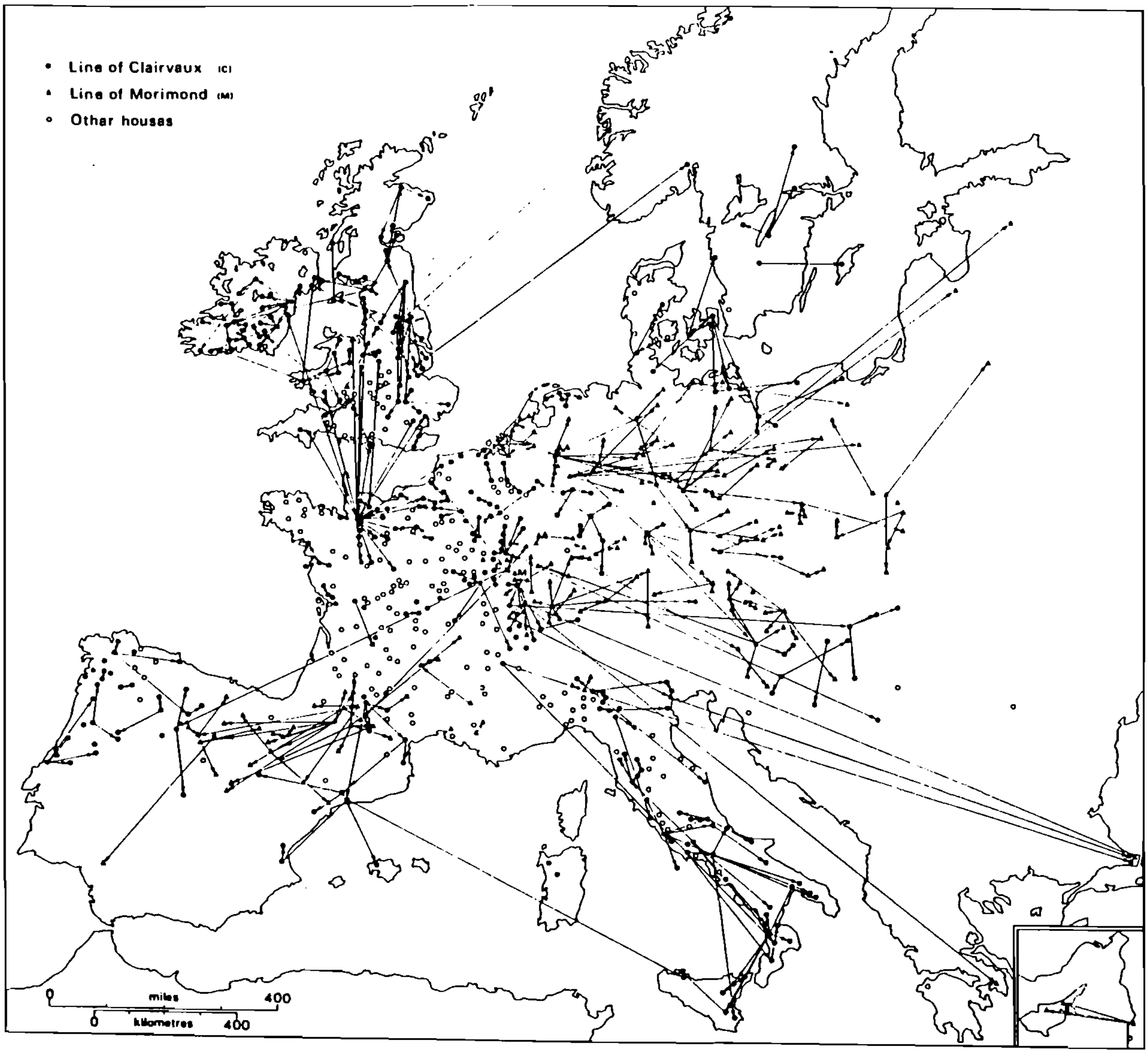

Figure 2. Saptial diffusion of Cistercian settlements (lines of Clairveaux and Morimond). Source: Donkin, 1978.

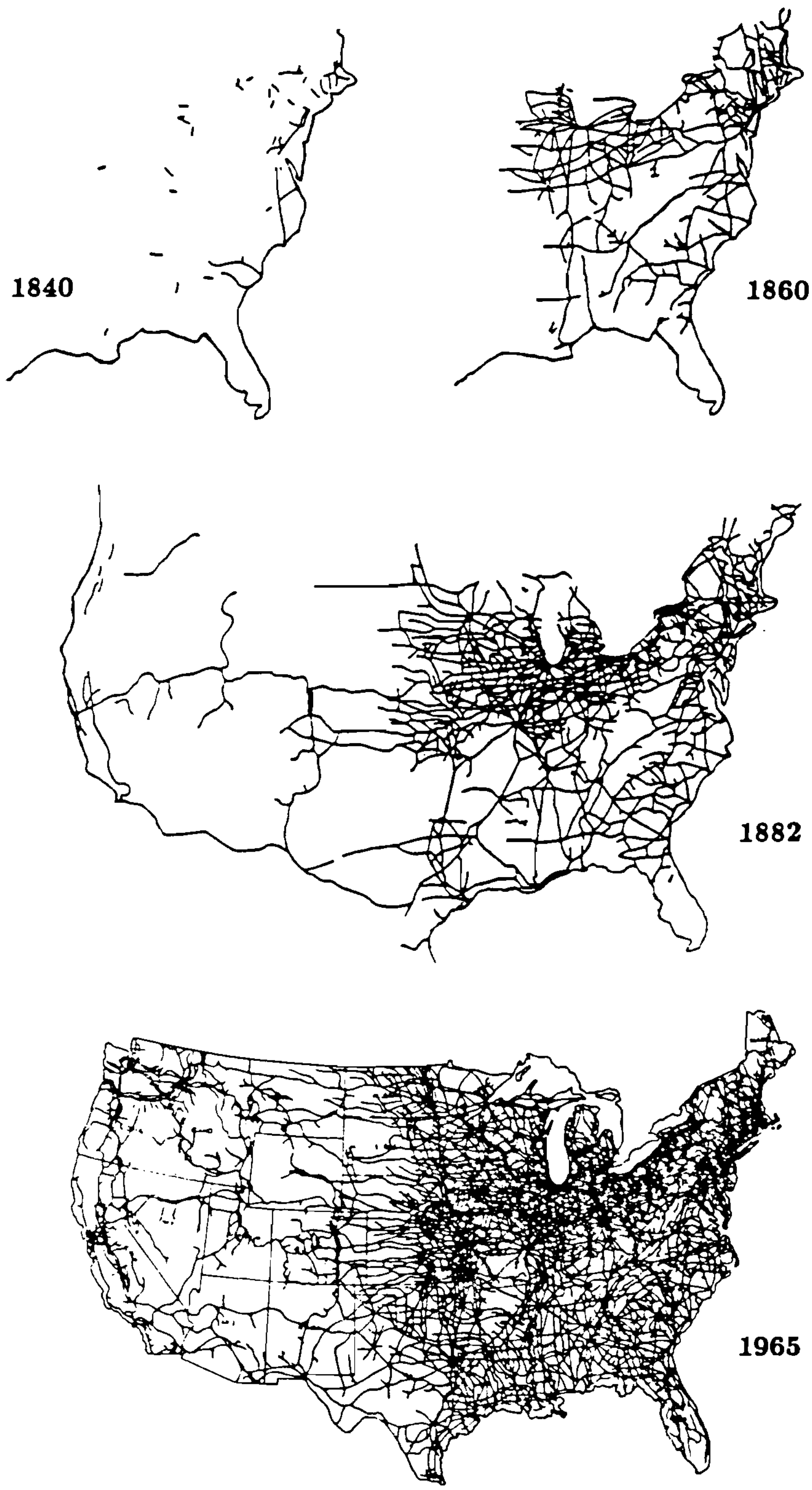

Figure 3. Spatial spread of the railway network in the USA. Source: adapted from Lord and Lord, 1953, and Morill, 1970.

