Escaping Lock-in: the Case of the Electric Vehicle *

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The Lock-in of Technologies

Many established technologies are today being challenged as not meeting the demands of modern society. The problem can be that they do not represent the best known technology, for example the QWERTY keyboard and light water nuclear reactors, or that they produce negative environmental effects, for example pesticides in agriculture and CFCs in refrigerators. What makes these challenges interesting and difficult is that many of these technologies appear to be very well-entrenched in the technological system.

This paper will discuss the possibility of escaping lock-in after a technology has achieved dominance in the market and has been able to enhance its comparative advantages over many decades. The case to be discussed is that of the secular competition between the electric vehicle and the gasoline car. The competition can be separated into 5 phases: 1) the formative years of the automobile industry, 1885-1905, when no technology dominated, 2) the establishment of the gasoline car as dominant 1905-1920, 3) the consolidation of the position of the gasoline car 1920-1973, 4) the questioning of the gasoline car 1973-1998, and perhaps 5) the legislated, forced introduction of large scale production of electric vehicles after 1998.

The first four phases represent the history of a technological lock-in, with the gasoline car becoming more and more firmly entrenched. The fifth phase, if it occurs, will be an example of an escape (or partial escape) from technological lock-in. Concerns about noise and pollution, especially in inner cities, have raised questions about whether such an escape is possible.

In the 1970s, many projections of the penetration of the electric vehicle in the automobile market were made. The predictions were about the proportion of the 1995 automobile market that would be held by the electric vehicle. They ranged from a low of 0.3 percent of the market to a high of 100 percent, with an average of 6.7 percent, which was thought would amount to 3.16 million cars. (Estimates made or commissioned by Exxon and Gulf Oil were 5% and 25% respectively.) Projections made in 1995 for the year 2005 are even more optimistic. The current stock of electric automobiles is much closer to 10,000 than 3 million cars, however. Nonetheless, a French Parliamentary report has stated that the electric car within 30 years may be a serious contender of the gasoline car (Lafitte, 1993, p. 13).

An important part of the explanation for the under-performance of the market relative to projections is that progress in battery technology did not live up to expectations. Current electric vehicle technology uses lead-acid batteries–the same basic technology used 90 years ago. These batteries are heavy and have low storage capacity. Currently, they can store about 40 watt-hours per kilogram (Wh/kg). Gasoline, by contrast, stores 13000 Wh/kg. While these two numbers are far from telling the entire technological story, they do point to the heart of the matter–electric cars do not have the performance features (in particular range and speed) thought necessary by today's consumer. Optimists point out that in spite of this problem the electrical vehicle does represent a reasonable substitute for some urban uses, even though it is not yet a serious contender for extended highway use.

Early this century, when the electric vehicle was one of the three prospective technologies, research on battery technology effected significant improvements in their capacity. In the 1890s battery capacities were in the vicinity of 10 watt-hours per kilogram (Wh/kg). By 1901 this had been improved to 18 Wh/kg and by 1911 was close to 25 Wh/kg. This trajectory of technological improvement was stopped at that point, however, and it has taken close to 80 years to double the capacity since then. A key factor in the halt of progress was the introduction of the starting-lighting ignition into the gasoline car. This technology meant that every gasoline car would use a battery, and it was introduced at a point where sales of gasoline cars were beginning to grow very rapidly. This marked a dramatic change in the nature of demand for batteries, and battery manufacturers changed their R&D strategies accordingly, away from increasing capacity, since this was not nearly so important to the gasoline car, towards large-scale production.

There is some evidence now that the technological trajectory abandoned around 1915 is again being picked up. Nickel-cadmium batteries now have capacities of 65 Wh/kg and zinc-air batteries are up to 120 Wh/kg. Some of this progress is no doubt due to the new market for batteries, namely as a part of portable electronic goods. The growth in this market, and the accompanying demand for lighter, long-lasting batteries which can be quickly re-charged, has created a strong enough demand for improvements that they are in fact taking place. These improvements, combined with advances in more exotic technologies suggest that the battery may cease to be the main bottleneck for the penetration of the electric vehicle into the automobile marketplace.

If we suppose this to be a reasonable conjecture, and that the battery problem will, finally, be solved, should we also suppose that the penetration of the electric vehicle into the automobile market is straightforward? We will argue that the answer must be no. There are many things besides technological considerations that affect whether a technology is capable of entering a market and competing successfully with existing technologies. Technological learning, which has been emphasized in the literature, is not the only source of lock-in. In particular, links with other industries, both up and down-stream, are very important factors that determine the success or failure of a technology.

Path-dependent, path-interdependent and path-independent technical change

The path that leads to the lock-in of a technology often starts with a small historical event or a sequence of such events. The historical event is often an accident, a haphazard marketing gadget or a political problem demanding immediate action. In standard models of path-dependence an initial advantage gained by one technology can create a snowballing effect, based on learning-by-doing, learning-by-using and learning-about-pay-offs, which quickly makes the technology preferred to others.

The path-dependence model has tended to focus on situations in which competing technologies already exist, and where most of the decisive technological development is produced within the industry. We broaden this assumption and acknowledge that the development of a technology is linked to developments elsewhere in the economy and that ruptures that appear to be independent of the technology may affect its development. Thus, the path-dependence of a particular technology is path-interdependent with economic, technical and political decisions that gradually develop in the economy. A technological interdependency may be a reciprocal, constructive interaction between technologies and may prevent developments in other technologies. The economic-technical linkages that exist between industries have been highlighted in Dahmén's development block concept. A development block is a set of interrelated complementarities that connect firms from different industries into a network. The complementarities appear sequentially as inventors and innovators solve economic-technical problems that have blocked the realisation of the economic benefits of earlier innovations. These problems have been labelled bottlenecks, reverse salients or structural tensions. The problem-solving involved in this development process is not confined within industrial boundaries. Hence, the resolution of a problem in an industry can often find a much wider application than was originally imagined, and conversely, relevant innovations may be made by actors only loosely related to the industry.

