THE AUTOMOBILE ROAD TO TECHNOLOGICAL CHANGE
Diffusion of the Automobile as a Process of Technological Substitution

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RR-87-1
February 1987

Reprinted from *Technological Forecasting and Social Change,* volume 29 (1986)

INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
Laxenburg, Austria

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Printed by Novographic, Vienna, Austria

FOREWORD

During 1986 IIASA initiated a new research program on Technology, Economy, and Society (TES). One of the research objectives is to describe the dynamics of technological development. The results of this effort will be used in other activities of the TES program to gain a better understanding of the dynamics of technological changes in new transport, energy and manufacturing systems.

In this report, Nebojsa Nakicenovic analyzes technological changes in motor vehicles. It is shown that motor vehicles developed as an integral component of road transport systems, through a series of interlaced substitutions of old for new technologies. A major finding is that technological substitutions within road vehicles in general and automobiles in particular were considerably faster than technological changes in the whole transport system and in other large infrastructures, such as the expansion of roads and railroads or changes in primary energy sources.

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TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE 29, 309–340 (1986)

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ABSTRACT

Advancement of the motor vehicle and its production methods is analyzed as a process of technological change. In a broader context, motor vehicles evolved as an integral component of road transportation through a series of interlaced substitutions of old by new technologies. Building on a large number of studies that described technological substitution processes, first it is shown how new energy forms replaced their predecessors and how the old marine-transport technologies were substituted by new ones. These examples constitute some of the oldest, empirically documented technological changes and show that many events in the dynamics of energy substitution and marine transport are related to technological changes in road transportation. It is shown that these substitution processes can be described by simple rules and that the replacement of old by new technologies in the energy and transport systems lasted about 80 years. The technological changes within road transportation, however, were more rapid. Replacement of horses by automobiles and older by newer generations of motor vehicles and production methods lasted only a few decades in the United States. Thus, technological substitutions within the road-transportation system were considerably shorter than the expansion of railroads, surfaced roads, all road vehicles together, and the more recent expansion of air transportation.

Introduction

Analysis of the historical replacement of old by new technologies has shown that most of these processes can be described by simple rules that are captured in the logistic-substitution model [13, 14, 15, 16]. The evolution of motor vehicles during the last 100 years can also be seen as a series of interlaced technological changes of production methods and vehicles. It will be shown that these changes can be captured by logistic-substitution analysis and that they have occurred with a high degree of regularity. We will distinguish the substitution processes in terms of annual production of motor vehicles from equivalent processes at the level of the whole fleet.

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 0040-1625/86/$03.50

In order to illustrate and describe the properties of the model, we will first give examples of how new energy forms replaced their predecessors, because technological changes in the energy system constitute one of the first and most complete applications of logistic substitution analysis and because many events in the dynamics of energy substitution are related to technological changes in the transportation system. In addition, we show some of the oldest documented technological changes within the transportation system—the substitution of sailing by steamships. Because the United States has the oldest recorded history of the development and expansion of the automobile, the examples of technological change in production methods and vehicles will be illustrated exclusively by the U.S. experience. Thus, although the results may apply in other industrialized countries with a similarly long history of motor vehicles, it would be necessary to determine whether or not the same or equivalent results can be obtained for other countries.

Energy Substitution

Analysis has shown that the competitive struggle between various sources of primary energy obeys a regular substitution process that can be described by relatively simple rules [14, 15, 17]. The dynamic changes in this process are captured by logistic equations that describe the rise of new energy sources and the decline of the old ones. Figure 1 shows the primary energy consumption in the United States since the middle of the last century. In addition to fossil-fuel and nuclear-energy consumption, the figure shows the use of more traditional forms of energy during the last century, including fuel wood, direct uses of water and wind power, and use of working animals (calculated in terms

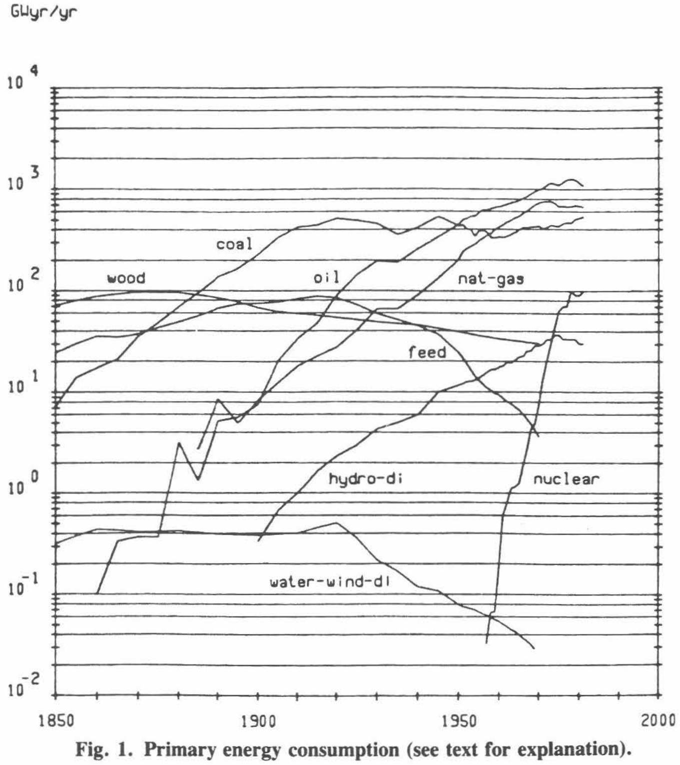

Fig. 1. Primary energy consumption (see text for explanation).

of energy content of animal feed). Data are plotted on a logarithmic scale and show exponential growth phases in consumption of the most important sources of primary energy by piecewise-linear, secular trends. Thus, it is evident that energy consumption grew at exponential rates during long time periods, but no other regularities are directly discernible. The evolution of primary energy consumption emerges, however, as a regular substitution process when it is assumed that energy sources are different technologies competing for a market.

Substitution of an old way of satisfying a given need by a new path has been the subject of a large number of studies. One general finding is that substitution of an old technology by a new one, expressed in fractional terms, follows characteristic S-shaped curves. Fisher and Pry [8] formulated a very simple but powerful model of technological substitution. Their model uses a two-parameter logistic function to describe the substitution process between two competing contenders.[1] The Fisher and Pry model cannot be used to describe the evolution of primary energy consumption, because evidently more than two energy sources compete for the market simultaneously. However, we can group the primary energy sources into two broad classes: traditional (or renewable) and contemporary (fossil, hydro, and nuclear) forms of energy. The traditional energy sources include fuel wood, direct use of water and wind power (that is, water mills and windmills and water flotation), and energy inputs of work animals expressed as the energy content of the feed consumed (that is, feed equivalent). The contemporary energy sources include coal, crude oil, natural gas, hydroelectric power, and nuclear energy. Figure 2 shows the two classes of energy use in terms of their respective fractional market shares (f) of

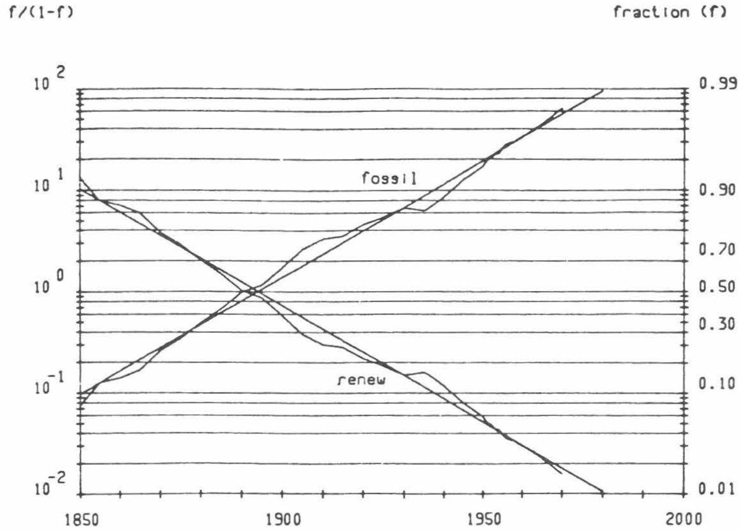

Fig. 2 Substitution of fossil, hydro, and nuclear for renewable energy.

[1]The basic assumption postulated by Fisher and Pry is that once a substitution of the old by the new has progressed as far as a few percent, it will proceed to completion along the logistic substitution curve:

$$f/1 - f = \exp(\alpha t + \beta),$$

where t is the independent variable usually representing some unit of time, α and β are constants, f is the fractional market share of the new competitor, and $1 - f$ is that of the old one.

total primary energy consumption plotted in terms of the quantity $f/(1-f)$. The substitution process is remarkably regular over the entire time period (over 130 years). The linear, secular trends indicate that the substitution of traditional energy sources by fossil, hydroelectric, and nuclear energy can be described with remarkable accuracy by the logistic function. It is interesting to note that the 50% mark in the substitution process was reached shortly before the turn of the century. The time constant of the substitution process is quite long—more than 80 years were required before commercial energy sources could capture 50% of the market after their introduction at the 1%-market share level back in the 1820s. In fact, the emergence of coal at the 1% level (the first of the fossil-energy sources to find widespread use) dates back to the 1820s (see Figure 3 and Nakicenovic [16], in which the substitution of fuel wood and fossil energy sources is traced back to 1800), indicating once more the remarkable regularity of the substitution process.

In dealing with more than two competing technologies, we must generalize the Fisher and Pry model, because in such cases logistic substitution cannot be preserved in all phases of the substitution process. Every competitor undergoes three distinct substitution phases: growth, saturation, and decline. The growth phase is similar to the Fisher and Pry model of two competitors, but it usually terminates before full substitution is reached. It is followed by the saturation phase, which is not logistic, but which encompasses the slowing down of growth and the beginning of decline. After the saturation phase of a technology, its market share proceeds to decline logistically.

We assume that only one competitor is in the saturation phase at any given time, that declining technologies fade away steadily at logistic rates not influenced by competition from new competitors, and that new competitors enter the market and grow at logistic rates. The current saturating competitor is then left with the residual market share (that is, the different between 1 and the sum of fractional market shares of all other competitors) and is forced to follow a nonlogistic path that joins its period of growth to its subsequent period of decline. After the current saturating competitor has reached a logistic rate of decline, the next oldest competitor enters its saturation phase and the process is repeated until all but the most recent competitor are in decline. In effect, our

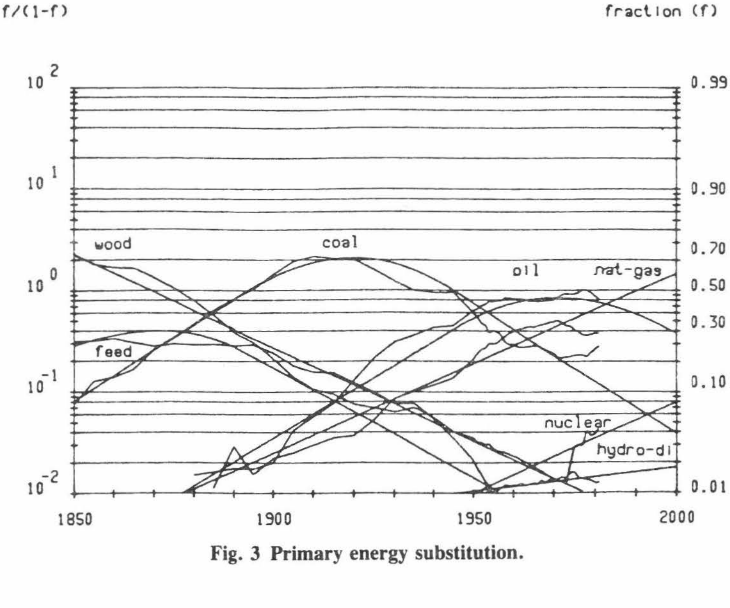

Fig. 3 Primary energy substitution.

model assumes that competitors that have already entered their period of market phase-out are not influenced by the introduction of new ones. Deadly competition exists between the saturating competitor and all other more recent competitors (the approach was first described in Marchetti [14]; a more comprehensive description of the model and the assumptions is given in Nakicenovic [16, 17]). This generalized model offers a phenomenological description of the substitution process and has been successfully applied for about 300 cases to date, involving examples from biology, various technological processes (such as substitution of energy forms or steel production methods), and so on.