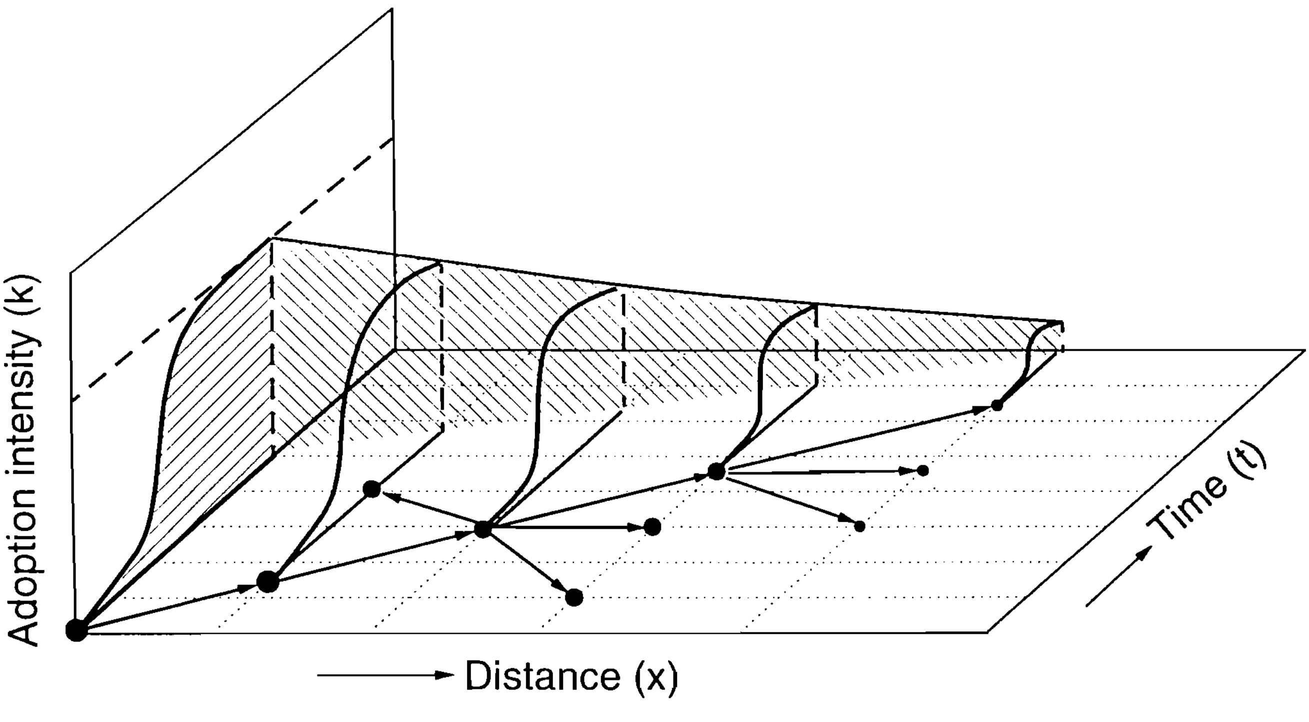

Figure 4. The diffusion process in time and space. Source: adapted from Morril, 1968.

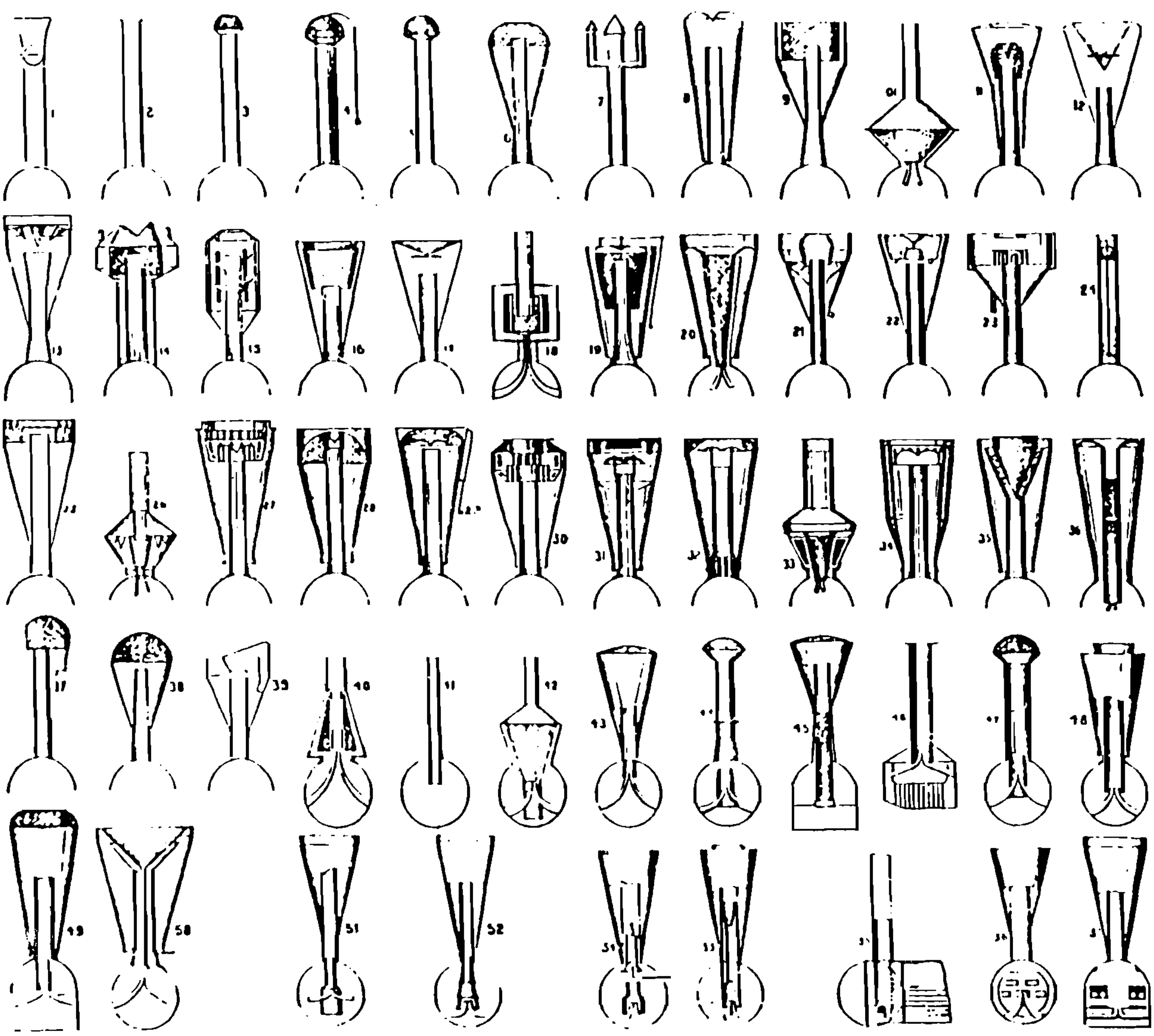

Figure 5. Technological variety in response to an environmental and risk hazard: examples of patents for smoke spark arresters for wood burning steam locomotives. Source: Basalla, 1988.