Path-interdependency consists of three types of positive externalities: knowledge spill-overs; economies of scale through demand for the same inputs; and positive user externalities through technologies using the same infrastructure. As an example, the motives for choosing digital rather than analogue transmission for the pan-European standard of mobile telephony were that it benefited more from advances in electronics (knowledge spill-overs), the decreasing costs of electronic components (economies of scale in the production of common inputs) and the possibilities of using the mobile telephone network for value-added services (positive market externalities through multiple use of the network).

While path dependence, and to a lesser extent path interdependence, have received attention in the literature on technology in recent years, the neo-institutionalists direct our attention to the possibility of path-independent development of institutional structures and industries. In an institutional context ruptures are changes in the institutional structure that are independent of "prior historical circumstance, ideational habit or behavioural regularity." But in the Schumpeterian sense economic development is both path-dependent and path-independent. Inventions, regardless of their impact on society, are new combinations developed from within the economy and built on the existing stock of knowledge. Though we tend to think of the railway, for example, as revolutionary, and therefore path-independent, the path dependent aspect is evident when considering that the transition from horses to steam locomotives lasted for nearly two decades. Even when the first important railway (the Stockton&Darlington) opened in 1825 it had to be constructed so as to accommodate both steam-driven and horse-powered trains. Indeed, for 8 years steam locomotives competed with horses as the power source on this railway.

Technological lock-in has roots both within and outside the industry in which the technology operates. This suggests that the problem of lock-in may be even more serious than is suggested by the competing technologies literature. Thus, to examine the possibility of escaping lock-in, we must look outside the industry, beyond the technologies themselves, to address other factors that may impinge.

Escaping lock-in

Some initiating events may give a technology an early advantage, but it is the processes that emerge in response which produce the vested interests that lock in the technology. Users become unwilling to switch technologies because they have invested time and money in the technology that dominates; producers benefit from production economies of scale and investments in R&D.

To escape lock-in, therefore, it is not enough that the competing technology is better. David suggests that time savings of 20-30 per cent of using the Dvorak keyboards rather than QWERTY are not enough to spur the users and producers to change keyboard. To overcome lock-in it is necessary that some extraordinary events occur. We discuss the possible impact of six factors whose existence or strength could help the automobile market escape (or un-lock) the lock-in of the gasoline car technology.

1. Crisis in the existing technology. This factor has, in some cases, stopped the use of pesticides in agriculture, where conventional technologies have begun to fail to control damaging pests.

2. Regulation. This option is currently being used in the case of CFCs in refrigerators, as concerns about the ozone layer prompt regulations aimed at reducing the damage done to it.

3. Technological break-through producing a (real or imagined) cost break-through. The ascendancy of the gasoline car was propelled by the implementation of Taylorism and factory automation by Henry Ford. Light water nuclear reactor power plants gained momentum through the believed future cost break-through that was to emerge when the industry matured.

4. Changes in taste. The growing awareness of the environmental effects of some products has created mass markets for environmentally adapted products.

5. Niche markets. The growth of emerging technologies is facilitated if there exist a relatively large number of consumers willing to invest in the new technology before low cost production, (internal production economies), and well developed after-sales services, (external consumption externalities) emerge. Early adopters provide the learning and scale economies needed to generate these externalities.

6. Scientific results. Science may provide tools to better measure the external effects of an industry or may enable inventors and entrepreneurs to transform basic science into inventions and innovations. Consequently scientific results can put development pressure on an old technology both by questioning its global efficiency and by providing knowledge about alternative technologies.

The Initial Defeat of the Electric Vehicle

A brief history of the competition among automobile technologies that took place at the turn of the century is useful in drawing attention to factors that may be important in future developments.

The automobile industry began to develop rapidly in the 1890s. Developments in the US market lagged behind the leading nations in Europe until the turn of the century, but the general patterns are similar. From the start of the industry in the US electric, steam and gasoline cars competed for the market. Not until 1896 was more than one car of the same design made in the US, and at the turn of the century the most popular car was the steamer, the "Locomobile".

In a counterfactual history, 1899 could have been a crucial year in a story of how the electric vehicle won the competition for the automobile market.

The market for automobiles in the US was principally divided between electric and steam. In 1899 1575 electric vehicles, 1681 steam cars and 936 gasoline cars were sold. In February of that year the Electric Vehicle Company ordered 200 vehicles and the next month announced that it would introduce electric taxi-cabs on a massive scale. The industrial and technological network under-pinning the electric vehicle industry also seemed to be strong. The producers of electric vehicles had easy access to commercially obtainable components, since they used the same motors, controllers, switches, and batteries as the the streetcars, albeit in smaller size. T.A. Edison promised that the problem of the battery's poor capacity to store energy was about to be solved. The crucial patent for the gasoline car industry–the so-called Selden patent–was purchased by the Electric Vehicle Company. The following year it began a successful litigation against the then leading producers of gasoline automobiles. Furthermore, the electric car seemed more technically advanced than its rivals: that year an electric vehicle, "La Jamais Contente", became the first car to reach 100 km/h.

All this looked promising for the future prospects of the electric vehicle, but the early promise did not last. While the sales of electric vehicles more than doubled in the US from 1899 to 1909, the sales of gasoline cars increased more than 120 times. The Selden patent seemed not to hinder new firms from producing gasoline cars. The trade association ALAM, which was formed by a small group of manufacturers to exploit the patent, was never able to stop infringement, and finally in 1911 they lost a decisive patent infringement case against Henry Ford. By the early years of this century, the gasoline car had surpassed its competitors in the US market. The same development had taken place in France, Great Britain and Germany a few years earlier. However, while in Europe the automobile continued to be produced in small series targeted for the rich, the growth of the production of gasoline cars in the US was synonymous with large scale production, lower prices and the creation of a mass market.

The success of the gasoline car was not triggered by any single small historical event or accident. The case histories of the early automobile industry suggest that the interaction of several economic and technical factors gave the gasoline car a decisive advantage between 1900 and 1905.