Figure 3 shows the primary energy substitution for the United States. Data and model estimates of the substitution process are plotted on a logarithmic scale using the quantity $f/(1 - f)$ versus time (f representing fractional market shares). The piecewise-linear, secular trends indicate logistic substitution phases. The departure of historical market shares from their long-term paths, described by the logistic substitution model, sometimes last for over two decades only to return to the trend after the prolonged perturbation. This is the case with the marked shares of coal and oil during the 1940s and 1950s, and fuel wood and animal feed during the 1860s and 1870s. This may also indicate a possible absorption of the departure of coal and natural gas market shares from their long-term paths during the last ten years.

The substitution process clearly indicates the dominance of coal as the major energy source between the 1870s and 1950s, after a long period during which fuel wood and animal feed were in the lead. In the United States, wood remained the principal fuel for the railroads up to the 1870s, although railroads are considered the symbol of the coal age. The last phases of railroad expansion up to the 1920s, the growth of steel, steamships, and many other sectors are associated with and based on the technological opportunities offered by the mature coal economy. The dominance of fuel wood, and later coal, shows an interesting symmetry, each period of dominance lasting slightly over 60 years. After the 1940s, oil assumed the dominant role simultaneously with the maturing of the automotive, petrochemical, and many other modern industries. It is interesting that oil reached a 1% market share about two decades before the first automobiles were produced in the United States (actually four were manufactured in 1895, see Epstein [5]). Further, the first use of oil and natural gas dates back to 1859, preceding the first automobiles by almost half a century.

Animal feed reached its highest market share in the 1880s, indicating that draft animals provided the major form of local transportation and locomotive power in agriculture, despite the dominance of railroads and steamships as long-distance transportation modes. Horse carriages and wagons were the only form of local transportation in rural areas and basically the only freight transportation mode in cities. In addition, they moved goods and people to and from railroads and harbors. It is curious that the feed and crude-oil substitution curves cross in the 1920s, as if to suggest the simultaneous substitution of the horse carriage and wagon by the motor vehicle that will be described below. Figure 3 projects natural gas as the dominant energy source after the 1980s, although crude oil still maintains about a 30% market share by the end of the century. Nevertheless, the projected dominance of natural gas may imply changes in the kind of automobile-propulsion systems that can be expected in the longer-term future (beginning of the twenty-first century). Certainly enough crude oil would be available for gasoline distillation, but the importance of natural gas indicates the possibility of either direct use of natural gas in the transport sector or its transformation into synthetic fuels, such as methanol.

The logistic substitution model indicates that it is possible to describe the broad features of the evolution of the energy system in the United States over very long periods of time by rather simple mechanisms, despite many turbulent and profound changes during the last 130 years. More importantly, these changes are paralleled by transformations of the transportation system, from sailing ships and animal-drawn vehicles to steamships and railroads, and later to motor vehicles and air transportation. Before returning to the analysis of technological change of the automobile, we will first consider the substitution process in the merchant fleet of the United States, because this example illustrates the evolution of one of the oldest modes of transportation. The automobile is barely 100 years old, whereas the recorded changes encountered in the evolution of the merchant fleet cover a period of 200 years and include a fundamental transformation of propulsion systems, increased speed and size of the vessels, and changes in the construction methods and materials.

The traditional means of ship propulsion, in use ever since ancient times, was wind power, and the traditional construction material was wood. With the development of the steam engine and the relatively high energy density of high-quality coals, it was possible to slowly replace sails with steam engines. The first designs were of a hybrid type employing both steam and wind power. With the increase in the size of vessels, along with the expansion of overseas trade, and with the growth of the iron and steel industries, wood was increasingly substituted by iron and later by steel as the basic construction material. In fact, the number of vessels remained practically constant between the end of the eighteenth century and the 1940s at about 25,000 ships, doubling to almost 50,000 during the last three decades up to 1970. During the same period of almost two centuries the total registered tonnage of the merchant fleet increased by almost two orders of magnitude, implying that the average vessel is about 100 times larger today than in 1800. This enormous increase in the tonnage capacity of an average vessel can only be explained by continuous improvements in propulsion systems, construction materials, and design.

Figure 4 shows the tonnage growth of the merchant fleet in the United States since 1789 and Figure 5 shows the substitution of sailing by steamships, both coal and oil fired, and later the market penetration of motor, diesel, and semi-diesel ships in terms of their respective tonnage. Sailing ships dominated the merchant fleet until the 1880s, although steamers acquired a 1% share of the total tonnage in 1819, more than half a century earlier (at the same time as coal reached a 1% share in primary energy). By the 1920s steam vessels constituted more than 90% of merchant tonnage, thus the replacement

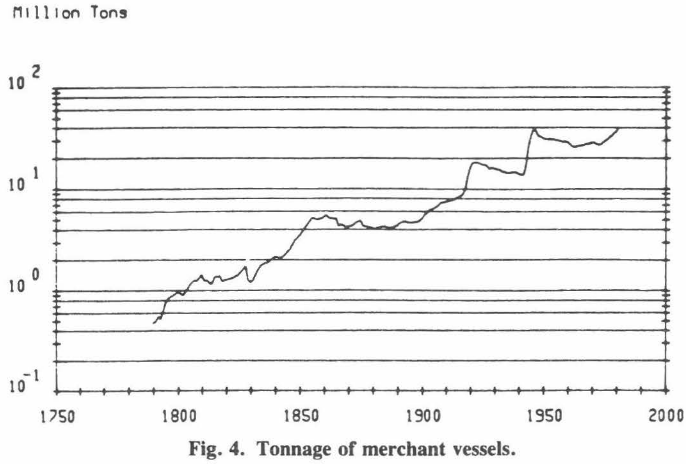

Fig. 4. Tonnage of merchant vessels.

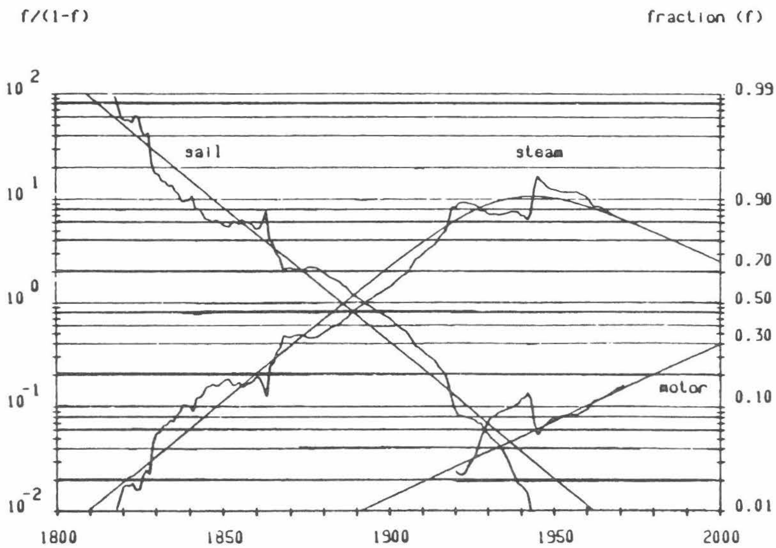

Fig. 5. Substitution in merchant vessels by propulsion system.

of the traditional sailing ship lasted almost 100 years. During the same decade motor ships were introduced and their share of total tonnage has increased ever since, although even today they have not acquired much more than one tenth of the fleet tonnage. Consequently, steamships are still an important type of merchant vessel and are projected in Figure 5 to remain so until the end of the twentieth century, although today they are fueled by oil and in some cases use steam turbines instead of coal-fired atmospheric engines. During World War II, the share of motor ships sharply increased and accordingly the share of steamers was below the long-term trend during this period. But these perturbations were reabsorbed during the 1960s to return to the long-term trend indicated by the logistic substitution model.

Figure 6 shows the share of wood and metal ships in the merchant fleet of the United States. The replacement of wooden ships was a rather rapid process that started soon after the introduction of Bessemer steelmaking in 1857. The first metal ships were made out of iron, but later steel was also used. The data are not available for the period before 1885, so we can only extrapolate ("backcast"), using the logistic-substitution model, that metal ships achieved the 1% share around the year 1850. By 1910, half of all merchant tonnage consisted of metal ships and today virtually all ships are made out of metal.

The above applications of the logistic-substitution model to the historic replacement of older by newer forms of energy and propulsion of merchant vessels indicate that improvements and growth are achieved through a regular, but discontinuous, process and that new energy and marine-propulsion technologies needed more than 80 years to replace one half of the older competing technology. From the time of its first commercial use, each new technology grows logistically until it reaches a saturation phase and then proceeds to decline logistically while being replaced by a newer and more promising technology. During each phase of the substitution process the dominant technology appears to be strong and unassailable, but with time it decays as emerging competitors "attack" the newly exposed position of the mature technology. It is interesting to note that the saturation point is not, by and large, determined by mere physical or resource limitations,

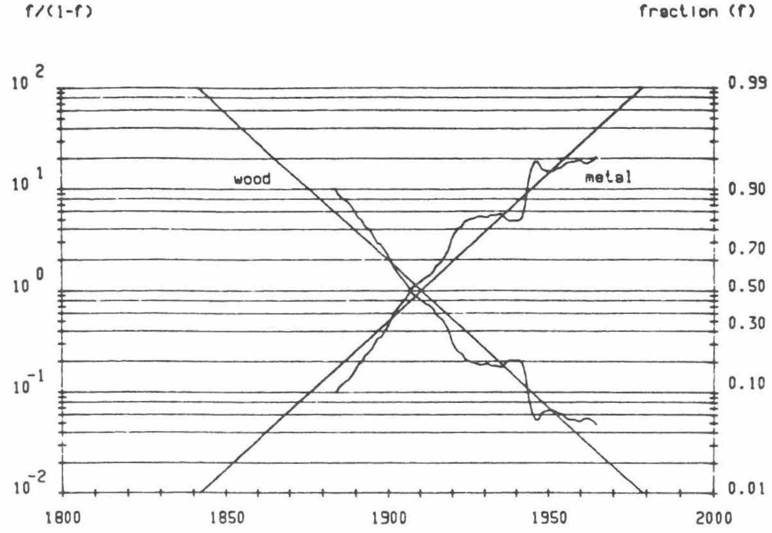

Fig. 6. Substitution in merchant vessels by structural material.

but rather through the dynamics of the introduction of new technologies. Thus, the market shares increase until limits are encountered that appear to be endogenous to the market (or system) itself. These limits are encountered before complete market takeover.

Motor Vehicle or the Horseless Carriage

The first motor vehicles were curious, and very few proponents of the automobile envisaged its rapid development and dissemination throughout the world during the twentieth century. In the United States the first *horseless carriages* posed an alternative to the horse-drawn buggies and wagons. Especially as a commercial vehicle, the motor car offered many potential advantages. Perhaps the most important was the possibility to increase the radius of local transportation compared with horse-drawn vehicles. In the 1930s the average distance traveled per day by horse-drawn vehicles was between 10 and 20 miles and that by motor vehicles was 35 and more miles per day. Because the automobile was faster it allowed many entrepreneurs to expand their circles of customers and offered a more flexible mode of leisure and business transport. Also, railroads were not challenged by the beginning of the automobile age, but rather helped the expansion of motor vehicles, because they offered an efficient form of long-distance transport that combined well with motor vehicles as the local, urban, and rural road transportation. Within a few decades the automobile became an important form of transport in the United States and started also to compete with railroads, especially for long-distance passenger travel. From the 1930s to the present, the total mileage traveled by automobiles, and motor vehicles in general, was divided almost equally between rural and urban travel.