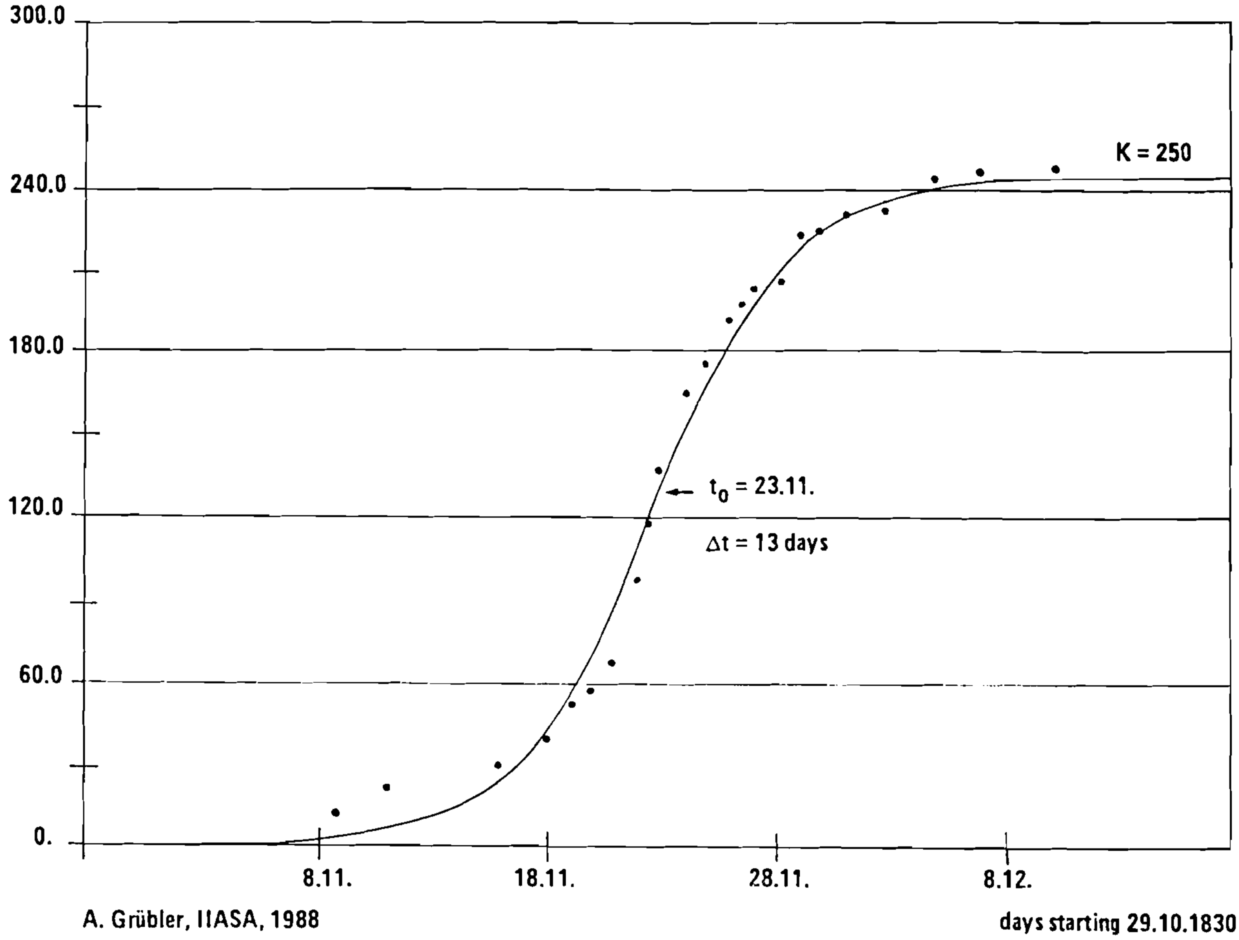

Figure 6. Resistance to technology as a diffusion process. Number of threshing machines attacked during the Captain Swing movement in England in 1830. Note in particular the speed of the spread of this manifestation of social opposition. Data source: Hobsbawn and Rudé, 1968.

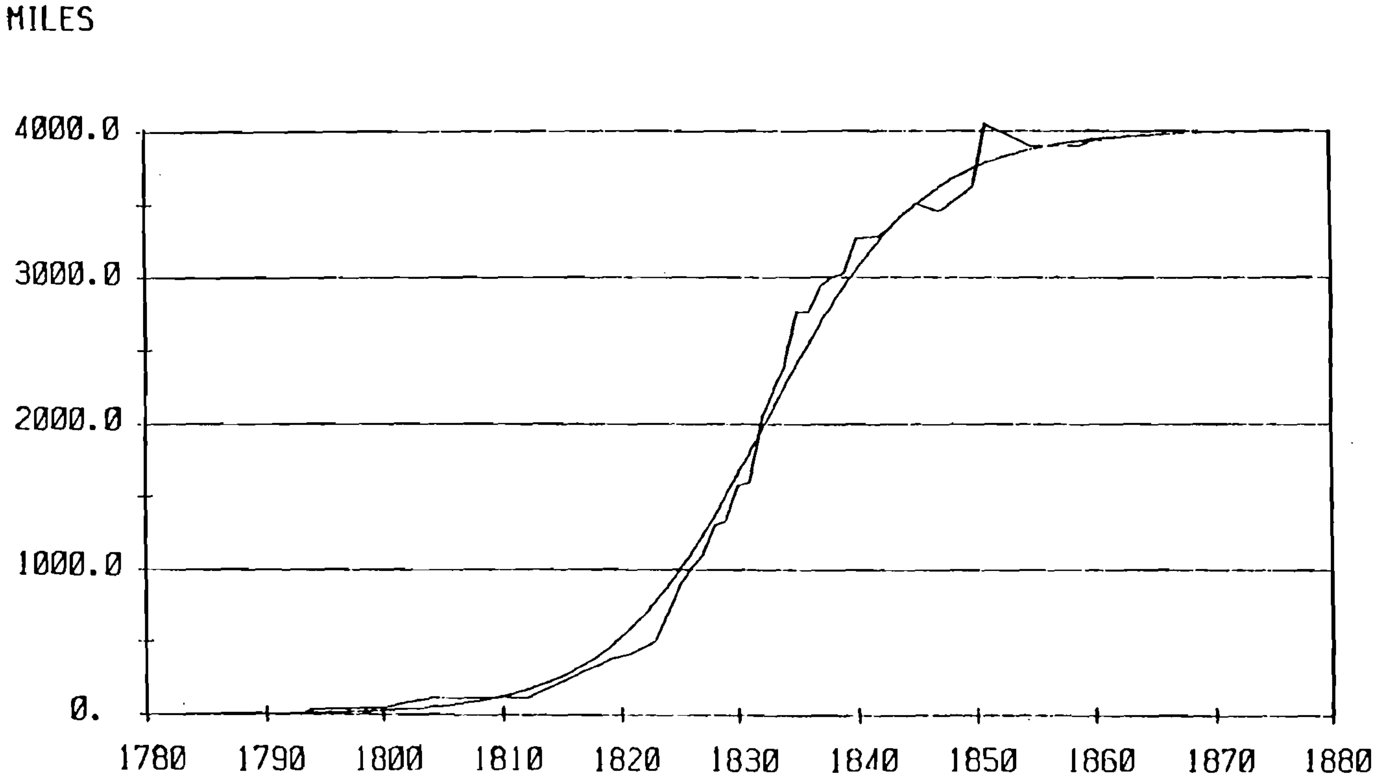

Figure 7. Growth of the canal network in operation in the USA. Source: Grübler, 1990.