Production and Marketing

Gasoline car producers as a group pursued a larger variety of strategies than their competitors in the steam car and electric vehicle industries. Price, however, became a key factor. In 1900 the range of prices for electric vehicles was $1250 to $3500, in contrast with $1000 to $2000 for gasoline cars and $650 to $1500 for steam automobiles. Thereafter the price differences increased, largely because of differences in the strategic choices made by the manufacturers. In particular, low-cost mass production practices were introduced earlier and more vigorously in the gasoline car industry than in the competing car industries. The first mass produced gasoline car, the Oldsmobile Curved Dash, appeared in 1901. It cost only 650 dollars and more than two thousand were sold in 1902.

The choice of mass-production by the gasoline car industry is in sharp contrast with production and marketing decisions made by steam and electric manufacturers. In 1902 the leading manufacturer of steam cars, Locomobile, switched over entirely to the production of gasoline automobiles. This left the Stanley brothers, considered the most inventive producer of steam cars, as the largest firm. They produced only 6-700 cars a year: a small output, but enough to enable the owners to live comfortably. They focussed on high performance cars, and sold all cars on cash payment. Critically, they also refused to move to mass production and were averse to advertising. If there was excess demand for their cars, their rationing criteria were based on the "suitability" of prospective buyers.

During this early period the electric vehicle industry followed a different market structure trajectory, and was moving towards a vertically integrated monopoly–from production to use as electric taxi-cabs. But its architect, the capitalist W.C. Whitney "was backing the wrong horse". Whitney's principal business activity consisted of the streetcar lines in New York owned by his syndicate, the Metropolitan Traction Company. His attempt at vertical integration involved the Metropolitan Traction Company and the Electric Vehicle Company, which he also controlled. This attempt signalled the beginning of the decline of the Electric Vehicle Company, however. The firm explored several different business opportunities before 1907 when it filed for bankruptcy.

A lasting feature of the majority of the other electric vehicle companies was that they were more interested in selling their cars to the right customers at a high price than they were in developing a mass market. In 1914 the average price for the 18 listed electric vehicles was 2950 dollars. The leading manufacturer of electric vehicles, Detroit Electric, with a yearly production stabilized around 1000 vehicles, charged 2850 dollars for a standard four-seat Detroit Electric. It is true that some producers of electric cars imitated the design of stylish gasoline cars, thus lowering the prices. In 1914, for example, the Columbia Electric Vehicle Company sold such a car for 785 dollars. The same year a Ford town car cost 640 dollars, though, and a four-seat roadster only 440 dollars.

Technical Solutions

While all three technologies exhibited early technical problems, gasoline car manufacturers rapidly found solutions while the producers of steam and electric vehicles were unable or unwilling to reduce the faults of their cars.

The deficiencies of the gasoline car were that they: 1) were noisy, a problem that still has not been solved, 2) were difficult to start, 3) consumed a lot of water, 4) had a relatively short range and 5) had low maximum speed. The internal combustion engine car technology developed rapidly during the first decade of the 20th century. Inventions helped to reduce water leakages, increase the range and give higher speeds. This can be seen for example in the speed records. After a steam car set the speed record in 1902, nine gasoline cars consecutively set new speed records. A Stanley steamer in 1906 raised the speed record from 105 to 122 m.p.h., but this was the last steam-held record. It was beaten in 1909 by a gasoline car. After that the internal combustion engined cars dominated for many decades. With the introduction of the starting-lightning-ignition (SLI) in the 1912 Cadillac the gasoline car manufacturers satisfactorily solved the four last problems.

Problems with the steam cars were that: 1) they needed heating up 20 minutes before travel and 2) they consumed immense amounts of water. The first problem was solved after a few years but the problem of water consumption remained until the disappearance of the steam car industry in 1920.

The electric vehicle's major drawbacks were: 1) that they couldn't climb steep hills, 2) they had a short range and 3) had low top speed. All these problems were related to the poor electric power storage capacity of the batteries, and since the batteries were very slow to develop, the problems ultimately remained.

Advances were made in electric vehicle technology, but they were outpaced by technical change in the internal combustion engine. By increasing the storage efficiency of batteries the range of the electric vehicles was increased from 30 kilometres in 1900 to 80-130 kilometres in 1914. In addition, a network of recharging stations was built: Boston had 32 by 1903; and in 1905 New York had 41. While this appears to be the beginning of a strong electric vehicle system on the downstream side, on the upstream side we observe, perhaps, one of the negative effects of path interdependence. The apparent spillovers from electric streetcars to electric automobiles were not as beneficial as one might have expected. Batteries originally designed and constructed for the streetcars were used in the electric cabs produced in 1899-1900. They were not well suited, however, and had a lifetime of only six months. Battery technology did improve at the beginning of the century, but it took ten years to fulfil the expectations of 1900. It was too late though. In 1910 the performance of the batteries was still uncompetitive because of advances that had taken place in the gasoline car technology.

The arrival of the SLI in gasoline cars in 1912 was the concluding disaster for the electric car. There are two reasons. First, it eliminated the need for a crank start, which was one of the most undesirable features of the gasoline car. This removed one of the perceived advantages of the electric vehicle, namely that women could drive them. Second, the SLI concentrated the R&D efforts of battery manufacturers on mass production techniques for relatively low capacity batteries, rather than on increasing storage capacity, which would have been necessary for the competitive position of the electric vehicle.

Interlude 1920-1973

By 1920 the gasoline powered car was clearly dominant. In 1924, 391 electric vehicles were produced in the US, compared with 3,185,490 gasoline cars. The next 50 years saw the consolidation of the position that had evolved in the first two decades of the century. Networks of petrol stations were constructed, and the petroleum refining industry grew, both in size and in technical capability. In addition, a network of mechanics specialized in the repair of gasoline engines emerged. As the sophistication of the automobile has increased, the network of car dealerships, petrol stations and auto mechanics have become intimately linked. The three networks are stable, extensive and strong, and provide an important source of the externalities that make the position of the gasoline car difficult to assail.

The gasoline car also influenced society in a manner unparalleled by other products. Where people lived, how far they could commute, and how they spent their leisure time were all affected by this technology. Gasoline cars were instrumental in promoting the growth of middle class suburban areas. People started to go on holidays in their own cars and many teenagers spent much of their free time "cruising". The car industry became one of the biggest industries in most developed countries, and new manufacturing techniques were tested there ahead of their implementation in other industries. The car was also used for races and as a status symbol. Its impact was felt more or less everywhere in society, and as the society changed in response to the development of the gasoline car, its properties and operating characteristics came to form the definition of what an automobile is.