Early motor vehicles resembled horse-drawn buggies and wagons, because most of the rural roads were not paved. Large spoked wheels, high road clearance, and a wooden body characterized both horse-drawn buggies and wagons and motor cars. All told, our initial working hypothesis is that in the United States the automobile first displaced the horse-drawn vehicle. Only after the completion of this substitution process did it emerge as an important transportation mode in competition with the railroad for long-distance movement of people and goods and perhaps also as a competitor with urban transportation modes, such as the tram or local train. Therefore, we will divide the evolution of the motor vehicle in the United States into two phases: the first phase encompasses the substitution of horses and animal-drawn vehicles and the second phase marks a widespread diffusion of individual transportation based on the motor vehicle, after other vehicles essentially disappeared from U.S. roads.

The automobile had a relatively late start in the United States compared with European countries. Certainly, no single individual can be credited with its invention. Steam motor vehicles emerged in the early nineteenth century, but the first prototypes with internal combustion engines appeared in the 1880s. Karl Benz was probably the first to design and build a fully functional motor car based on a tubular frame and a single-cylinder internal-combustion engine (rated at 1.5 horse power allowing speeds of up to 16 km/hr). Other designs of the time were limited to transplanting engines on to vehicles designed for other purposes. Be that as it may, the first motor vehicles that appeared in the United States during the 1890s included both U.S. and European designs. In 1895, four motor vehicles were recorded to be in use in the United States. The initial expansion of the automobile was very impressive—16 vehicles were in use a year later, 90 in 1897, 8,000 in 1900, almost half a million ten years later, and more than one million after another two years. In terms of both production and number of vehicles in use, the United States quickly surpassed European countries. For example, Germany produced about 800 motor vehicles in 1900, France about 3,000, and the United States more than 4,000. By 1922 more than ten million motor vehicles were in use on U.S. roads and the 100 million mark was surpassed in 1970. In 1983, 125 million automobiles, 0.6 million buses, and 35 million trucks were registered in the United States. Figure 7 shows the total registrations of cars, buses, and trucks in the United States since 1895. The expansion of motor-vehicle fleets is characterized by two, distinct secular trends with an inflection in the 1930s for cars and trucks and a less pronounced inflection in the 1950s for buses. Because the two secular trends of each curve appear to be roughly linear on the logarithmic scale in Figure 7, the motor-vehicle fleets evolved through two exponential *pulses*. In accordance with our working hypothesis we contend that the two exponential trends indicate two different phases of dissemination of motor vehicles in the United States. The first characterizes the substitution of horse-drawn road vehicles and the second the actual growth of road transport at large. Thus, the first expansion phase is more rapid because it represents a "market takeover," whereas the second represents the actual growth of the road-vehicle fleets and the associated infrastructure such as the highway system.

Sometimes it is said that the automobile caused the need for good roads, sometimes that the construction of good roads caused the great development of the automobile industry (see, e.g. Epstein [5]). Actually, the expansion of the road-vehicle fleets is paralleled by the growth of surfaced roads mileage, whereas the total mileage of all roads increased very slowly from 3.16 million miles in 1921 to 3.85 million miles in 1981. Figure 8 shows the total road mileage in the United States and the mileage of urban streets (earlier defined as municipal streets), rural road mileage and mileage of all urban and rural surfaced roads (bituminous penetration, asphalt, concrete, wood, stone, and other). The figure illustrates that the growth of surfaced road mileage paralleled the growth of the motor-vehicle fleets after the 1930s. However, the expansion of surfaced roads preceded the expansion of motor vehicles. In 1905, 8% of all roads were surfaced, but less than 80,000 motor vehicles were used compared to about 3.3 million non-farm horses and mules (22 million draft animals were used for farming). Thus, early roads were developed for horses and not automobiles, but motor vehicles expanded quickly into the

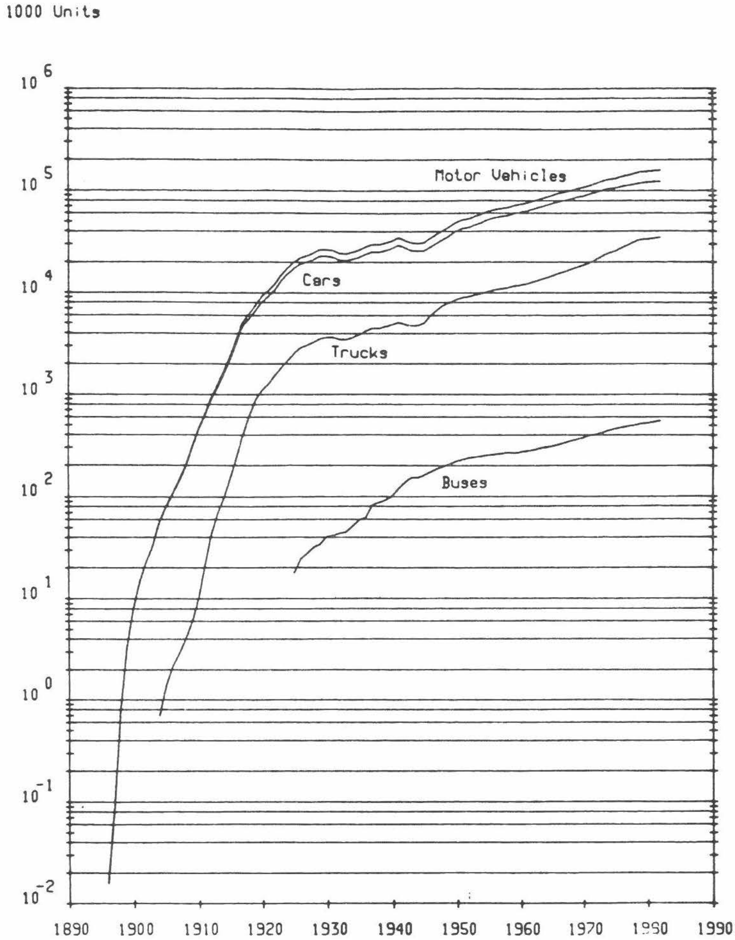

Fig. 7. Number of cars, buses, and trucks registered in the United States.

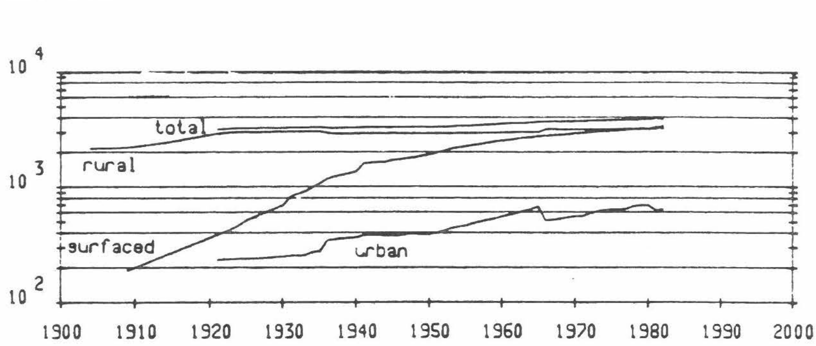

Fig. 8. Road mileage in the United States.

growing infrastructure of surfaced roads. Figure 9 shows the substitution of unsurfaced by surfaced roads. In 1910 about 10% of all roads were surfaced, during the 1940s about one half, and today about 90% are surfaced, so that in retrospect the substitution process lasted longer than 75 years.[2] This is about the same time constant as observed for the replacement of propulsion systems in the merchant fleet and primary energy substitution in the United States. Projecting this substitution process into the future indicates that by the end of the century virtually all roads will be surfaced. Therefore, we can conclude that the introduction of surfaced roads preceded the introduction of motor vehicles in the United States, but that the first rapid-growth phase of motor-vehicle fleets occurred while less than one half of U.S. roads were suitable for their use. It is also interesting to note that the substitution process does not reflect the vigorous road-construction effort after the depression years in the United States, but rather indicates a lack of such effort during the 1910s and 1920s because the actual expansion of surfaced mileage is somewhat below the long-term trend during these two decades. A similar underexpansion occurred during the early 1970s but appears to have been reabsorbed during the last few years.

Due to the obvious problems associated with the lack of historic records about the exact number of horse-drawn vehicles in the United States during the first decades after the introduction of the automobile in 1895, we can only approximately describe the assumed substitution of horse-drawn vehicles by the motor car during the first, more rapid, expansion phase of the motor-vehicle fleets. As a rough approximation of this substitution process, we use the number of draft animals and motor vehicles given in Figure 10. Sometimes horse and saddle were used as a "road vehicle," but often more than one horse was used to pull buggies and wagons, so that Figure 10 may overemphasize

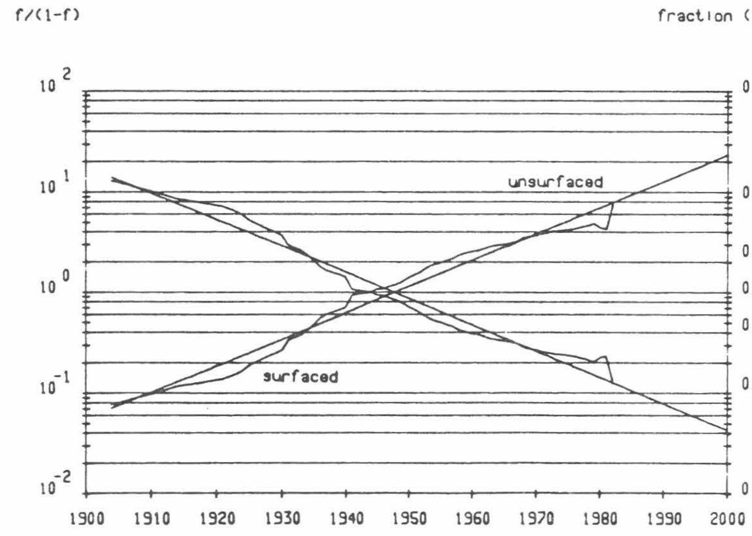

Fig. 9. Substitution of unsurfaced by surfaced roads.

[2]The growth of surfaced roads mileage can be described well with a logistic growth curve that has an inflection point in 1947, growth rate of 7.63% per year, and a saturation level of 3.42 million miles. This is in good agreement with the substitution process of surfaced for other roads, given in Figure 9, because the total road mileage has remained almost constant during the last 80 years.

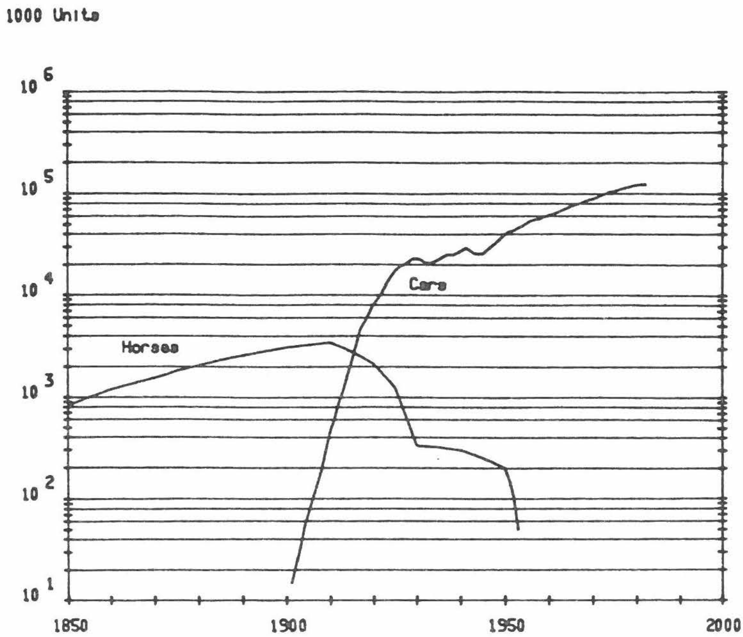

Fig. 10. Number of non-farm horses (and mules) and cars.

the number of horse-drawn vehicles if the number of draft animals is used as a proxy for the number of vehicles actually in use. Nevertheless, we will make this assumption in order to analyze the postulated substitution process.