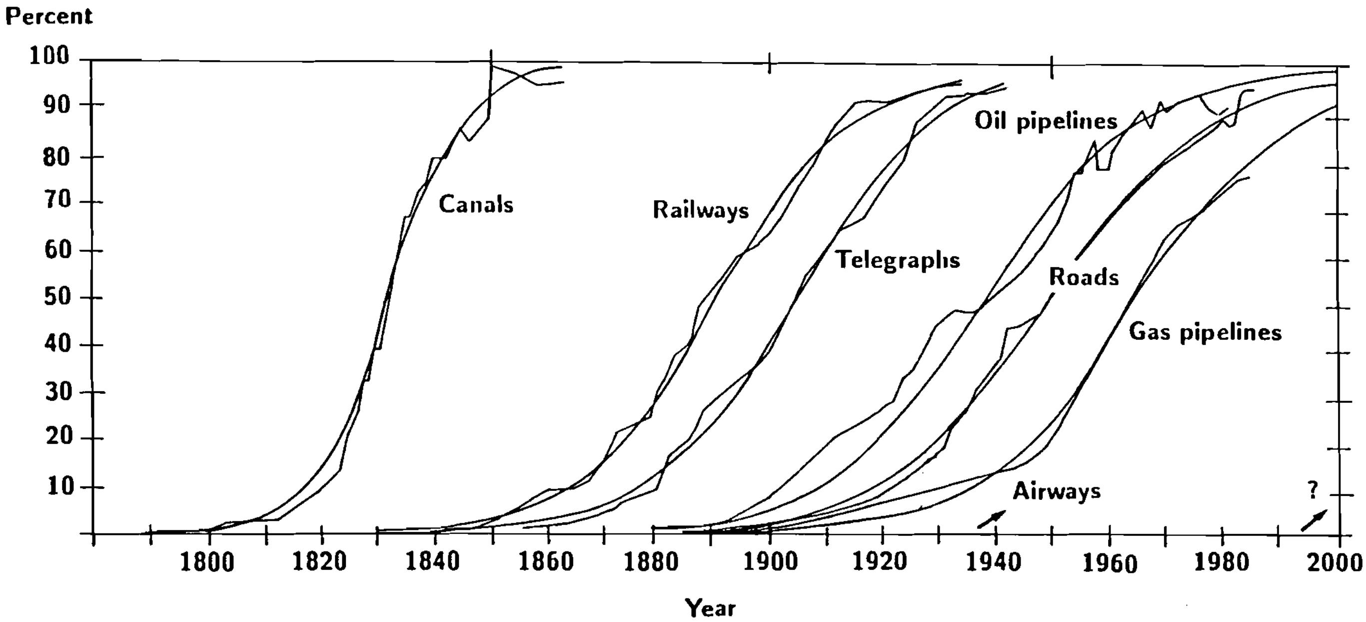

Figure 8. Growth of infrastructures in the USA (in percent of maximum network size). Source: Nakićenović, 1991.

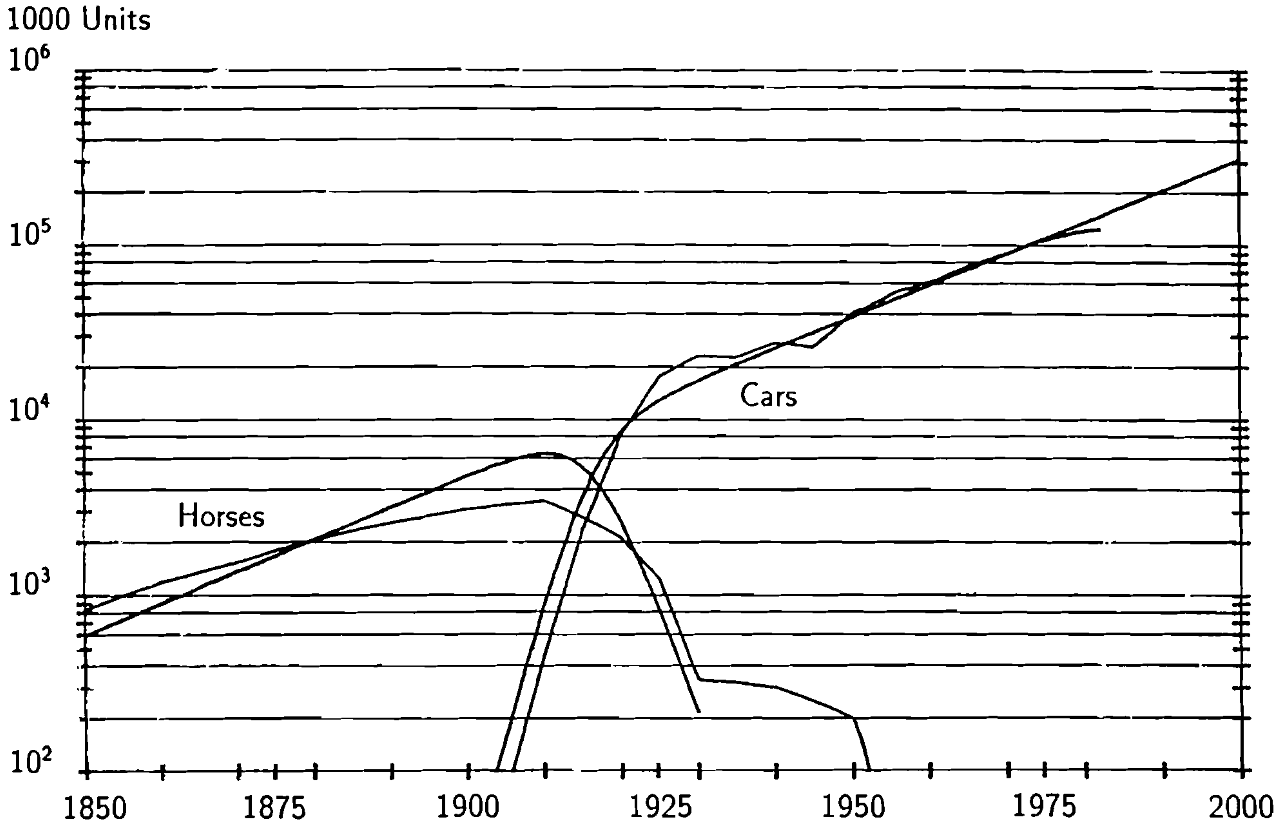

Figure 9. Number of draft animals and automobiles, data and estimates derived from a logistic substitution model. Source: Nakićenović, 1986.