Renewed Interest in the Electric Vehicle 1973-1990

Eventually, however, the gasoline car was called into question. Congestion in the road networks of large cities, car accidents that yearly claimed thousands of lives and air pollution were three reasons that prompted doubts about the ultimate value of the technology. In addition, the oil crises in 1973-74 made many politicians think about the dependence of the major transport system on the politics of unstable political regimes in the Middle East.

The oil crises in particular promoted the creation of electric vehicle programmes in many advanced capitalist states. One of the most ambitious programmes was launched in France. In the 1970s a network of big French firms, aided by state funding, sought to construct a market for electric vehicles in France. The most active firm was the French electric energy producer EdF. This firm initiated the creation of a group of public organizations that were potential users of electric vehicles. Members of the group were the French Post Office, EdF, Paris airport, SNCF, the local transport organization in Paris RATP, among others. The goal of the work in the group was to evaluate the needs of potential users which would enable the industry to specify its possibilities in relation to the requests and measure the gap between the required performance with the technically possible. It quickly became apparent that the demands were impossible to meet with the then existing battery technology.

In 1976 in the US the Senate authorized the Energy Research and Development Association to launch a federal programme for the development of electric and hybrid vehicles. The programme had a budget of 160 million dollars which was to be used to develop nickel-iron and nickel-zinc batteries on the one hand and vehicles on the other. The aim was to facilitate the building of 2500 electric and hybrid cars between June 1978 and December 1979, and later to increase production to 5000 and to 50000 vehicles yearly. The programme never fulfilled the ambitious plans and it was stopped by the Reagan administration for budgetary reasons in 1982-83.

Japan began a redevelopment programme for electric vehicles in 1965. This was considered a fundamental technical research programme. From 1971 to 1976, 19 million dollars was spent in a large national project headed by MITI. During this period two generations of electric vehicles were developed, and some 300 vehicles of different types were constructed. In 1976 the Japanese Electric Vehicle Council fixed an objective of 200,000 electric vehicles in 1986. This objective was of course not reached.

Similar research projects were carried out in many other countries. Nowhere in the 1970s and the 1980s did the projects result in mass production of electric vehicles, though. The majority of the projects launched in the 1970s built on the assumption that the batteries could be improved rapidly. This did not happen and electric and hybrid vehicles have remained uncompetitive.

Towards Legislated Introduction of Electric Vehicles? 1990-

The first example of a legislation to promote the development of electric vehicles is written by CARB (California Air Resource Board). To overcome health problems in Los Angeles CARB decided in 1990 that by 1998 2 percent of all new cars sold in California must be "zero emission". In the year 2000 all new cars sold must be either "low emission", "ultra low emission" or "zero emission". And by 2003 75 % will be low emission, 15 % ultra low emission and 10 % zero emission cars. Most experts believe that only electric or hybrid vehicles can be made zero emission.

The legislation in California has attracted considerable interest and ten additional states in the US have decided to apply the same regulation. If the legislation is enforced, it implies that a market for 3-400,000 electric vehicles will exist in the US by 2003. In other countries local regulations about air pollution have also given some support to electric vehicles. This has been the case for example in Switzerland.

Ultimately, regulation notwithstanding, the keys to success of a technology lie in demanders and suppliers–the market for it, and the supply of it. Connected with this, of course, is the state of the technology itself. In the next three sections we discuss these aspects of the electric vehicle.

The Market for Electric Vehicles

When the car was a novelty electric cars attracted wealthy women. This is clearly expressed in this advertisement from 1914 for Detroit Electric:

"At the intersection you pause and are suddenly startled at the car slowing to your right–a lady driving an automobile!

"But then you see it's a Detroit Electric and know it is quite within the bounds of reason… You shake your head with a little smile, knowing that in this marvel-filled day of 1914, the Detroit Electric has put safe and happy motoring in the hands of our women folk–as well as our gentlemen drivers."

The next substantial market for electric vehicles developed in Great Britain after the First World War. The driving force behind this market was a regulation stating that delivery vehicles making repeated stops in housing areas must be non-polluting. The rudimentary technology under-pinning this industry has not changed and has attracted very little research. In 1968 there were 45000 such small electric vehicles in service. Currently, fewer than 25000 are used.

Today electric vehicles are mainly owned by large companies and public organizations. Europe's biggest owner of electric vehicles is EdF, the French state electric company, with a fleet of 3-400 electric vehicles out of a total of 60000 vehicles. In Sweden the most important electric vehicle users are local authorities and electric power plant companies and electric current distributors. A substantial number of the electric vehicles in Europe form part of evaluation projects measuring the technical performance of the cars.

Car manufacturers, component suppliers, public utilities and government agencies participate in electric vehicle development projects. In the French town La Rochelle a test of 50 electric Citroën AX and Peugeot 106 began in 1993. Peugeot owns the cars and leases them at a very competitive price to the users–private consumers, public organizations and firms.

The total number of electric vehicles world-wide remains insignificant compared with ownership of gasoline cars. In Sweden there were 367 registered electric vehicles in 1993, in Switzerland there were nearly 2000 and in Germany just over 1800. Switzerland is in many respects the most advanced electric vehicle country in Europe. There, vehicles are to a large extent owned by individuals, and the relative importance of electric vehicles is higher than in any other country. However, sales have contracted from 686 vehicles in 1991 to 220 vehicles in 1992. Germany shows signs of being the next front-runner in electric vehicles sales. While total numbers are still small, from 1989 to 1993 the number of electric automobiles (which excludes things like milk floats, golf carts, forklifts and so on) has increased tenfold. See table 1.

Table 1. Numbers of electric vehicles in selected European countries 1993

Great Britain	20-25000
Switzerland	1500-2000
Sweden	2-300*
France	600-1000
Germany	3-4000

Note: In Sweden 367 electric vehicles were registered in 1993. This sum includes golf carts and minor trucks.