Figure 11 shows the substitution of non-farm horses and mules by cars. Thus, we implicitly assume that the number of non-farm horses and mules corresponds to the number of animal-drawn road vehicles. Cars represent all registered motor vehicles, omitting

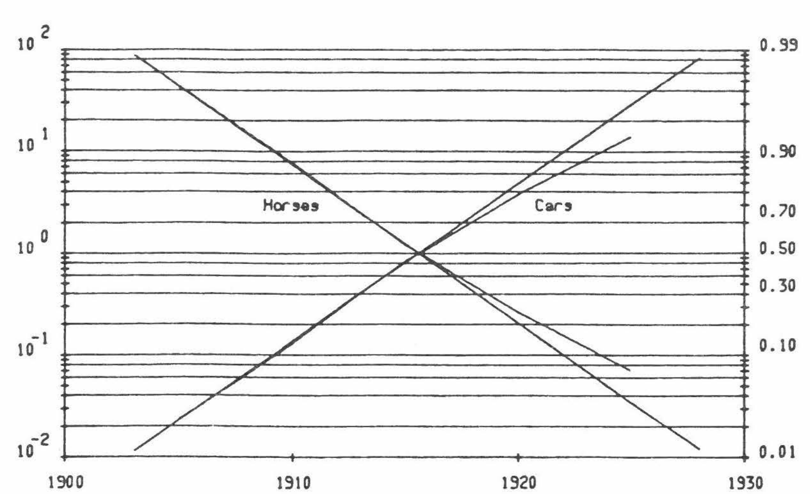

Fig. 11. Substitution of non-farm horses (and mules) by cars.

trucks and buses from Figure 7. The disadvantage of this rough comparison of numbers of animal-drawn vehicles and motor cars is that the estimates of the number of non-farm horses and mules are certainly not very accurate and they are unevenly spaced in time. Thus, annual fluctuations of the actual number of draft animals cannot be reconstructed from the available historic records.

Despite these disadvantages, Figure 11 indicates that the automobile replaced horse- and mule-drawn road vehicles during a relatively short period and that the substitution process proceeded along a logistic path. Motor vehicles achieved a 1% share in road vehicles shortly after 1900 and a 50% share in 1917. The complete takeover of the "market" for road vehicles occurred in 1930 with 23 million cars in use and 0.3 million non-farm horses and mules. This result indicates that the inflection point of the secular trend of registered cars from Figures 7 and 10 actually coincides with the end of the substitution of animal-drawn road vehicles. This result also explains the "saturation" of motor vehicles in the United States perceived by many analysts during the late 1920s and early 1930s. However, the perceived saturation of cars was actually the end of the substitution of animal-drawn vehicles and the beginning of a new phase in the motorization of the United States, with growth rates comparable to those for the expansion of horse carriages and wagons before the automobile age. Seen from this perspective, the growth in the total number of road vehicles is a continuous process without any pronounced changes over the entire period from 1850 to date, with an average annual growth rate of about 4.2%. Figure 12 shows the number of non-farm horses and mules and cars from Figure 10, together with the estimates from the logistic substitution model based on a 4.2% per year growth of the "market" for all road vehicles, whereas Figure 13 shows the growth of all road vehicles by summing the number of horses, mules, and automobiles.

Although this result strengthens our working hypothesis of two different phases in the dissemination of the automobile, it is by no means conclusive due to the rough approximation of the number of road vehicles drawn by horses and mules. It should also be observed that the smooth growth of all road vehicles corresponds well to the continuous growth of surfaced roads in the United States during the last 80 years. By the time horses

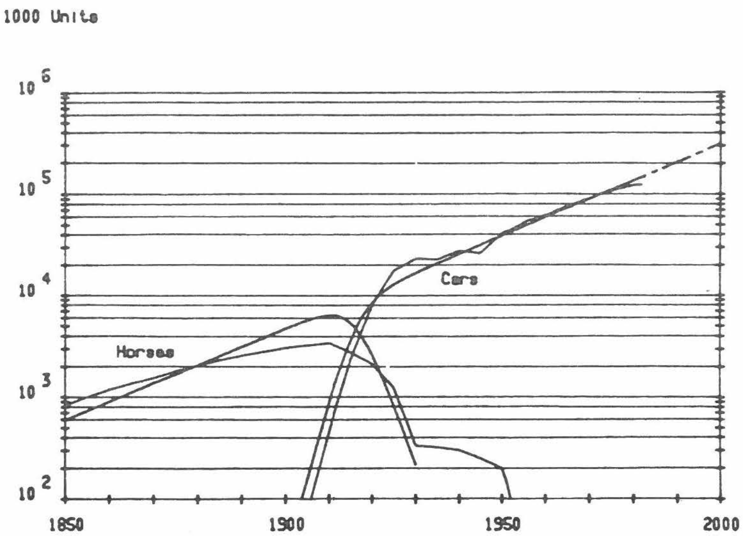

Fig. 12. Actual and estimated number of horses (and mules) and cars.

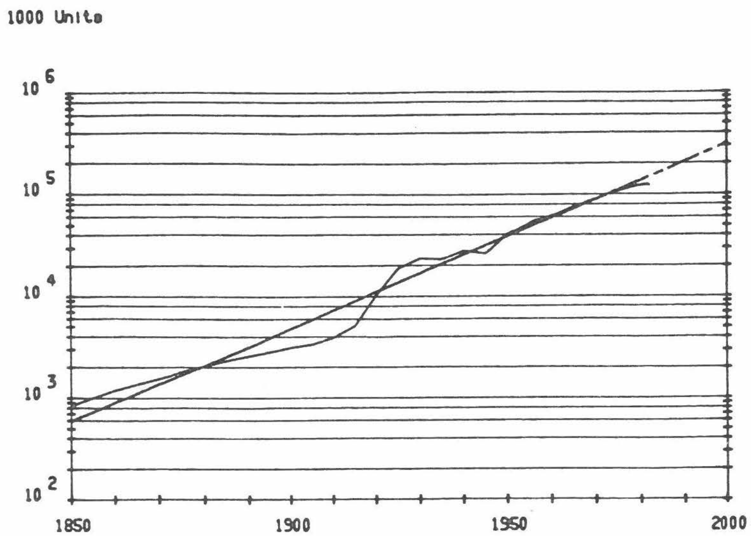

Fig. 13. Actual and estimated number of road vehicles.

disappeared from the U.S. roads one half of the roads were surfaced and thereafter annual construction rates of new surfaced roads declined. Thus, while the infrastructural change of the U.S. road system took almost as long as the substitution of merchant fleets and primary energy, the substitution of vehicle fleets was a much swifter process lasting only three decades.

The next example serves to verify this result by independent observations. Figure 14 shows the production of buggies (including carriages and sulkies) and factory sales of motor cars in the United States. We have not extended the curves beyond 1950 because

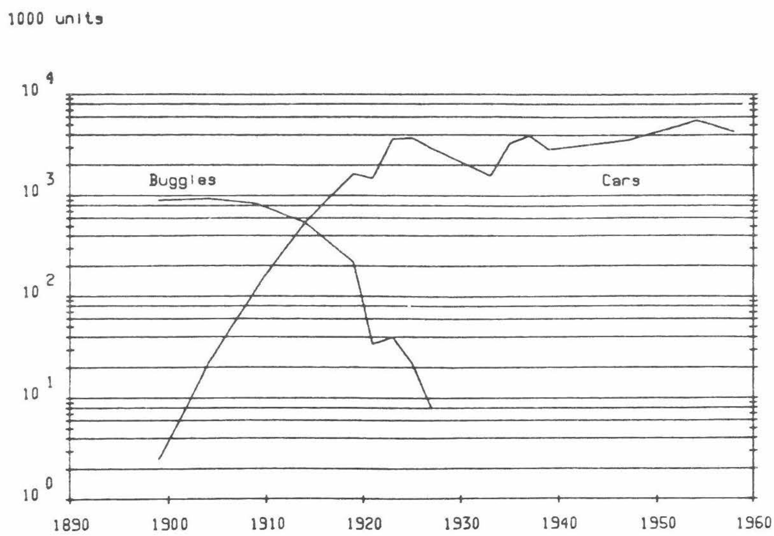

Fig. 14. Production of buggies (carriages and sulkies) and cars.

the factory sales (or production) of motor vehicles cease to be a good proxy for actual vehicle sales due to the emerging importance of imports. Because of the scrapping rates of road vehicles, the two curves do not exactly represent "derivatives" of the actual number of road vehicles in use. Nevertheless, they exhibit trends similar to the number of non-farm horses (and mules) and registered cars. In fact, the secular trend of motor-car production shows an inflection during the 1920s preceding the similar inflection in the growth of the automobile fleet by less than ten years.

Figure 15 shows the substitution process in production of buggies, carriages, and sulkies (representing animal-drawn road vehicles) and factory sales of motor cars. This substitution process confirms the results from the previous example. Automobile manufacture achieved a 1% share in the production of road vehicles shortly after 1900, a 50% market share in 1914, and by 1924 virtually all road vehicles produced (that is, sold) in the United States were automobiles. Thus, the market takeover in production precedes the takeover in the vehicle fleets by about six years. This may be due to the longer life span of animal-drawn vehicles compared to cars; however, this is only a speculation, because the statistics are not available. The lag of about six years between the substitution of vehicle fleets and vehicle production indicates that the average age of all road vehicles could have been about six years by the 1930s, which is in a good agreement with the average age of 5.5 years for cars (and 5.6 years for trucks) in 1941 (earliest year for which the data were available, see [2]). Nevertheless, in both examples the major deviations from the logistic substitution paths occur toward the complete replacement of horse-drawn vehicles.

In general, older technologies tend to serve recreational or esthetic roles once the replacement is complete. This was the case with fuel wood, sailing ships, horses, convertible (open) cars, and many other examples. Thus, it is conceivable that the departures of the actual market shares from their logistic paths could be reduced toward the end of the substitution process by eliminating this "non-substitutable" niche for older technologies from the analysis.

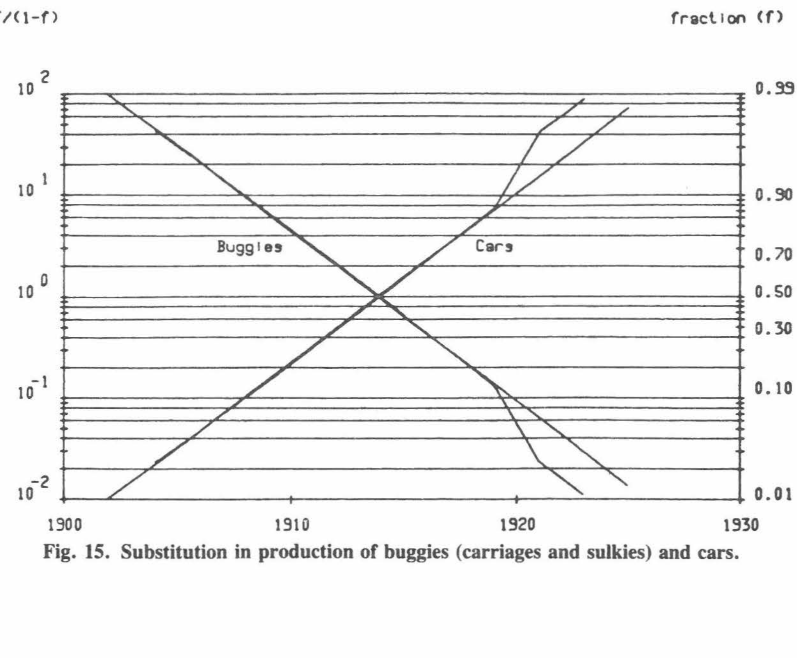

Fig. 15. Substitution in production of buggies (carriages and sulkies) and cars.