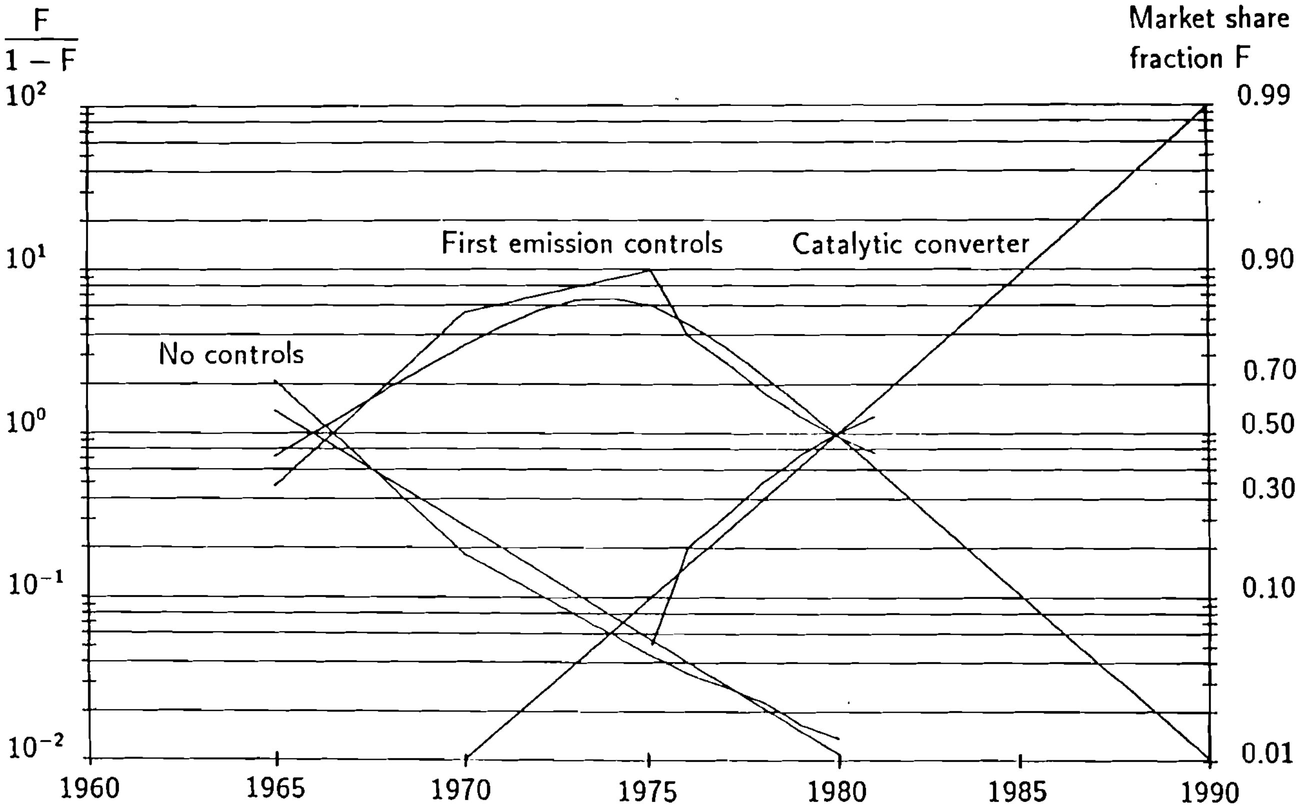

Figure 10. Diffusion of cars with first emission controls and of catalytic converter cars, USA, in fractional shares of total car fleet, logit (log[f/1-f]) transformation. Source: Nakićenović,

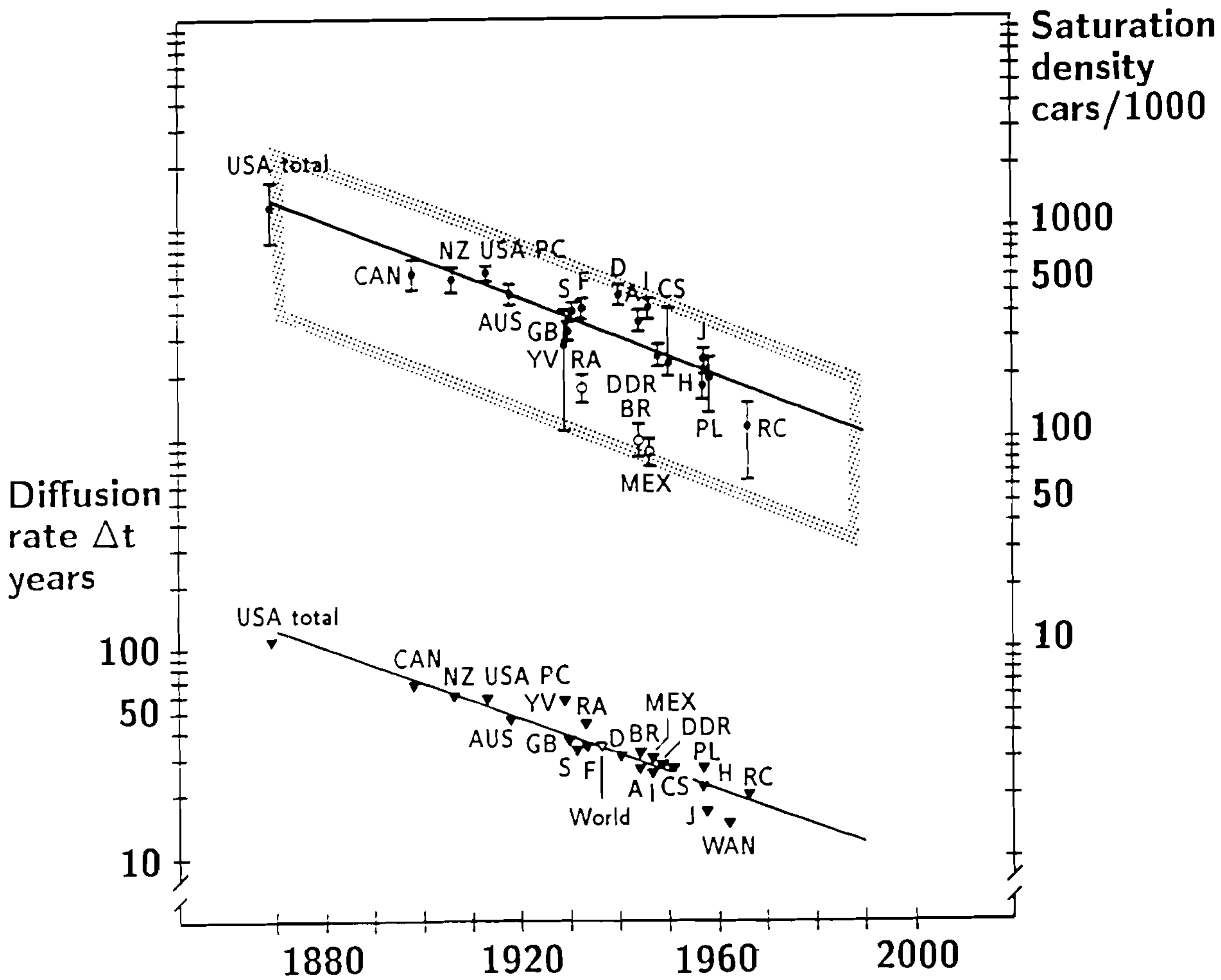

Figure 11. Passenger car diffusion at the global level: catch-up, but at lower adoption levels. Estimated saturation levels of car density (cars per 1000 population) and diffusion rates (Δt's) as a function of the introduction date of the automobile. Source: Grübler, 1990.