Sources: Renault (1993) and Mobil E nr 6 1993.

Undoubtedly there exists an unsatisfied demand for electric vehicles and other environmentally adapted vehicles. When Volvo presented its hybrid car, the Volvo ECC, a leading spokesperson for the environmental movement wrote in a daily paper that he wanted to order one, but to no avail. General Motors received spontaneous orders after the company presented its electric car, the "Impact". "In some cases, people sent a letter containing a cheque as an initial payment. This occurred even though no production plans existed. These cheques were, of course, returned with thanks."

Many private car owners take the pains to rebuild their gasoline cars into electric cars. And even larger numbers of car owners have switched from gasoline to electric cars despite the fact that the latter are relatively low performance and relatively expensive: in 1993 a two-seat electric car with a range of 60-80 kilometres–for example the Danish Kewet–cost as much as a VW Golf with either a gasoline or a diesel engine. An electric Golf costs twice as much as a gasoline Golf.

The price differential between electric and gasoline cars is expected to drop substantially within a few years though. The French car manufacturers Renault and Peugeot claim that a production of 1000 cars annually reduces the price gap to 30 % (Renault, 1993). Peugeot calculates that the price difference will disappear in 1998 when the firm produces 50000 electric cars per year. This claim is slightly disingenuous, since the prices referred to by Peugeot do not include batteries. In the fall of 1995 Peugeot and Renault launched their first electric vehicles targeted for the private market. The prices are 40-50 per cent higher than the cheapest version of the equivalent gasoline makes. The prices include a reduction of 5000 FRF in state aid and 10000 FRF in aid from EDF the state owned supplier of electric energy (l' Auto Journal, 1995).

Table 2 presents the 1993 prices for a selection of electric cars and vehicles, and prices for their petrol counterparts.

Table 2. Prices and key data for electric vehicles in 1993

Model	Seats	Range (km)	Maximum speed (km/hr)	Price Electric model	Price Gasoline model
Kewet	2	50-100	70	129,000 SEK	
Erad Junior	2	70-80	75	74,000 FRF	48,500 FRF
VW Golf	4	71k	100	288,000 SEK	110,000 SEK
Microcar Lyra	2	65 k	75	146,000 FRF	69,900 FRF
Puli City	2	50-80	65	88,000 SEK	
Elektro Marbella	4	50-100	80	149,000 SEK	60,000 SEK
Renault Clio	4			177,000 FRF	79,500 FRF

Prices include batteries, and are for basic models.

Sources: Industrie et Techniques, novembre 1993, Kewet company information, Elektra nr 3 1993, Mobil E 1993 nr 6 och Elektro 2. Auflage.

Future users of electric vehicles have become much more active in recent years. In Sweden in 1994 the world's largest buyer consortium promised to buy at least 200 electrics if the suppliers can meet a set of specified demands. The consortium consists of two sub-consortia: one for buying electric cars and the other for buying electric vans. Three of the key performance factors are a 90-100 km/h maximum speed, a range in city traffic of 100 kilometres and a battery life of 750 cycles. The specifications set by the consortia also included price limits and a demand for after-sales services. Of course the vehicles must also meet the emission requirements set in the California regulation. These requirements are met by the cars currently used in the La Rochelle test. Members of the consortia come from many different sectors of the economy– local authorities, state agencies, the post office, real estate owners, electric power supply companies, harbour and airport authorities, car rental agencies and freight transport companies, and their motives vary considerably. The public organizations are interested in the environmental benefits; the freight transport firms would like to overcome local regulations limiting the access to city centres; the real estate owners are keen on limiting the disturbance of their transports in the housing areas; the car rental firm's owner believes in variety; other organizations are interested in improving their environmental profile. The consortium plans, as in many of the evaluation projects, to monitor the use of the cars.

In 1995 the consortium found that no offer from fourteen participating organizations, in Europe, USA and Taiwan, fulfilled the technical demands within the price restrictions. The offers from Peugeot and Renault were considered to be the best and these firms were invited to sell ten cars each. These cars will be tested for one year before a new decision will be taken at the end of 1996.

Producers of Electric Vehicles

In the mid 1960s many important car producers started R&D projects on electric vehicles. Common to all projects were that the prototypes were expensive and uncompetitive. The R&D efforts continued in the 1970s and the 1980s but no marketable electrics emerged. In 1990-92 the sales figures for electrics produced by the large (gas) automobile producers were so unimpressive that it was possible to list nearly all buyers on one page in a leaflet.

Electric vehicles are currently being produced by between 10 and 20 firms in Europe (the precise number varies due to the rapid entry and exit of firms; the figure today is probably closer to 20) but the total output is fewer than 2000 electric vehicles annually. In 1993 production was still largely dominated by small producers, for example the Danish Kewet, the French Volta, Ligier and Microcar and the Swiss Puli. A few large gasoline car producers sell electric cars, for example Volkswagen, Peugeot/Citroën and Renault. In addition, gasoline cars are being transformed to electric vehicles by some very small firms.

If the projections made by some of the established car producers are fulfilled, the output will have grown tenfold by 1998. Renault planned in 1993 to produce 4000 electrics in 1995, 3000 are planned to be of the model Clio. Peugeot aims at producing 50,000 electrics in 1998. Even if the projected growth emerges, though, total sales of electric vehicle will remain insignificant relative to the production of gasoline cars. Other manufacturers have developed advanced, potentially competitive prototypes with futuristic designs already exist: Volvo's ECC; GM's Impact; Renault/Matra's Zoom; and Citroën's Citela. In 1995 an electric car rally organized in Sweden and Norway saw some fairly powerful electric cars competing. The top speeds of the winning cars ranged from 125-150 km/hr .

Table 3. Production of electric vehicles and of gasoline cars

	Electric (1993)	Gasoline (1987)
General Motors US		7,765,000
Renault	100-200	1,965,000
Peugeot/Citroën	100-200	1,886,000
Volta	150	
Kewet	200	
Ligier	150	1000
Erad	450	
Microcar	200	

Sources: Renault, 1993 and Industries et Techniques, novembre 1993

Technical Possibilities

The electric vehicle's most significant problems are small scale production, the heating and cooling of the passenger space, and the poor energy storage capacity of the batteries. In combination these make the electrics expensive and relatively unattractive.