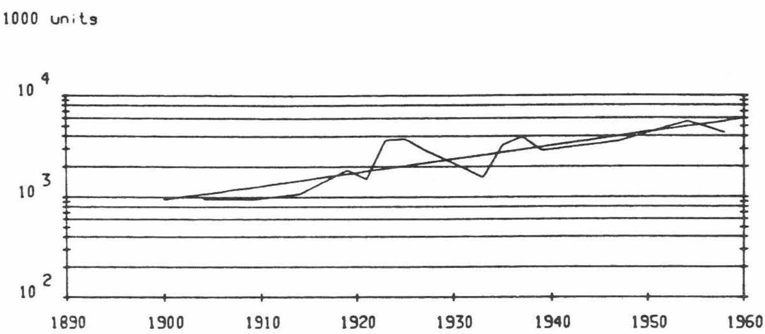

Fig. 16. Actual and estimated production of road vehicles.

Given the poor quality of historical records, it is obvious that the two examples give a consistent description of the introduction of the automobile as an alternative to older road vehicles. Furthermore, Figure 16 shows that the production of all road vehicles (carriages, buggies, sulkies, and motor cars) grew with a constant average annual growth rate of about 3.1% between 1900 and 1950 without a change in the secular trend.

By the time the automobile had replaced the horse-drawn vehicles (during the 1920s), fundamental technological changes in production had occurred, as well. These changes were probably an important factor in further diffusion of the automobile once it became the exclusive means of road transport by making it more reliable, cheaper to purchase and maintain, and easier to operate.

Technological Changes

It is usually very difficult to distinguish between technological changes in the production of motor vehicles and changes in the vehicles themselves. These changes went hand in hand: new design and performance characteristics imposed changes in production and new production processes made changes in the vehicles possible. In 1914, when Ford introduced the moving assembly (by analogy to the moving "disassembly" in a Chicago slaughterhouse), about as many horse-drawn vehicles were produced as automobiles (see Figure 14). Abernathy [1] points out that another ten years went by before techniques for the mass production of car bodies were rapidly developed. They could not be applied successfully, in spite of moving-assembly methods, as long as wooden construction materials were used. As if symbolically, wooden bodies were used in almost all models (except a few high-price vehicles) throughout the 1920s and from this point of view were no different from carriages. By the time the automobile became the main mode of road transport, major manufacturers were producing steel bodies. This went hand in hand with the introduction of closed bodies that depended upon advances in the widths and surface finish of rolled steel, the development of welding technology, and new paints and painting methods [1].

Once these changes were introduced into the moving assembly, mass-production techniques emerged and new methods of sheet-metal forming with presses and welding were necessary. A moving assembly of metal bodies was based not on sheet-metal forming but primarily on machining or metal removal and was thus similar to the first form of moving assembly for wooden bodies.

Figure 17 shows the substitution of open by closed car bodies. This substitution process can be considered a proxy for changes in production techniques and the replace-

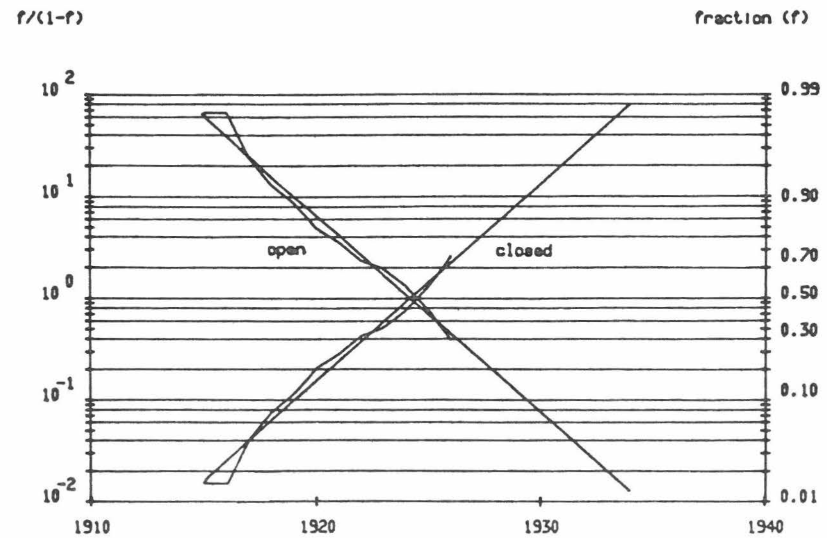

Fig. 17. Substitution in production of open and closed car bodies.

ment of wood by steel in automobiles in the United States. In 1915, closed bodies acquired a 1% market share in total production, only a year after Ford introduced the moving assembly. Ten years later, 50% of all cars were sold with closed bodies and by the middle 1930s they were universal, leaving only a small segment of the market to convertibles. All told, the diffusion of fundamental changes in automobile manufacturing and design occurred after most of the traditional road vehicles had been replaced by automobiles and was concluded by the time one half of U.S. roads were surfaced.

Up to the late 1920s most automobiles were literally horseless carriages and probably did not need to be much more, because, as such, they were inherently superior to carriages. However, to acquire new customers, once the horse had almost disappeared from U.S. roads, the automobile needed to fulfill functions besides individual transport in the crudest sense of the word. Epstein [5] classified the purposes for which automobiles were bought during the 1920s into four main categories: transportation service, sport, personal possession, and social prestige. The fulfillment of these four and probably other criteria placed on the automobile implied the necessity for large improvements. Most importantly, the automobile had to become easier to use and more reliable. Both of these improvements were realized through technological changes. Reliability was achieved mostly through better materials, design, and machining. Convenience, however, necessitated further changes: the electric self-starter, electric lights, low-pressure pneumatic tires, closed, metal bodies, and so on. It appears that the period starting in the late 1920s marked a certain tendency toward reconsolidation and increasing homogeneity in the industry. Although automobile design and production methods varied widely during the phase of horse and carriage substitution, during the 1930s most manufacturers adopted moving-assembly methods and basically similar designs. Most of the "unconventional" vehicles disappeared, including steam and electric cars. At the same time, the "conventional" automobile and production improvements disseminated throughout the industry, making product differentiation necessary as a replacement for genuine alternatives. Another way of phrasing this new feature of the automotive industry is that successful innovations disseminated rather quickly and once adopted were improved rather than replaced by most firms as if to reduce the risk of making changes that might not be to the customer's liking. Examples include the spread of four-wheel brakes and low-pressure balloon tires. In 1923, a little more than 1% of all new cars were offered with four-wheel brakes, by 1927 they were standard equipment on 90% of new cars. In 1924, only one tenth of all tire production was of the low-pressure balloon design. By 1926, balloon and traditional high-pressure tires had about equal shares in total tire production. This shows the rapid spread of two important automobile improvements throughout the industry during the 1920s and, with a lag of a few years to a decade, also throughout the automobile fleet. Here we cannot analyze in detail all the changes that have been implemented since the 1920s, but will rather consider those that are documented and can be empirically assessed.

If we neglect for the time being the recent use of electronics, most other features of the modern automobile (including aerodynamic styling) were introduced soon after the replacement of animal-drawn vehicles. However, the introduction of a new automobile component or design characteristic usually precedes by few decades the widespread adoption of this innovation by the whole industry. Thus, many innovations that were originally introduced during the early days of the automobile did not diffuse throughout the industry until the recent decades.

Figure 18 shows the substitution process of three major types of transmissions in the United States. The oldest transmission, also used in some of the first vehicles, is the three-speed manual gear box. In the United States, the automatic transmission was basically the only alternative to the three-speed manual gear box, mainly due to the use of high torque and displacement engines. In Europe, due to different driving conditions and generally smaller cars, four-speed gear boxes were also common in the early days of motor vehicles. Automatic transmission was in many ways superior to manual and certainly offered more convenience to the average motorist by simplifying the operation of the automobile. The first designs for an automatic transmission appeared in 1904 in the United States and Europe. Frictional and centrifugal variants turned out not to be viable alternatives and definitely not competitive with manual transmissions.

Along with these less successful designs the first hydraulic automatic transmissions with torque converters also appeared. Torque converters and fluid-coupling designs were adapted to motor vehicles from similar German inventions of the early 1900s for marine power and torque-conversion systems. The first automobiles with hydraulic automatic transmissions were offered in the United States in the late 1930s. In 1937, Oldsmobile offered a semi-automatic transmission, Chrysler introduced "Fluid Drive" in 1938 and Oldsmobile "Hydra-Matic" in 1939, the first fully automatic transmission with fluid coupling and a four-speed planetary gear box. Thus, the late 1930s mark the introduction of automatic transmissions as a competitive alternative to the manual gear box.

The next breakthrough occurred in 1942 when Buick introduced "Dynaflow," an automatic transmission utilizing a torque converter. Soon after World War II other manufacturers introduced similar automatic transmissions, although fluid coupling was the typical design until they were replaced by torque-converted transmissions. By 1948, one third of all new cars had automatic transmissions, by 1953 one half, and by 1963 two thirds. Figure 18 shows this rapid diffusion of the automatic transmission in the United States. By the late 1960s almost 90% of new cars were equipped with an automatic transmission and fewer than 10% still had the much cheaper three-speed gear box.

At this time the automatic was challenged from its position of dominance by the introduction of the four-speed manual transmission and the later five-speed variant (in most cases, it was basically a four-speed transmission with an additional overdrive gear,

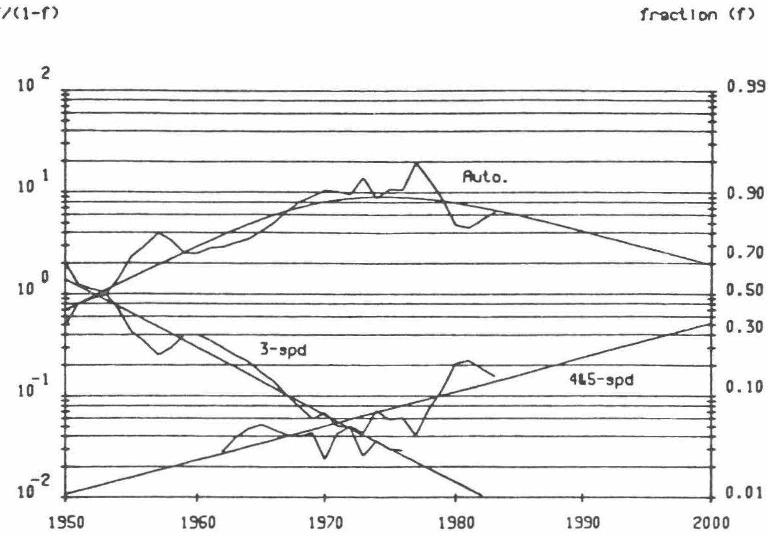

Fig. 18. Substitution in production of factory-installed transmissions.

the "sports" five-speed transmission being restricted to a few high-performance cars). Thus, it is interesting to note that the torque-converted automatics replaced the less-efficient fluid-coupling transmissions during these years as if to compensate for some of the efficiency advantage of the four- and five-speed manual transmissions.

Higher fuel-economy requirements and the prolonged recession of the last decade have favored the displacement of more expensive and less-efficient three-speed automatics, although more than 80% of new automobiles in the United States are still supplied with an automatic transmission. Some of these new cars already have more efficient four-speed automatics; however, due to the lack of appropriate data, it is not possible to analyze this substitution process in its full complexity by including three-, four-, and five-speed manual transmissions as well as three- and four-speed automatics. Figure 18 shows that automatics may incur additional losses to the four- and five-speed manual transmissions during the next two decades, shrinking the market share of automatics in new cars to about 70%; that is, below the 1955 level. This will probably not represent the ultimate state of this competition process. Instead, it is likely that new designs will be introduced in the future that will in turn replace the four- and five-speed manual transmissions. There are a number of candidates, ranging from continuously variable-ratio transmissions to electric conversion using batteries as intermediate storage in order to flatten the power requirements.