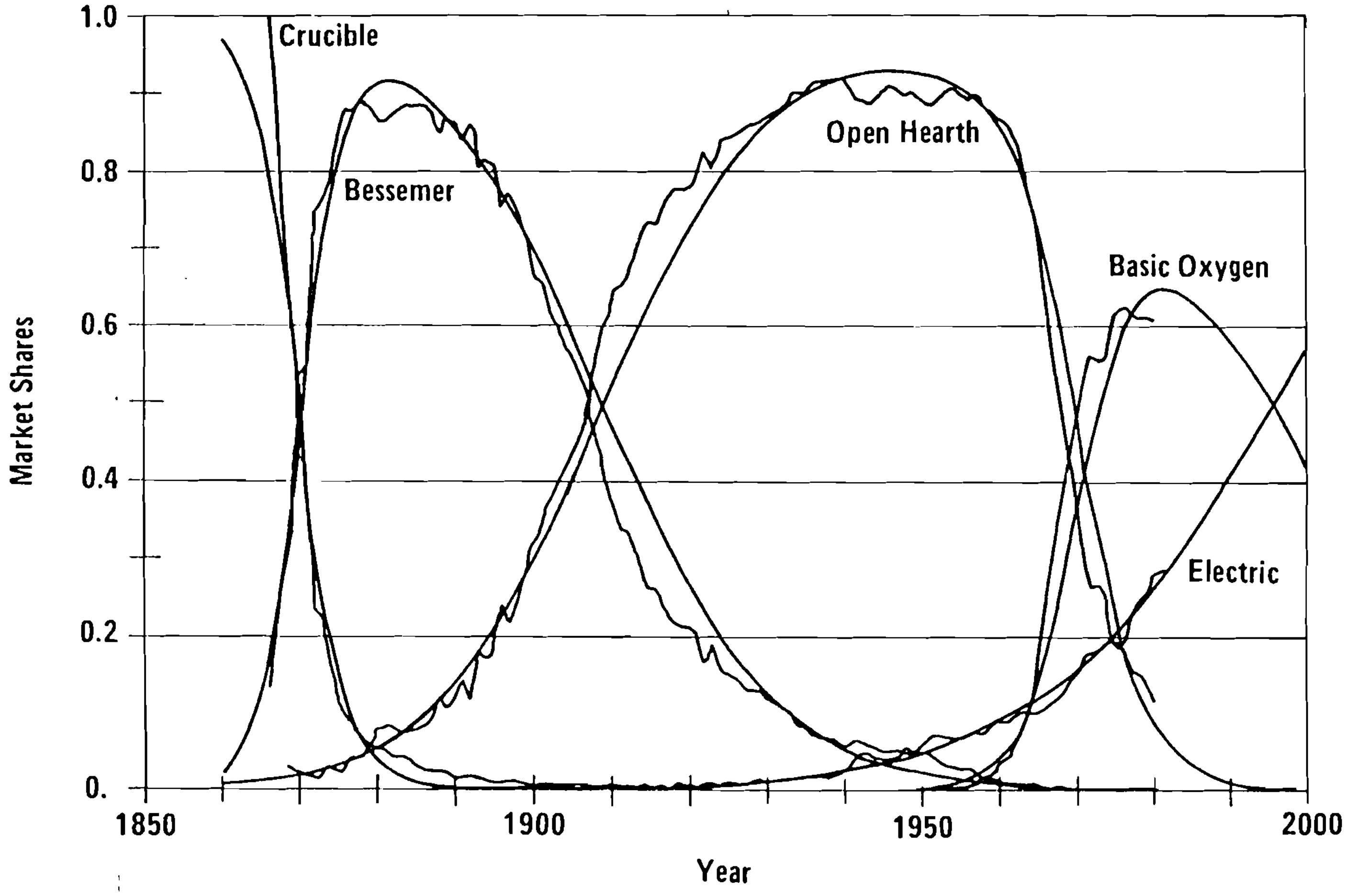

Figure 12. Process technology change in USA steel manufacture, in fractional share of raw steel tonnage produced. Source: Nakićenović, 1987.

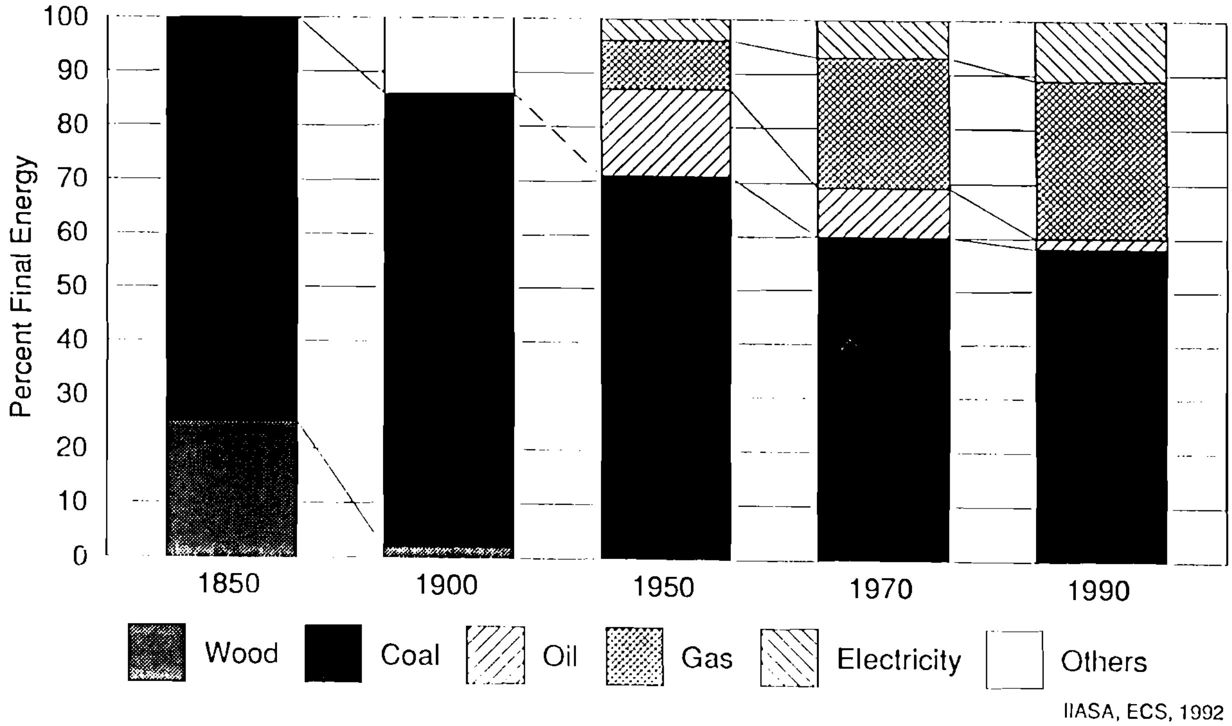

Figure 13. Changes in the final energy carrier mix used in USA steel industry. Source: Grübler, 1992.