Today no electric vehicle industry exists in the same way as there does the gasoline car industry. The components of electric vehicles are mostly supplied from other industries: the electric motors in French electrics are taken from electric trucks; the chassis and bodies are identical either to minicars or standard gasoline cars; and the heating equipment is normally an Ebersprächer heater, the same make that heated the air-cooled Volkswagen Beetle.

In general, unlike in the petrol car industry, production numbers are so small that parts specifically designed and built for electric cars do not exist. Thus there is an inability to take advantage of increasing returns to scale in custom part manufacture because the market is too small. Nonetheless, there have been some advances in electric vehicle technology.

Initially, we observe that some of the problems associated with small-scale production are being addressed, as specialty parts begin to emerge. Regenerative brakes are available, and electronic devices designed for electric vehicle power trains are being offered. These advances are linked to the fact that more and more car models exist as electric prototypes. The emergence of specialty parts due to an increase in the number of units produced, will lower the price of the units. If this price change increases demand, this clearly has features of a virtuous circle.

Batteries remain a problem. The storage capacity of the batteries in the first electric vehicles in 1890-1900 was less than 10 Wh/kg. This figure was nearly doubled within a couple of years but after that the lead-acid battery technology went into a technological stalemate. It took 80 years to double the energy storage of lead-acid batteries after the rapid improvements in the first decade of the 20th century. Alternative technologies existed but did not improve sufficiently to replace lead-acid. As the 1998 CARB regulation is approaching car manufacturers still plan to make do with the lead-acid batteries.

Many 100s of millions of dollars have been spent on R&D that aims at new batteries tailor-made for electric vehicle. Advances in the last three to four years suggest that competing battery technologies may become commercially viable. The US Advanced Battery Consortium (USABC), which comprises the three big American car manufacturers and a number of power generating utilities, states that the storage capacity of batteries need to be ten times higher than today's commercially available batteries. This is not considered to be realistic and consequently USABC has formulated less ambitious goals for the mid-term and long-term horizons. (See table 4.) According to information from organizations that market nickel-cadmium batteries, their batteries can already compete on cost with diesel vehicles; in cooperation with Renault, a test was conducted with light utility transport vehicles that is said to prove the cost competitiveness of electric vehicles. Nickel-cadmium batteries are also increasingly being used in test cars in Europe. Test results from Germany indicate that zinc-air batteries have moved from theoretically interesting to high-performance batteries. Table 4 describes the development of battery technology in the last 100 years.

Table 4. Development of the storage capacity of batteries		
Type	Year	Storage capacity
Lead	1901	18 Wh/kg
Lead	1943	24 Wh/kg
Lead	1950	27 Wh/kg
Lead	1978	33 Wh/kg
Nickel-cadmium	1984	35 Wh/kg (test)
Lead	1990	40 Wh/kg
Nickel-cadmium	1993	55 Wh/kg
Nickel-cadmium	1995	65 Wh/kg (planned)
USABC	mid-term goal	80 Wh/kg
USABC	long-term goal	200 Wh/kg
Zinc-air	1993	120-300 Wh/kg (test)
Zinc-air	theoretical possibility	1070 Wh/kg
Aluminium-oxygen	theoretical possibility	4030 Wh/kg
Gasoline		13000 Wh/kg

With mass production many of the technical problems facing the electric vehicle industry would be solved. Business Week reports that the costs of AC drive motors will go down from 4000 dollars to 500 dollars if production runs are 5-10000. The electronic components will also become much cheaper if demand increases. The electrics may be helped by the increasing use of electrical and electronic components in gasoline cars. These components currently accounts for 25-30 per cent of total production costs (I. Cordi, 1994). The battery problem remains, however, at least in the short run.

Discussion

We stated earlier that six factors can provide ways of escaping lock-in. Let us review these factors in the light of the recent developments in the electrical vehicle industry.

1. Is there a crisis of the existing technology?

There is no real crisis of the existing technology. Gasoline or diesel cars are still regarded as the best means of private transportation by most consumers. The technology performs as people expect it to at predictable costs. In fact it defines our perception of automobiles and private transportation. In addition, a steady rate of technical progress continues to make the gasoline car gradually better. The total amount invested in R&D far surpasses all other technologies. To take a whimsical example, the combined salaries of the top three Formula 1 drivers (30-50 million USD annually) amounts to the total world-wide annual investments, excluding R&D in battery technology, in the electrical vehicle industry.

2. Will regulations have an impact on the car industry?

Regulations are clearly seen as one of the principal forces in the construction of an electric vehicle industry. Local regulations limiting the access to city centres helped to increase the demand for electric vehicles in Switzerland. The decision in California to force the car manufacturers to supply low, ultra low and zero emission vehicles has been instrumental as an incentive for the car industry to develop electric vehicles. But after presenting some dramatic advances of electric vehicles in the early 90s the large producers of gasoline cars have changed tactics. They are currently claiming that it is difficult and wasteful to build electric or hybrid cars and that the gasoline car can be made much more fuel efficient relatively easily. If this claim is true, then it, combined with the ability of established manufacturers to take advantage of existing relationships with parts and service suppliers, makes it very difficult for a new technology to break into the market, no matter how technically competitive it is.

3. Has a technological or cost break-through occurred in the electrical vehicle industry?

The electric vehicle market was, until 1980-85, dominated by the three pillars of: 1) simple delivery vans in Great Britain, 2) golf carts and 3) home made cars. The technology used in these cars was more or less the same as the technology used in 1910-20. The R&D programmes spurred by the second world war and the oil crisis of 1973 effectively changed nothing. The lead-acid battery kept its position, the traction system remained the same, small scale production was omnipresent and recharging of batteries was slow. Despite the absence of a technological break-through producing a major shift in the cost structure of electric vehicles, the fundamental characteristics of the industry have begun to change. New batteries are introduced with better storage capacity and enhanced power ratings. The development of new electric motors and the recapturing of braking energy increase the overall performance of the cars. The prices of electronic components should decrease with increases in scale. Gradually the small manufacturers are increasing the size of their plants and new entrants have plans for large-scale production. New recharging techniques make possible fast recharging–10 to 30 minutes for a 20 % recharge instead of 8 hours for a complete recharge.