The continuously variable transmissions have the additional advantage that they offer faster acceleration than manual transmissions with the same vehicle weight and engine performance. This means that they offer the potential of reducing fuel consumption with the same weight and acceleration performance, because smaller engines can be used. Because weight reduction is usually very costly and aerodynamic improvements usually easier to implement, it is conceivable that the continuously variable transmission could offer the solution to two conflicting objectives, namely to improve fuel efficiency with better aerodynamics and smaller engines without significant weight and acceleration reductions (Seiffert and Walzer, 1984). Thus, the continuously variable-ratio design approaches the ideal transmission performance, which is basically to allow the engine to operate in a very small interval with highest fuel efficiency, and best power and torque characteristics. Actually, Ford and Fiat will be introducing fully electronically-controlled variable-ratio transmissions integrated with electronic engine management in late 1986 on some Ford Fiesta and Fiat Uno models [4]. Transmissions, however, should be quiet, safe, efficient, and reasonably priced, so a practical design usually represents some compromise between the ideal design requirements and the actual product characteristics. In view of these limitations, it is probable that the next generation of transmissions will constitute an evolutionary refinement and that a revolutionary solution, such as a continuously variable transmission, could be introduced by most manufacturers thereafter. An obvious candidate is a hybrid design incorporating the advantages of the operating convenience of an automatic with the efficiency of a five-speed manual transmission. The first versions of such transmissions include microprocessors as a replacement for the hydraulic mechanisms for the shift operation. In addition, a microprocessor could also, in principle, replace the torque converter and operate a transmission directly by choosing optimal shift intervals and engine-operating conditions. Thus, an algorithm could control everything from the engine to the wheels (including brakes) and the driver would activate the controls by two pedals (accelerator and brake) like in an automobile with an automatic transmission. Some manufacturers already offer similar but simpler microprocessor-controlled automatic transmissions. Assuming that 1% of all new cars were offered with such advanced automatic transmission by 1990, one could speculate on the basis of the substitution dynamics shown in Figure 18 that it could take up to three decades before such a new transmission type would be installed in one half of all new cars. Another way of describing these technological changes is that the manual clutch was replaced by the hydraulic mechanism in the past and that both will be replaced by electronically controlled systems in the future.

Figure 18 illustrates that the market substitution of different transmission types is as regular as other technological changes. The interesting element here is that this technological substitution process can be seen as the competition of a given type of automobile component for the share of new cars. An abstraction of this substitution process implies that all new cars constitute the environment or "ecosystem" for different types of transmissions and that within this environment they struggle for dominance or survival in different "eco-niches". This is in many ways equivalent to the competition in some biological environments. For example, Marchetti [12] has described a similar competition process between different human diseases for "shares" of sick people.

Disc brakes are another example of an automobile component that was already in use on some cars in the early 1900s, but did not replace conventional drum brakes until half a century later. Another similarity to the automatic transmission is that, although both disc brakes and automatics appeared on some daring automobile designs in the early 1900s, they did not replace the drum brake and the three-speed manual transmission until the final design was developed for another purpose and applied to the automobile. The hydraulic torque-converted automatic transmission was invented for marine engines and the caliper-disc brake was used in the aircraft industry during the 1940s. Although diffusion of the automatic transmission started soon after World War II in the U.S. automobile industry, the disc brake was a late starter in the United States. Thus, diffusion of the automatic transmission had a definite lead in the United States compared to Europe, but disc brakes became standard equipment on European cars long before they were common in the United States. Once the replacement of drum by disc brakes on the front wheels was initiated in the 1960s, a complete switchover was accomplished within a

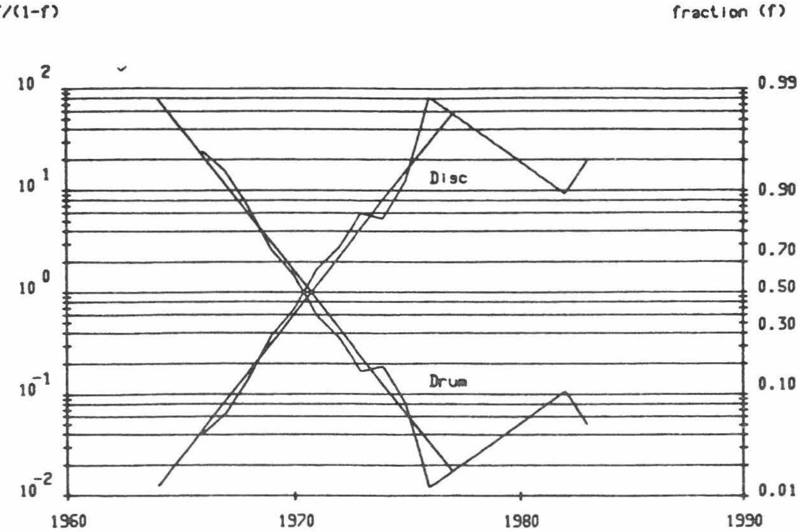

Fig. 19. Substitution in production of drum and disc brakes.

decade. Figure 19 shows that soon after the Studebaker Avanti was offered as the first U.S. automobile with standard disc brakes in 1963, most other manufacturers followed and that by 1970 half of all new U.S automobiles were equipped with front-wheel disc brakes. A decade later they were standard on more than 90% of new cars.

Figure 20 shows the diffusion process of air conditioning as factory-installed equipment in new U.S. cars. After-market installments are not included and all variants of climate-control equipment are grouped together, including automatic and manual air conditioning. Although air conditioning is qualitatively a different kind of automobile

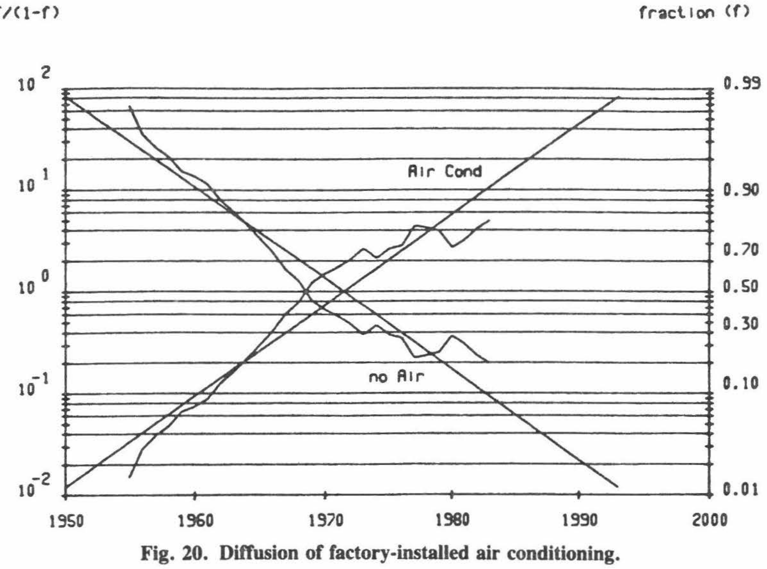

Fig. 20. Diffusion of factory-installed air conditioning.

component than transmission or brakes, because it does not directly serve a function necessary for operating the vehicle, it is a very important factor in contributing to comfort. Although air conditioning is not such an important automobile component in Europe compared with the United States, other factory-installed "comfort" options, such as the sliding sun roof or sport seats, may have comparable importance to that of air conditioning in the United States. Figure 20 shows that the introduction of air conditioning in new automobiles portrays basically the same dynamics as the diffusion of the other automobile components analyzed so far—transmissions and brakes.

Figure 21 shows the substitution of diagonal by radial tires as factory-installed equipment on new U.S. cars. The introduction of radial tires by U.S. manufacturers is analogous to the dynamics of disc-brake diffusion. Both components, as factory-installed equipment, were late starters in the United States compared with Europe, were introduced as standard equipment at about the same time, and replaced their predecessors in one half of new cars within one decade. Unfortunately, Figure 21 does not tell the whole story about the diffusion of radial tires, because manufacturers did not report radial-tire installment before the 1973 model year. It is likely that this may account for the relatively poor description of the substitution process by the logistic curve (compared with other examples).

The last example of technological change at the level of factory-installed equipment is the case of power steering. Figure 22 shows that during the 1950s more than 10% of all new U.S cars were delivered with power steering, but that the 90% market share occurred in the late 1970s, more than two decades later. Thus, we have observed that the diffusions of disc brakes and radial tires were similar with respect to their initial introduction and the substitution rate. Both of these substitutions improved the performance and safety of the vehicles. Air conditioning and power steering, on the other hand, primarily improved the comfort of operating an automobile and are thus more a function of consumer choice than technical performance, although in some cases the consumer does not have a real choice, because some cars have power steering and automatic transmission as standard, factory-installed equipment. In any case, these four examples

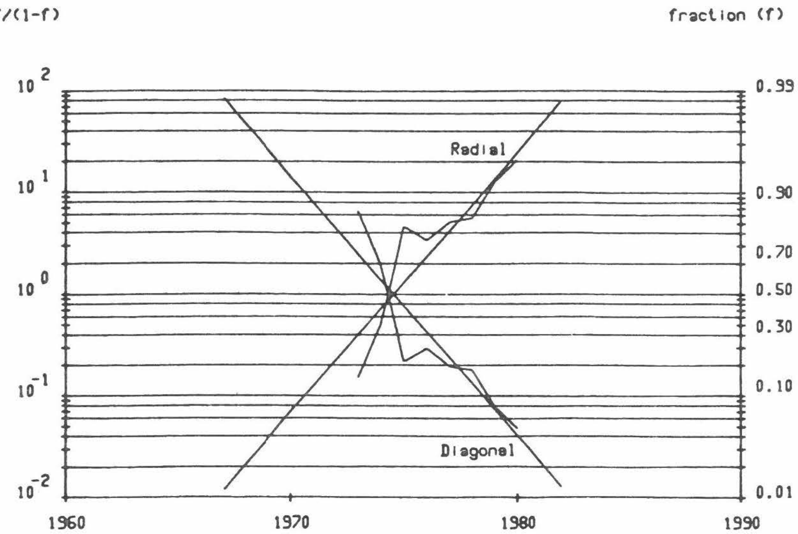

Fig. 21. Substitution of factory-installed diagonal and radial tires.

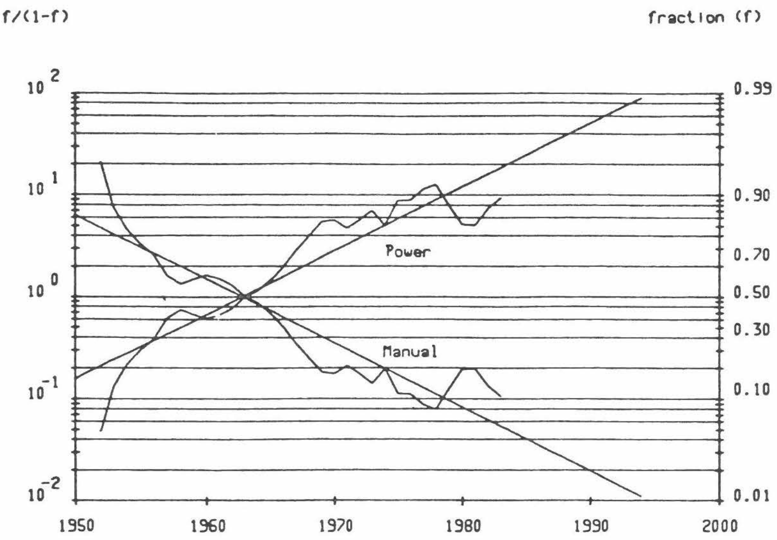

Fig. 22. Substitution in production of manual and power steering.

indicate that technological rather than comfort improvements occur faster in the automobile industry, although it is clearly dangerous to generalize on the basis of such a small sample. Nevertheless, it is curious to note that the substitution of the three-speed manual by automatic transmission can be placed somewhere between these two groups of factory-installed equipment with respect to the duration of the substitution process, because automatic transmission affects, to some extent, both comfort and technical performance.