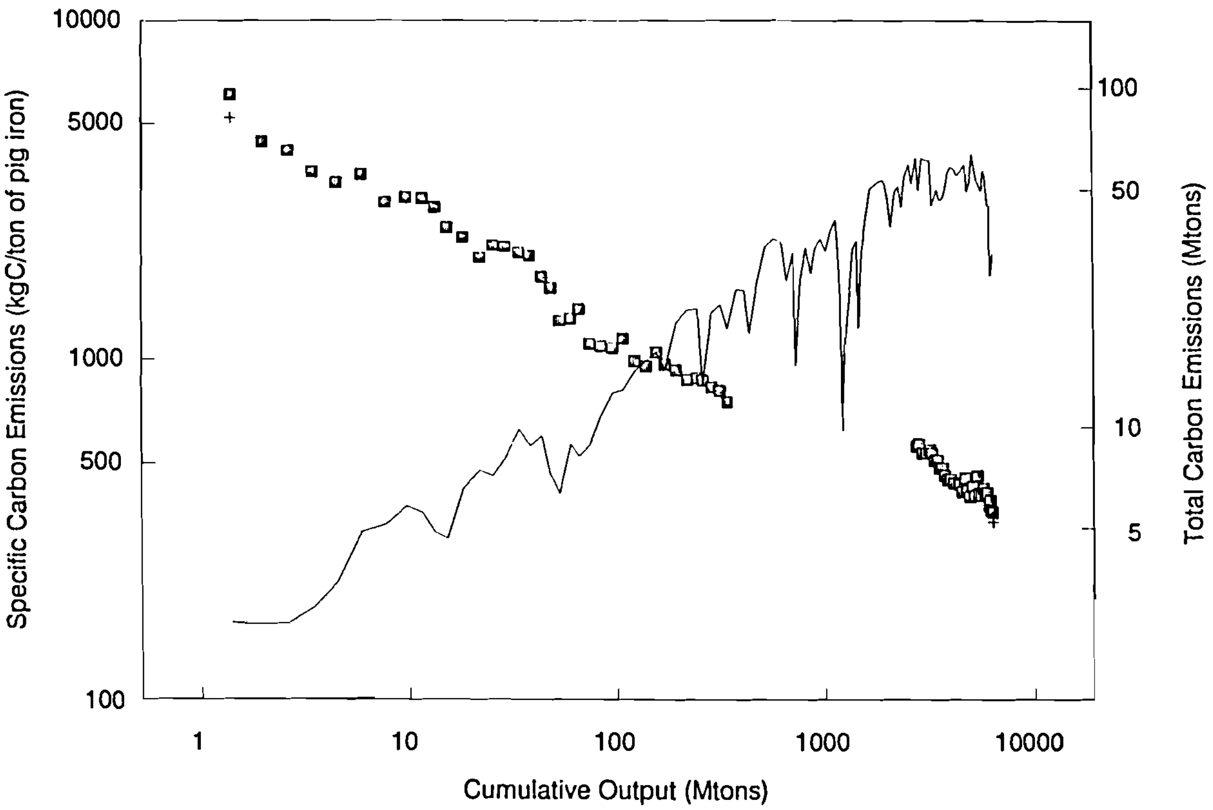

Figure 14. Specific carbon emissions versus total sector emissions for USA steel industry. Note in particular the functional of a learning curve in the improvement of specific emissions (**decarbonization**). Source: Grübler, 1992.

Cluster	1750–1820 "textile"	1800–1870 "steam"	1850–1940 "heavy engineering"	1920–2000 "mass production/consumption"
Dominant				
E	water, wind, feed, wood	wood, feed, coal	coal	oil, electricity
T	turnpikes	canals	railways, steamships, telegraph	roads, telephone, radio & TV
M	iron	iron, puddling steel	steel	petrochemicals, plastics, steel, aluminum
I	castings	stationary steam, mechanization	heavy machinery, chemicals, structural materials	process plants, NC machinery, consumer goods, drugs
C	textiles (wool, cotton), pottery	textiles, chinaware	product diversification (imports)	durables, food industry, tourism
Emerging				
E	coal, coke	city gas	oil, electricity	gas, nuclear
T	canals	mobile steam, telegraph	roads & cars telephone, radio	air transport, telecommunication, computers
M	puddling steel	mass prod. steel	synthetics, aluminum	"custom-made" materials, composites
I	stationary steam, mechanical equipment	coal chem., dyes, structural materials	fine chemicals, drugs, durables	electronics, information technologies
C	chinaware	illuminants	consumer durables, refrigeration	leisure & recreation, products, arts
Organizational "style"				
Plant/company level	indiv. entrepreneurs, local capital, small-scale manufacture	small firms, joint stock companies	"giants", cartels, trusts, pervasive standardization	Fordism/Taylorism multinationals, vertical integration
Economy & society	breakdown of feudal & medieval economic structures	"laissez-faire", Manchester liberalism	imperialim, colonies monopoly & oligopoly regulation, unionization	social welfare state, Keynsianism "open" society
Industrial Geography				
"Core"	England	England, Belgium	Germany, USA, France, Benelux, England	USA, Canada, JANZ EC-6, England
"Rim"	Belgium, France	France, Germany, USA	Central Europe, Italy, Scandinavia, Canada, JANZ, Russia	USSR, Central & Eastern Europe, Southern Europe

JANZ = Japan, Australia, New Zealand

Figure 15. Clusters of pervasive technologies.

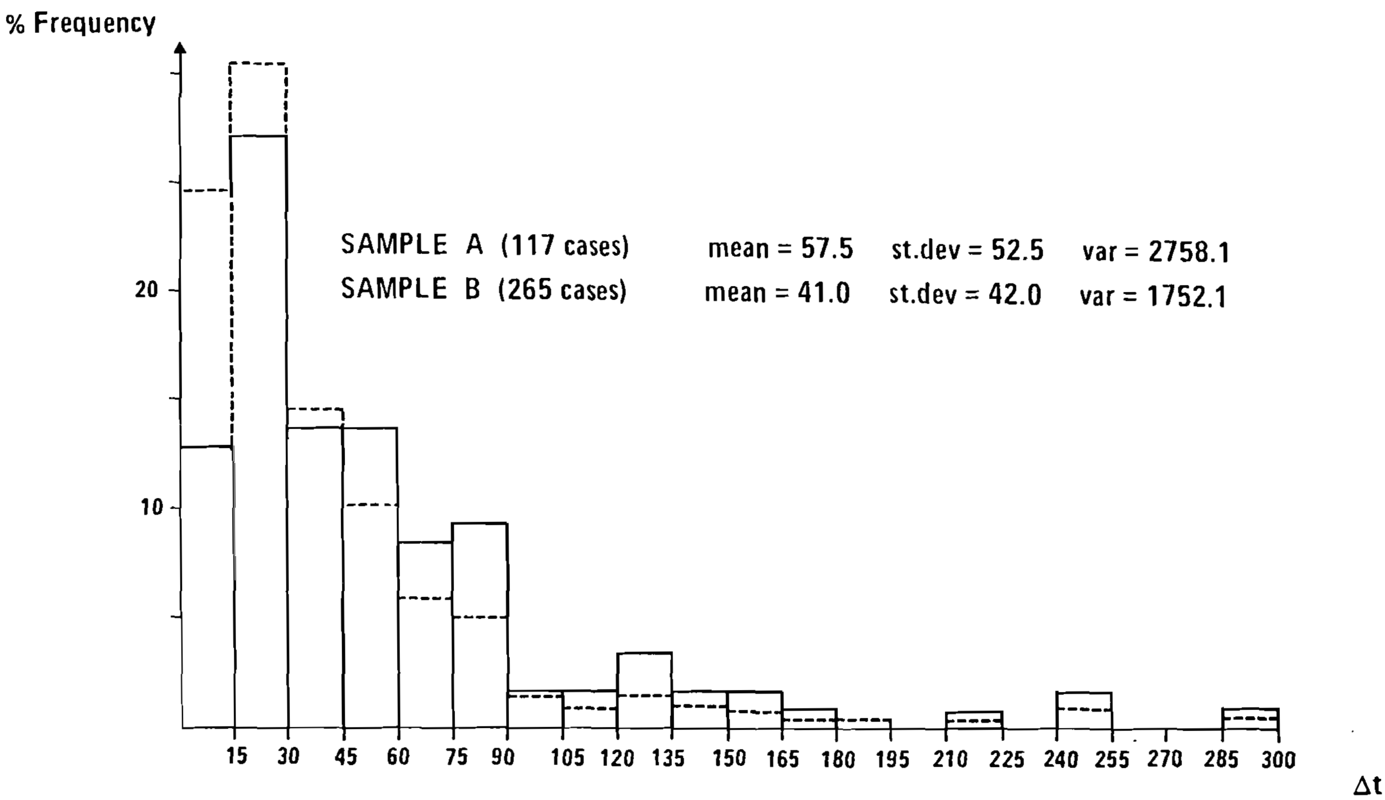

Figure 16. Histogram of diffusion rates, measured by Δt for two samples of 117, and 265 diffusion histories in the USA. Source: Grübler, 1990, and 1991.