The electric car industry has become much more serious about improving the technology in the last ten years, and this has resulted in the improvements mentioned. To date, however, there has not been any important breakthrough in what appears to be the biggest problem, namely increasing the range at high speeds of the electric car, and as a consequence changing it from a means of very localized transportation into a technology that will compete directly with the personal automobile as we know it.

4. Will changes in taste propel the electric vehicle industry into self-sustained growth?

In some ways, this consideration is central. Tastes of consumers have, in general, changed dramatically over the last decade. We refer, of course, to the increased taste for environmental friendliness. This change has been instrumental in precipitating the policy changes described above under point 2. And it has to a great extent been encouraged by the scientific findings discussed below under point 6. Tastes must be dealt with carefully though.

In the first instance, the electric vehicle is seen as an environmentally friendly form of transportation. This is certainly true at the local level: there is no exhaust, and the vehicle is virtually silent. One must be careful, though, since the electricity on which it runs must be generated, and exactly how this is done will determine how friendly the electric automobile really is. Coal-fired generating stations, of course are not particularly friendly, hydro-electric dams, and perhaps nuclear power both are.

The second issue regarding tastes is that consumer tastes, as regards automobile services, have been generated and developed in the era of the gasoline automobile. They have been tailored to and by the gas car. This means that to compete as an automobile, the electric vehicle must provide all the services provided by the gas car, or close to all of them plus something extra. The extra is obviously environmental. The question is, then, how much of what the gasoline car provides are consumers willing to give up in order to gain the environmental benefits (which may turn out to be small, see point 2 above) the electric vehicle provides. Put another way, the taste for the environment referred to above may, and typically does, conflict with other tastes: for example the taste for individual, private control over long distance travel, that is to say, desire for the kind of services that the current automobile provides. It is by no means obvious that the taste for the environment will dominate.

5. Are there sufficiently active niche markets?

The existence of a large set of "early adopters" is very beneficial to any technology trying to create a market share. Early adopters form the foundation of the installed base, and provide the experience needed for early learning by doing and learning by using. One effective way to create a large number of early adopters, is to tailor the technology to a particular niche in the market. If the technology is very valuable to consumers in that niche, then the early adoption problem is solved. But for a niche market to provide the location of the necessary learning and scale to make a new (or resurrected) technology a viable competitor it must be relatively large, and the demanders in it must press the suppliers for economic and technical improvements. The markets for electric milk floats in the U.K. and for golf carts have not provided this stimulus.

To provoke learning by using that will be effective in making the technology attractive to many more potential adopters, learning must take place on a wide front. No matter how demanding are the consumers of golf carts, technological change made to produce the perfect golf cart will not make the electric vehicle desirable to the highway driver. Similarly, if the overwhelming concern of early adopters is the environment, and they are little concerned with other features of the automobiles, they are unlikely to provoke suppliers to improve performance in other ways. If, on the other hand, early adopters present variety in their uses and reasons for adopting, they are likely to present suppliers with many avenues along which improvements will increase the demand for the technology. There is some evidence that the niche of the new early adopters of the electric vehicle may be doing that. This is the case for example in the Swedish consortium referred to above. The motives of the member organizations vary and because of this they will probably use their cars in different ways. Hence they may provide the industry with useful input for the development of the next generation of electrics. Whether this is a large enough group of early adopters to provide enough stimulus to do that quickly remains to be seen.

6. Can scientific results help the electric vehicle industry?

In fact the electric vehicle industry is thriving on scientific results that question the global efficiency of the competing technologies. The gasoline car produces emissions that pollute locally and globally, and there are fears, based on research on the effects of this pollution, that irreparable damage is being done to the environment by the gasoline car, among other technologies. Without scientists measuring the pollution and estimating the future effects of it the electric vehicle would be far less interesting. On the other hand science has not, yet, provided an easy way out of the lock-in of the automobile industry. It is true that scientific measures show that one kilogram of an aluminium battery has the potential to store as much energy as a third of a kilogram of gasoline. This would represent a dramatic change in the economics of electric and gasoline cars. The problem of how to construct the battery remains however.

Conclusion

It seems clear that a rapid escape from lock-in, a move from gasoline to the electric vehicle, is not going to happen. In the present climate, the electric vehicle has to compete with the gas vehicle under conditions established by users’ 90-year relationship with the gas car, and there are technical problems that make the electric vehicle inferior. Recent developments make the battery problem seem less intractable, but an actual viable solution is not just around the corner. But secondly, even if the battery problem is solved, there are others, in particular stemming from the interdependence of the electric car industry with other industries. Some of these problems will be solved automatically (for example the cost of parts will fall as the scale of production increases) but others, the provision of after-sale services for example, are more difficult to solve spontaneously.

Bearing in mind that forecasts of this nature, as the experience from the seventies shows, are extremely speculative, a gradual shift, with the electric vehicle slowly taking a larger part of the market seems possible. Legislation may create niche markets, and if there is variety in the niches, which is likely to be the case if legislation is aggressive enough, technical advances will be promoted. This has two effects. The first is simply that costs will fall, especially when accompanied by the benefits from scale in production. The second is more subtle. As the technology advances in a variety of directions, more and more consumers will be willing to forego what appeared to be "necessary" features of the automobile (as defined by the gasoline car) in order to have access to the new features of the electric car. This type of effect will be crucial in creating the snowball that gives the electric car a chance to establish itself as a significant part of the automobile market.

References

Basalla, George, 1988. *The Evolution of Technology*, Cambridge University Press, Cambridge.

Business Week, 1994, May 30, Electric Cars, Will they work and who will buy them?