Automobiles and Emissions

Most of the technological changes described up to now served to improve some aspect of automobile production or performance. As such, new technologies were in some sense superior to those they replaced, but they generally also had some disadvantages. The most common drawback of new technologies is that they are usually more expensive than the older ones. New technologies, however, may also be an attractive source of profits in days of low unit profits, especially during phases of intensive competition and market saturation. For example, automatic transmission, disc brakes, radial tires, and power steering are all more costly than the equipment they replaced. In this sense, emission control or reduction equipment can also be viewed as a technological change: it improves some characteristics of the vehicle—in this case by reducing the emissions—but it is also associated with disadvantages, such as higher cost. Today, almost all passenger vehicles have some equipment that helps reduce emissions. To some extent, emission reductions were originally a "by-product" of other technological improvements of vehicles. For example, fuel-injected engines, especially in conjunction with advanced combustion-chamber designs, are more fuel efficient and have higher performance than the otherwise-equivalent carburetor engines. At the same time, they also can substantially lower hydrocarbon and carbon monoxide emissions. Other emission-control measures can be considered as mere add-ons that do not require substantial changes to the rest of the vehicle. One example of such a measure is the crankcase emissions control.

By contrast, vehicles with catalytic converters require changes in the engine, fuel, and exhaust systems. These cars are considerably more expensive than equivalent models without catalytic converters and also have *lower* fuel efficiency, although it is probably true that vehicles with converters achieve greater fuel efficiency than vehicles with other control methods meeting the *same* standards. Perhaps the most important difference between cars with catalysts and those with other emission controls, however, is that catalytic converters necessitate the use of lead-free gasoline. Thus, the use of catalytic converters requires the modification of the infrastructure for production and distribution of motor fuels. In this sense, the introduction of lead-free cars is comparable to the introduction of diesel and other vehicles powered by alternative fuels, although most of the older cars can use unleaded gasoline, which is not necessarily the case with alternative fuels such as diesel or methanol. Figure 23 shows the diffusion of emission controls in the U.S. automobile fleet, seen as the substitution process of three broad categories of vehicles. The oldest kind of automobile is without any explicit emission controls. Figure 23 shows that by 1967 only half of the automobiles in the United States had no emission controls whatsoever. Starting in 1965, crankcase controls were mandatory on all new vehicles in order to reduce hydrocarbon emissions. Beginning with the 1968 model, exhaust controls were required in order to reduce carbon monoxide and hydrocarbon emissions. Finally, in 1971, fuel-evaporation controls to eliminate losses from gasoline tanks and carburetors were required on all new cars. Although all of these emission controls are grouped together under one single category in Figure 23, it is obvious that this includes a whole host of different technological changes. Cars with some or all of these emission controls slowly replaced those with none. By 1975, almost 90% of all cars registered in the United States had some or all of these emission controls and cars without any controls were reduced to a bare 4% of the fleet.

Starting in 1971, some models offered nitrous oxide–reduction measures and by 1973 lower nitrogen oxide emissions were required on all new cars. In 1975, catalytic converters were mandatory to meet more stringent hydrocarbon, carbon monoxide, and nitrogen oxide emission standards. By 1980, half of all automobiles had such advanced

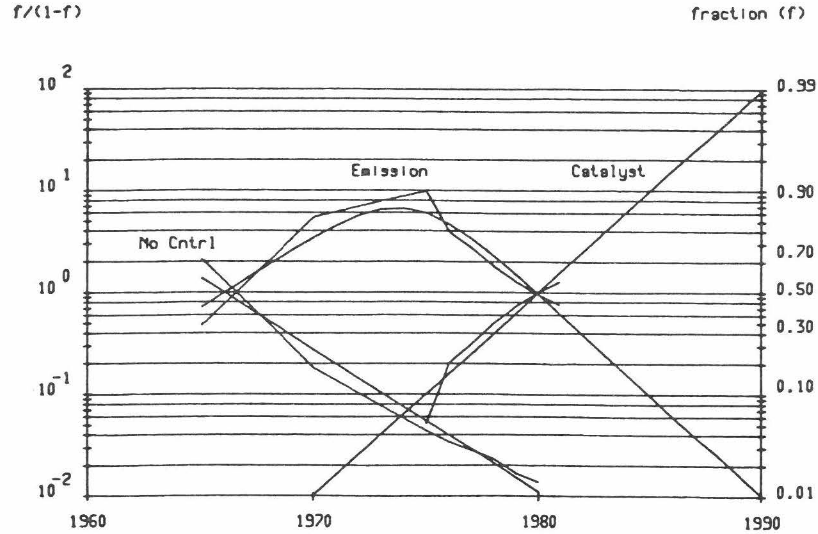

Fig. 23. Substitution of cars with emission controls.

emission-reduction controls and, according to Figure 23, it can be expected that by 1990 such emission controls will be almost universal. Thus, for the United States it can be concluded that the diffusion of automobiles with catalytic converters is a relatively long, although regular, process with a duration of about two decades. In other words, it took a decade from introduction to 50% penetration for both automobiles with emission controls and later for automobiles with catalytic converters. If this time constant was applicable in Europe, it can be expected that from the introduction date of catalytic converters at least *two decades* will be required for their complete diffusion.

This example of the diffusion of emission controls in U.S automobiles and the earlier example of the replacement of horses (and mules) by automobiles describe two substitution processes at the level of the fleet (or population), whereas all the other examples of technological changes in automobile production and vehicle components illustrated substitution processes in terms of production (or factory sales). In the case of replacement of horses and animal-drawn vehicles by automobiles, the substitution process was also described in terms of production. It was shown that the changes at the level of the whole fleet lagged behind equivalent changes, in terms of production, by about six years. We have concluded that this lag is largely due to the age structure of the vehicle fleets and that it corresponds to the average age of about six years for all vehicles. Thus, a distinction always exists between the market shares of a new and an old technology as measured by production rates and the market shares as measured by fleet composition, provided that a period of obsolescence exists for the embodiment of the old technology. The lag between the two substitution processes is usually a good proxy for the average age of the fleet, but it is not a good indicator for the average life span, especially in cases of rapid fleet growth rates.

Fisher [6] observed that the introduction of emission controls into the U.S. automobile fleet, given in Figure 23, illustrates very vividly the difference between the market shares of a new and an old technology as measured by production (or sales) rates and by fleet composition, because the emission controls were mandated by law as of a specific date. The percentage of new automobiles incorporating emission controls as a function of time rises rapidly from near zero prior to the legally mandated date to near 100% just after, whereas the logistic substitution takes about ten years from 1% of the fleet until one half of the automobiles are replaced (see Figure 23). Here the time constant of the logistic curve is not related to competition between the new and the old technologies, because replacement in terms of new cars was almost instantaneous. The substitution depends on the rate of obsolescence of old automobiles without emission controls and their replacement by new ones with controls and on the growth of the whole fleet in addition to the replacement level. Actually, the average age of automobiles in use in the United States has varied considerably during the last 45 years.[3] The last decline in the average age during the late 1960s and the subsequent increase could be an explanation for the somewhat more rapid decrease of market shares of automobiles without any emission controls than the logistic trend line until 1969 (see Figure 23) and for the somewhat slower decrease thereafter. Each phase of decreasing average age was accompanied by a more rapid growth of the whole fleet and each phase of prolongation of average age by a slower growth (see Figure 7). Thus, the actual life expectancy of automobiles is difficult to

[3]The average age of the fleet increased from 5.5 years in 1941 to 9 years by the end of the war and decreased again to 5.5 years by 1958, then it rose slightly to 6 years during the early 1960s, and decreased again to 5.55 years by 1970, and finally it rose again to 7.81 years by 1982 [2, 21].

assess, because fluctuations of the fleet growth rate appear to be an important factor in determining the average age of the fleet. Unfortunately, explicit statistics on the survival rate of automobiles by model year and type over longer periods are generally lacking. A good approximation for the life span of automobiles in the United States is about ten years. Marchetti [11] showed that the survivors curve for the 1967 "cohort" of U.S automobiles appears to follow a logistic trend with one half of the vehicles surviving 9.2 years. Nevertheless, it is possible that the life expectancy of automobiles changed in the past, converging toward ten years during the last two decades. A better understanding of the "demographic" aspects of the age structure and mortality rates together with the growth rates of the whole fleet would be very useful in determining the duration of future technological changes, once a substitution process has been initiated in new cars.

The fact that automobiles with catalytic converters must be fueled with lead-free gasoline in order to avoid catalyst damage can be used as verification for the accuracy of the projection and substitution dynamics of emission controls in automobiles. Figure 24 shows the substitution of leaded by lead-free gasoline in the United States. It is reassuring that the 50% substitution mark in 1980 corresponds exactly to the same penetration level of cars with a catalyst. Nevertheless, unleaded gasoline replaces the leaded variant somewhat slower than catalyst-equipped cars replace other ones. This somewhat slower diffusion could be due to the fact that new cars are more fuel efficient than the old ones (although they may be driven more) and also due to the illegal practice of some owners of automobiles with catalytic converters of using leaded gasoline due to lower cost, in spite of detrimental environmental consequences—such vehicles pollute more than do efficient automobiles without a catalyst. In fact, up to 40% of all automobiles with converter equipment in the United States are claimed to have a defective catalyst, usually due to the use of leaded gasoline [10]. If this trend should continue, it could be expected that the projected increase in market share of unleaded gasoline may be overestimated in Figure 24.

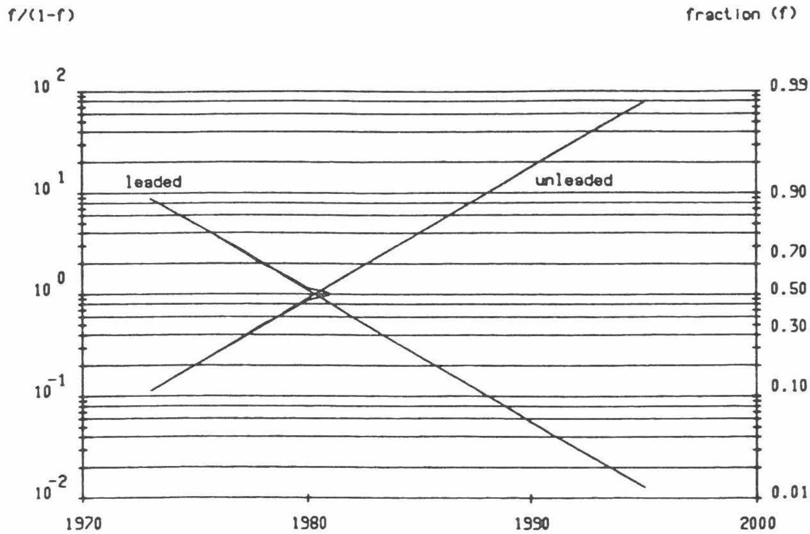

Fig. 24. Substitution of leaded by lead-free gasoline.

Automobiles and the Transportation System

The examples given above indicate that it is possible to consistently describe the evolution of motor vehicles in the United States as a series of technological substitution processes. First, the automobile replaced the horse and carriage and then new generations of motor vehicles replaced old ones. Through this replacement process the automobile fleet itself underwent fundamental changes with respect to the characteristics and structure of the vehicles. New technologies were introduced and their shares in new cars increased, generally along a logistic growth path, but with different rates. Substitution of old technologies ranged from an almost instantaneous takeover, as mandated by the law for catalytic converters, to between one to three decades until new technologies and automobile equipment were embodied in one half of the new cars. The corresponding diffusion throughout the fleet that lagged by about five to ten years, in accordance with the changing age structure of the vehicles in use, was, at least in the past, largely due to the short-term fluctuations in the growth rates of the whole fleet. The long-term growth of the vehicle fleet, however, followed a rather stable secular trend once animal-drawn vehicles were replaced (see Figures 7 and 10). This long-term growth trend describes the expansion of road vehicles in general and parallels the growth of surfaced roads mileage since the 1930s (see Figure 9). In a broader context the expansion of road vehicles as a part of the overall transport system must be compared with the development of other competing transport modes. Obvious competitors are passenger trains, buses, airlines, subways, and other forms of urban transport. Ships have been reduced to a small fraction of total passenger traffic so that they need not be considered as a viable alternative to the automobile. By excluding urban and metropolitan transport because explicit statistics are generally lacking, the competition for intercity passenger traffic is reduced to four significant transport modes. Figure 25 shows the substitution of railways, buses, cars, and airways as long-distance travel alternatives in the United States. The shares of each mode of transport are calculated in terms of passenger-miles traveled in a given year. According

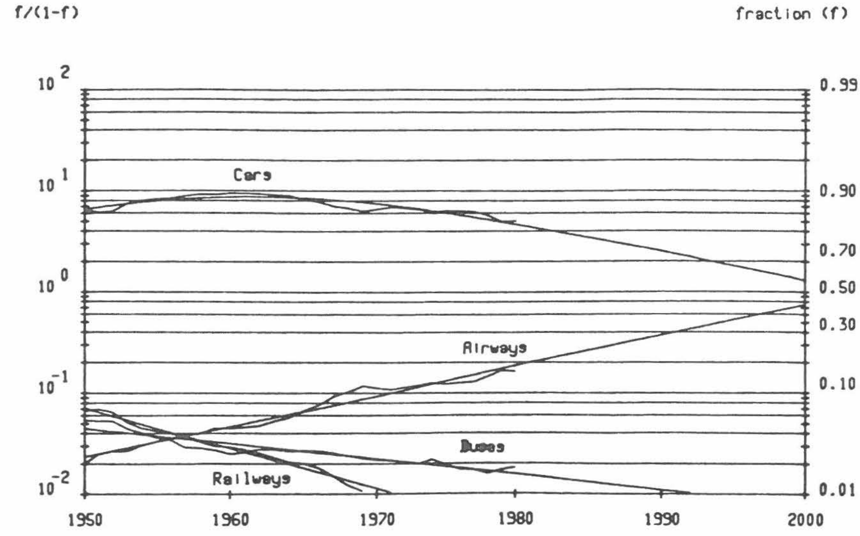

Fig. 25. Intercity passenger traffic substitution.

to the market-substitution analysis in Figure 25, the passenger car is still the main choice for the majority of people in the United States and will remain dominantly so well into the next century. The losers are the railways and buses.