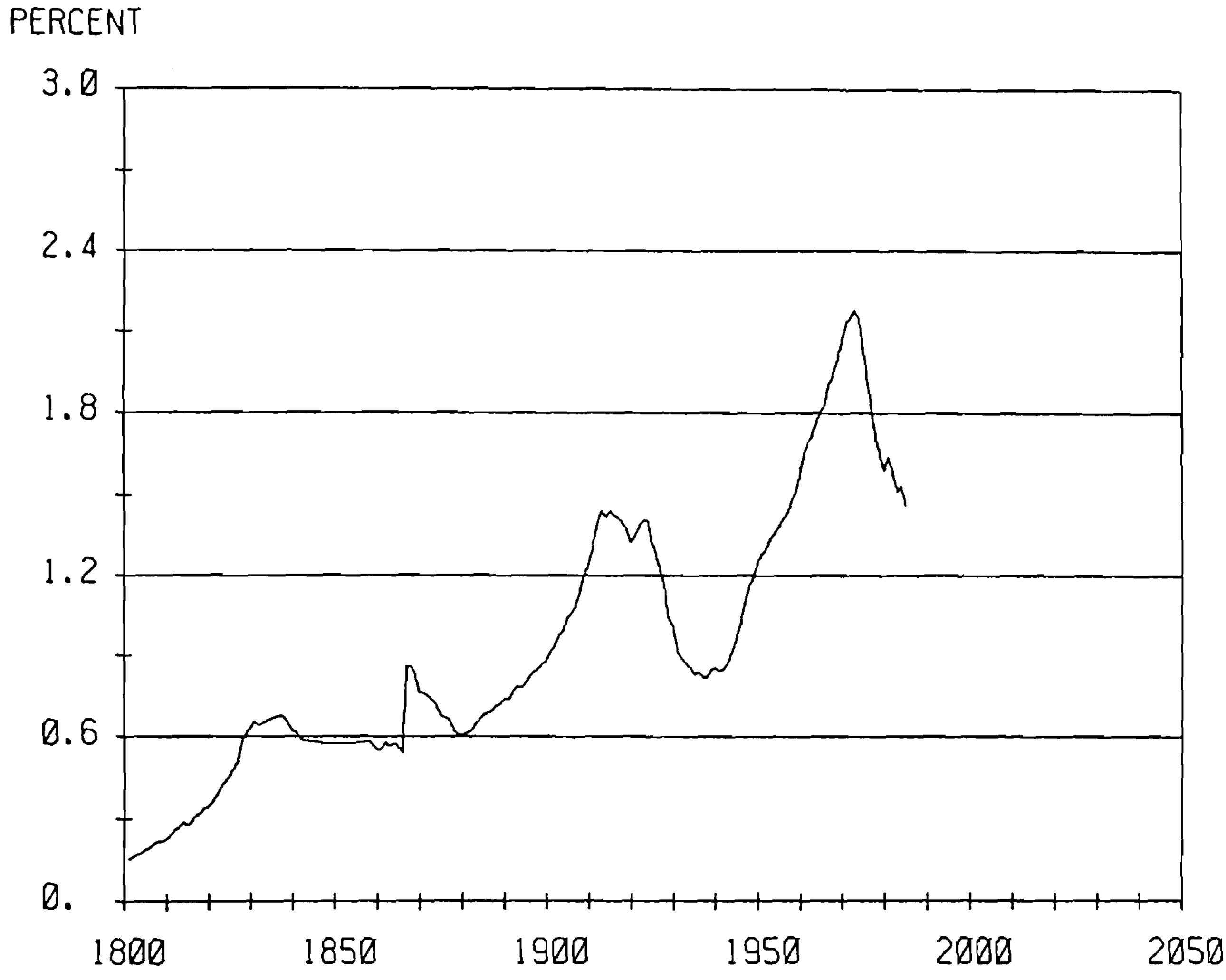

Figure 17. Average diffusion rate of a sample of 117 processes of technological, economic and social change in the USA. Source: Grübler, 1990 and 1991.

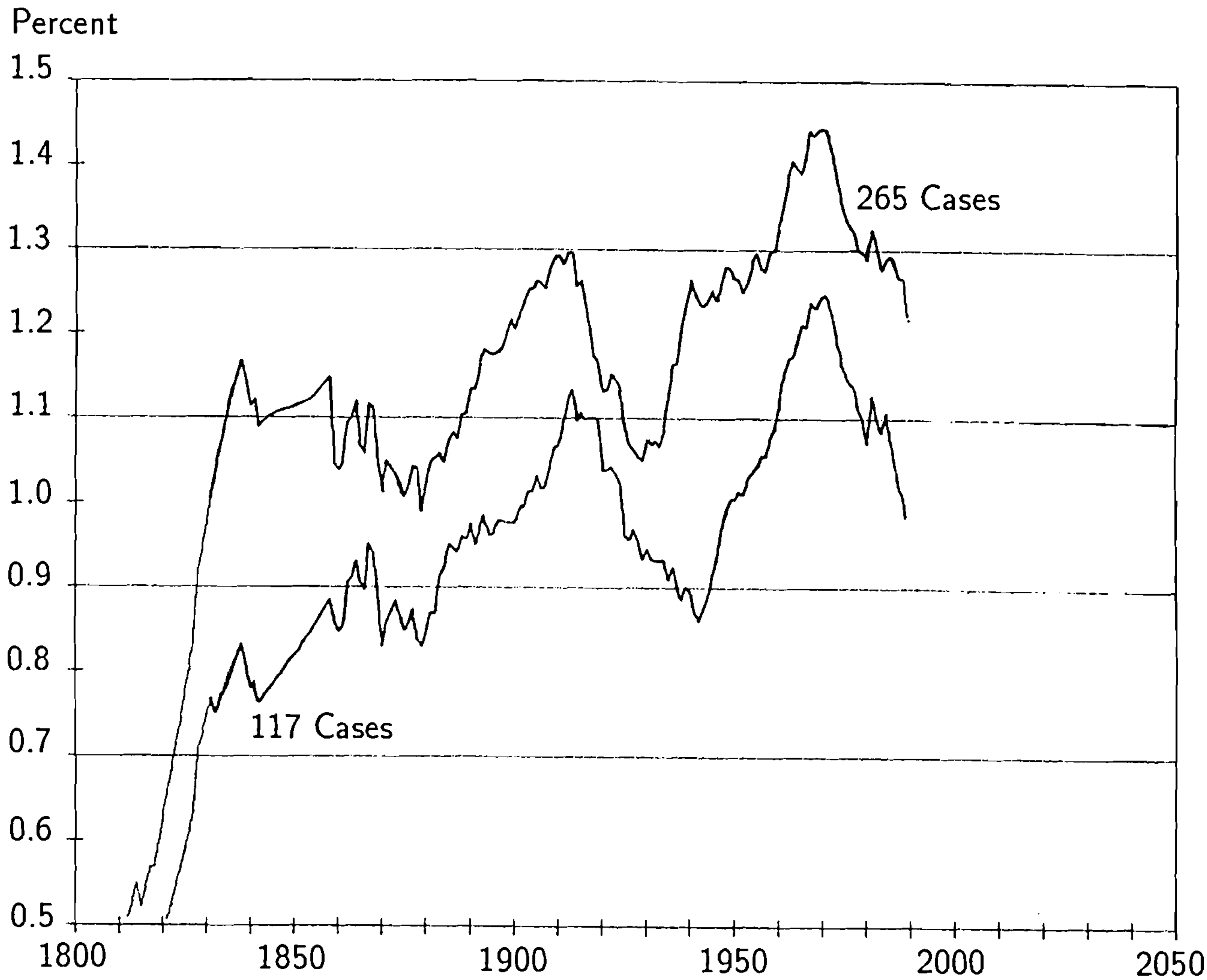

Figure 18. Weighted (by mean Δt) average diffusion rate of two samples of 117 and 265 processes of technological, economic and social change in the USA. Source: Grübler, 1990 and 1991.