Callon, M., 1986, The Sociology of an Actor-Network: The Case of the Electric Vehicle, in Callon, M., Law, J. and Rip, A., ed., *Mapping the Dynamics of Science and Technology*, Macmillan, London

Cordi, I., 1994, What is Today's Status of Electric Cars? A Brief International Look, Report written for Association of Swedish Automobile Manufacturers and Wholesalers and the Swedish Petroleum Institute, Danderyd

Cornu, J.P., 1993, Le Nickel-Cadmium: un atout majeur pour la cité, *Revue générale de l'électricité*, Nummer 10

Cowan, R., 1990, Nuclear Power Reactors: A Study in Technological Lock-in, *Journal of Economic History*, Vol 50

Cowan, R. and Gunby, P., 1996, Sprayed to Death: Pest Control Strategies and Technological Lock-in, *Economic Journal*, forthcoming.

Dabels, J., 1992, *Environmental Requirements and the Impact Prototype Vehicle*, OECD

Dahmén, E., 1950, *Svensk industriell företagarverksamhet, Kausalanalys av den industriella utvecklingen 1919-39*, 2 vols., IUI, Stockholm. English edition of Vol. 1, 1970, *Entrepreneurial Activity and the Development of Swedish Industry 1919-39*, Irwin, Homewood, Ill.

Dahmén, E., 1989, 'Development Blocks' in Industrial Economics, in B. Carlsson, ed., *Industrial Dynamics*, Kluwer, Boston

Dahmén, E., 1993, Research on Railways in a Historical Perspective, in Whitelegg, J., Hultén, S. and Flink, T., ed., *High Speed Trains, Fast Tracks to the Future*, Leading Edge, Worcester

David, P., 1985, Clio and the Economics of QWERTY, *American Economic Review*, Vol. 75:2

Dosi, G., 1982, Technological Paradigms and Technological Trajectories, Research Policy, Volume 11 pp. 147-162

Elektra Magazine, Number 1-4, 1993

Elektro 2. Auflage, undated brochure

Flink, J.J., 1970, *America Adopts the Automobile: 1895-1910*, Cambridge Mass.

Fogelberg, H., 1993, Renässans för elbilen?, TFB-rapport 1993:26, Swedish Transport Research Board, Stockholm

Granovetter, M.S., 1973, The Strength of Weak Ties, *American Journal of Sociology*, Vol. 78, No. 6, 1360-1380

Guibert, A., 1993, Accumulateurs au plomb et véhicules électrique, *Revue générale de l'électricité*, Nummer 10

Harbauer, W., 1993, Developing Drive Systems for the evolving Electric Vehicle Market, *Siemens Review, R&D Special*, Spring.

Hård, M and Knie, A., 1993, *The Ruler of the Game: the Defining Power of the Standard Automobile*, WZB, Berlin

Hartman, L., Cairns, J. and Hietbrink, H., 1978. (Electro Chemistry Department, GM Research Laboratories), Electric vehicles challenge battery technology, 5th Conference on energy, Washington D.C., 27 February.

Hultén, S. and Söderlund, M., 1994, Elbilar - tekniska möjligheter och marknadsspridning (in Swedish), EFI Research Paper

Industries et Techniques, numero 743, novembre 1993

Jamison, A., 1974, *The Steam-Powered Automobile. An Answer to Air Pollution*, Indiana University Press, London

Katz M.L. & Shapiro C., 1985, Network Externalities, Competition, and Compatibility, *American Economic Review*, Vol. 75, No. 3, 424-440

Kirsch, D. A., 1994, Flexibility and Stabilization of Technological Systems: The Case of the Second Battle of the Automobile Engine, Proceedings EUNETIC conference on Evolutionary Economics of Technological Change

Laffitte, P., 1993, Rapport sur l'interet du véhicule électrique au regard de la protection de l'environment, Assemblée nationale, No 680

Liebowitz, S. J. and Margolis, S.E., 1990, The Fable of the Keys, *Journal of Law and Economics*, Vol. XXXIII, 1-25

Midgley D.F., Morrison P.D. & Roberts J.H., 1992, The Effect of Network Structure in Industrial Diffusion Processes, *Research Policy*, Vol. 21, 533-552

Mobil E, Nummer 1, 1993 (French edition)

Mobil E, Nummer 6, 1993 (German edition)

The NiCd Electric Vehicle Information Center, not dated, Information leaflet, Brentwood, Essex

Nicholon, A., 1984, *Le véhicule électrique. Mythe ou réalité?*, Éditions de la maison des sciences de l'homme, Paris

Östlund, S. 1994, The Limits and Possibilities in Designing the Environmentally Sustainable Firm, Business Strategy and the Environment, Vol. 3 Part 2

Papanek, V., 1984, *Design for the Real World, Human Ecology and Social Change*, Thames and Hudson, London

Realités & perspectives du vehicle electrique, Journée CFE La Rochelle 16 novembre 1993

Revue générale de l'électricité, 1993, Number 10

Roberts, P., 1963, *Veteran and Vintage Cars*, Paul Hamlyn, London

Rogers E.M., 1990, The ''Critical Mass'' in the Diffusion of Interactive Technologies, paper presented at the 8th International ITS-conference Venice

Rolt, L.T.C., 1960, 1988, *George and Robert Stephenson. The Railway Revolution*, Penguin Books, Harmondsworth, Middlesex

Rosenberg, N. and Vincenti, W.G., 1978, The Britannia Bridge. The Generation and Diffusion of Technological Knowledge, The MIT Press, Cambridge Mass.

SAFT, Véhicule électrique: l'âge adulte, undated brochure.

Schallenberg, Richard H., 1982. *Bottled energy: electrical engineering and the evolution of chemical energy storage*, Philadelphia : American Philosophical Society.

Scott-Moncrieff, D., 1963, *Veteran and Edwardian Motor Cars*, B.T. Batsford, London

Sigvardsson, O., 1993, Inga raka rör i striden om elbilarna (in Swedish), Dagens Nyheter 19/12

The NiCd Electric Vehicle Information Center, Nickel-Cadmium Batteries, undated brochure, Brentwood, Essex

Tool, M. R., 1993, Institutional Adjustment and Instrumental Value: With Observations on "Reform" in Eastern Europe, Proceedings EAEPE 1993 Conference, Barcelona, Spain, 28-30 October