During the last century, animal-drawn vehicles and railways were the two principal modes of long-distance travel, with the exception of passenger ships (ships, however, provided connections between very few cities in the United States). After successfully replacing the horse-drawn carriage, the automobile proceeded to compete with the railways. Figure 25 does not indicate the full drama of this replacement process, because data are available only for the period after 1950. During the 1930s the automobile became the dominant form of road transport and, as Figure 25 shows, only 20 years later became the dominant and almost exclusive form of intercity travel. Buses were latecomers in the United States, and after they had acquired a few percent of the traffic they appeared to be left with the residual of the market. Their share did not decline as rapidly as that of the by-now almost-extinct passenger railroads, but according to Figure 25 they will also be reduced to less than a 1% share by the 1990s. Airplanes are the shining stars in the competition for long-distance travel. During the next two decades this trend will expand the share of airways in intercity travel to almost 40%, reducing the automobiles to little more than 60% and virtually eliminating railways and buses. Thus, automobiles will remain the most important, although declining, form of long-distance travel throughout this century in the United States, whereas aircraft will continue their rapid expansion by increasing the market shares they currently control.

Conclusions

The expansion and evolution of the automobile in the United States emerges as a regular process when seen through the paradigm of technological substitution. At the highest level of abstraction, the automobile itself diffused within the context of a broader substitution process. The replacement of horses and animal-drawn road vehicles by automobiles was completed by 1930 and from then on the expansion of the automobile fleet followed the same secular trend as did the horse-drawn vehicles earlier. Thus, the growth of surfaced mileage and road vehicles, animal drawn and motor powered, appears as the expansion of the same transportation service that evolved over time as it shifted to the horseless carriage. Concurrently, road vehicles themselves competed with other modes of transportation, as was illustrated in the case of intercity passenger transport. The dynamics of this substitution process indicate that the automobile will retain its place of dominance throughout the century, although its position for long-distance traveling is slowly being eroded by the airplane.

Thus, the expansion and use of the automobile emerges as a series of substitution processes from older to newer modes of transportation. The automobile itself, however, developed and evolved through many interlaced technological changes that profoundly improved the production process and the vehicles themselves. These technological changes are also described as substitution processes. The changes in the production methods and the components of the vehicles are much more dynamic and on a faster time scale than are the substitution processes in the overall transportation or energy system that lasted up to 80 years from the introduction date to the point at which one half of the older technology was replaced. Sometimes new automobile components or production methods were introduced almost instantaneously, but more often the process lasted 10 to 30 years before the new technology was embodied in one half of new cars.

The corresponding dissemination of the new automotive technologies throughout the fleets lasted up to a decade longer, spanning from the time of introduction a few automobile generations. For obvious reasons, such changes cannot diffuse within a shorter time interval than the span of a single automobile generation. Thus, these substitution processes can be characterized as dynamic because they occur almost as fast as the model changes. This illustrates the point that the volatile nature of the automotive industry is largely due to rapid changes in production processes and consumer demands—usually less than two decades are available for fundamental changes [3]. We can therefore expect that around the year 2000, almost all cars will have as standard equipment some of the successful innovations introduced during the last ten years, such as electronically controlled (anti-skid) brakes, fuel and ignition systems, suspension, and perhaps also transmissions (giving an indication of optimal shift times for manual versions and full control for automatics), on-board calculators and diagnostic systems, turbocharging and/or four-valve engines, and a higher share of light weight materials, such as composites, plastics, alloys, and ceramics, to name just a few features already available in some automobiles.

During the same period about one half of the fleet could also incorporate advances that are being developed today but not yet perfected, such as a gas turbine or a hybrid-propulsion system with an internal-combustion engine, electric generator, and motor with or without storage, continuously variable transmission, electronic guidance and information system, and perhaps also a fully automated vehicle with autopilot and navigation system. Some of these advances seem very likely today and will certainly be soon available on specialty automobiles; some are already incorporated in experimental cars, utility, and military vehicles (such as the hybrid diesel-electric propulsion, variable-ratio transmission and gas turbine); other are more speculative and may never be introduced.

A general conclusion is that changes in the characteristics of the automobile itself and its production process occur over a period of a few decades, whereas changes in the transportation system of which motor vehicles are but a part require much more time, spanning almost 80 years before one half of the old technologies or infrastructures are replaced. Thus, the automobile will remain the dominant form of personal transportation throughout this century, but concurrent rapid changes will affect both vehicle production and design, implying that there will be losers and winners in the industry, depending on who selects the "right" changes for the evolving markets.

Data Sources

PRIMARY ENERGY CONSUMPTION

All primary energy consumption series were converted from original units into GWyr/yr.

Consumption of Commercial Primary Energy Sources

Energy consumption is given in GWyr/yr. Fuel-wood consumption is from Putnam [18] for the period 1800 to 1849 and from the U.S Department of Commerce [26] for the period 1850 to 1970. Both time series are based on the reconstruction of fuel-wood use in the United States in Reynolds and Pierson [19] and Forest Service Report [9]. Putnam's series was adjusted to the same conversion from physical to energy units as in the U.S. Department of Commerce [26].

Consumption of bituminous, anthracite, and total coal are from Putnam [18] for the period 1800 to 1899, from Shurr and Netschert [20] and the U. S. Department of Commerce [26] for the period 1950 to 1970, from the U. S. Department of Energy [28] for the period 1971 to 1978, and from the U. S. Department of Energy [27] for the period 1979 to 1982.

Crude oil and natural gas consumption is from Putnam [18] for the period 1850 to

1899, from the U. S. Department of Commerce [26] for the period 1900 to 1965, from the U. S. Department of Energy [28] for the period 1966 to 1978, and from the U. S. Department of Energy [27] for the period 1979 to 1982.

Direct (mechanical) water power use is from Putnam [18].

Hydropower is from the U. S. Department of Commerce [26] for the period 1885 to 1965, from the U. S. Department of Energy [28] for the period 1966 to 1978, and from the U. S. Department of Energy [27] for the period 1979 to 1982. Hydroelectricity consumption was calculated as both fossil-energy equivalent and as direct electricity inputs.

Nuclear energy consumption is from the U. S. Department of Energy [28] for the period 1960 to 1978 and from the U.S. Department of Energy [27] for the period 1979 to 1982.

Consumption of All Primary Energy Sources

Consumption of fuel wood, draft-animal feed, direct (mechanical) wind and water power, hydropower, coal, oil, natural gas, and nuclear energy was taken from Fisher [7] for the period 1850 to 1950 in five-year intervals and annually from 1950 to 1970. We have extended the time series of commercial energy sources (coal, oil, natural gas, hydropower, and nuclear energy) from 1970 to 1982 from the consumption series given above (Consumption of Commercial Primary Energy Sources). Hydropower is given as both fossil energy equivalent and as direct electricity inputs. Direct wind and water power is also given as both animal-feed equivalent (by taking average efficiency of draft horses and mules to be 4%; that is, by multiplying wind and water power series by the factor 25) and as direct mechanical-energy inputs.

MERCHANT VESSELS

Tonnage of merchant vessels disaggregated by propulsion system into sailing, steamers, and motor ships and by structural material into wood and metal is from the U. S. Department of Commerce [26] for the period 1789 to 1970. Total tonnage of the fleet is from the U.S. Department of Commerce [23] for the period 1971 to 1980.

NUMBER OF CARS, BUSES, AND TRUCKS

Number of cars, buses, and trucks in use in the United States are represented by the motor-vehicle registrations. Registrations are from Epstein [5] for the period 1895 to 1900, from Ward's Automotive Yearbook [29, 30] for the period 1900 to 1982.

MILEAGE OF ROADS

The mileage of urban, rural, and surfaced roads is from the U. S. Department of Commerce [21, 22, 23, 24, 25, 26]. The mileage of surfaced roads is calculated as the sum of surfaced rural roads and all urban (earlier municipal) streets. Total mileage of all roads is the sum of rural roads and urban streets.

NUMBER OF NON-FARM HORSES (AND MULES) AND CARS

Number of horses and mules disaggregated by type of use are from Fisher [7]. Only non-farm horses and mules (those used for transport) are included in the data set. Number of cars in use are from Ward's Automotive Yearbook [29, 30], as above.

PRODUCTION OF BUGGIES, CARRIAGES, SULKIES, AND CARS

Production of buggies, carriages, and sulkies and factory sales of cars are from the U. S. Department of Commerce [26]. Factory sales of horse-drawn vehicles were not available, but in this case the inventories of new vehicles are probably small so that the difference between sales and production is not very large.

SUBSTITUTION OF OPEN BY CLOSED CAR BODIES

Percentage of closed car production to total passenger car output for the period 1915 to 1926 is from Epstein [5].

FACTORY-INSTALLED EQUIPMENT

Factory-installed equipment trends, including transmissions, disc brakes, air conditioning, radial tires, and power steering, for the whole period 1948 to 1982 are from Ward's Automotive Yearbook [29, 30]. The percentage of three-speed transmissions was reconstructed from the shares of automatic and other manual transmissions. Automatics include semi-automatics for earlier years. Air conditioning includes both manual and automatic. Radial tires were not reported prior to 1973 except for 4,649 radial tire installations on 1972 Eldorados reported by the Cadillac Division of General Motors. Power-steering installations were not reported prior to 1952.

EMISSION CONTROLS

Number of passenger cars with emission controls (whether or not the controls are in operation) are from the U. S. Department of Commerce [22]. Altogether, data were grouped into four broad classes: cars without explicit emission controls, cars with some emission controls (having some or all of the following controls: crankcase, exhaust—hydrocarbon and carbon monoxide emissions—fuel evaporation from tanks and carburetors, and lower nitrogen-oxide emissions controls), and cars with catalysts.

CONSUMPTION OF GASOLINE

Consumption of gasoline, both leaded and unleaded, represents domestic motor-gasoline supply (production plus imports less net increase in primary stocks) is given in barrels per day and is from the U. S. Department of Commerce [22].

INTERCITY PASSENGER TRAFFIC

Volume of domestic intercity passenger traffic disaggregated by private cars, buses, domestic airways, railroads, and inland waterways (ships) is given in passenger-miles per year and is from the U. S. Department of Commerce [22, 23, 24, 25, 26].

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Received 3 August 1985; revised 31 January 1986

Technological Forecasting and Social Change
An International Journal

Volume 29, Number 4, July 1986

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