‘TECHNOLOGICAL LOCK-IN’ AND THE POWER SOURCE FOR THE MOTOR CAR*

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* I am grateful to Masahiro Hayafuji for use of his computerised data base from Doyle (1963). I also have appreciated the helpful comments on an earlier draft of Joel Mokyr and J M Laux, as well as those of participants in the Business History Association conference in Ft. Lauderdale, Florida 1995, the Newcomen Society conference at Imperial College, London, November 1995, and members of the economic history seminars at the University of Leicester and the Free University of Brussels. None are responsible for remaining errors and omissions.

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As the nineteenth century ended, three principal types of engine competed to power the early motor car. Had some minor condition been different around the beginning of the twentieth century, perhaps therefore today's road vehicles would not be powered overwhelmingly by internal combustion engines. That at least is an implication of the "lock-in" hypothesis. However the choice of product technology depended not on chance but at first on differential relative endowments of natural resources and capital. Abundant oil deposits and water encouraged the American development of lower first cost steam engines, which used more fuel and less capital. Electricity also was cheaper in the United States than in Europe, outside Germany. Since European endowments were not as auspicious for steamers or electrics at the turn of the century, European entrepreneurs focused on the internal combustion engine. Judged by the rapid development 1895-1900, they chose the most progressive technological trajectory. By 1904, US motor firms were adopting European product technology and abandoning steam. By the end of the First World War they had also given up electricity.

Might we now be driving cars powered by steam or electricity but for a historical accident at the beginning of the twentieth century? During the formative years of the motor industry a little luck, or marketing skill, enabling steam or perhaps electric vehicles to enter mass production earlier than the internal combustion engine, would have secured a permanent lead for these technologies, some believe (Davison 1953 p3; McLaughlin 1954; Rae 1959 p41; Mokyr 1990 p131). More generally, a group of writers maintain 'technological lock-in' applies not only to the choice of power source for the car but also to many other innovations (Arthur, Ermoliev and Kaniovski 1988; Arthur 1989; David 1985, 1993; Liebowitz and Margolis 1990). For one case, the evidence leads to a quite different conclusion. Chance is more likely to be assigned a major role in technological evolution in the absence of a plausible theory. Yet there is a such a theory that accounts for the early development of the motor car's power source. We need not place much emphasis on unique historical events in this instance. The following section presents the central principles of the theory. The second section describes the competitive selection process for the three technological trajectories; steam, internal combustion and electricity. The third section explains the national comparative advantages underlying the pattern of innovation.

The Development of Technology

Comparing technological development in different economies indicates the key elements of the theory. The first is that there must be an effective demand for the new product technology. Good French roads and absence of legislative prohibitions encouraged the strongest demand for cars in the world around 1900. Poor US roads outside cities and restrictive laws in Britain at first held back motor car development in these countries. To that extent technology was socially determined.

Second, the technological groundwork must have been laid. Steam was a tried and tested nineteenth century technology. Developments in metallurgy and in rubber tyres by the end of that century permitted more successful, lighter, steam road vehicles than those of the 1830s. Electric traction was new but, drawing power from overhead cables, was already improving urban public transport in the 1890s. Equally novel was the internal combustion engine, evolved from the stationary gas light engine. Each of these three technologies were possible motor car power sources at the beginning of the nineteenth century.

The third principle is that some technologies have more progressive 'trajectories' than others at given stages of development, and these trajectories are largely determined by physical laws (Dosi 1984). However merely because steam was the oldest trajectory, we would be rash to assume it lacked potential- as the invention of the turbine and the flash boiler demonstrated. Conversely a new trajectory may hit an apparently immovable barrier, such as light and cheap electricity storage, which diverts it from directions that initially looked promising.

Fourth, innovators will tend to economise on relatively scarce materials and use more profligately abundant inputs. North America was well endowed with water, and especially oil, relative to Europe but skilled labour was harder to find (David 1975; Wright 1990). Early motor car development mirrored the availability of these resources. That was why steam, and to some extent electric, cars were more common in the US than in Britain or France at the beginning of the century.

Fifth, engineers and other applied scientists work with routines for problem-solving that are cultural distinctive (Vincenti 1990). These give rise to equally specific patterns of technical change (David 1975). But development is not necessarily 'locked-in,' irrevocably committed to one technical direction; if a competing technology demonstrates its superiority, market pressures can precipitate a switch between trajectories. Between 1900 and 1904, the US effectively abandoned steam cars, well before large scale production conferred scale economy advantages on the internal combustion engined car. Electric cars survived longer in US urban niche markets, but they too had largely disappeared by the end of the First World War.

Three Technological Trajectories

American internal combustion engined car production in 1900 was smaller than either steam or electrical car output (Table 1). Moreover steam cars were considerably cheaper than the other two types, according to the average value figures. In Britain the composition of sales must have been very different since an estimate of 1902 was that at least 9 in 10 of cars on British roads were propelled by internal combustion engines (Jenkins 1902 p310). France made more cars in total than the US, around 5800, most of them internal combustion engined, as Table 2 implies (Laux 1976 p79). The table shows the number of makers, classified by choice of power source, entering car production in the four principal industrial countries between 1895 and 1904. Patterns differ markedly and significantly between nations. French flirtation with alcohol fuel and British experimentation with coal gas suggests such differences may be related to resource endowments. By 1904 the Americans had largely abandoned steam; 178 US manufacturers produced 21692 cars, all but 300 internal combustion engined. France then made rather fewer cars in total, about 16900, but many more in relation to national population.

Table 1 US Car Output by Power Source in 1900

	steam powered	electrical	internal combustion	total
no. of cars	1681	1575	936	4192
av. value	$682	$1822	$938	

Source: United States (1902) Twelfth Census 1900, Manufactures , Washington DC pt. iv p255.

Table 2 Car Makers' Choice of Power Source 1895-1904

	Int. Comb.	Steam	Electric	Total
US	426	133	71	630
UK	294	20	20	334
France	292	9	21	322
Germany	80	2	12	94
Total	1092	164	124	1380

Source: Hayafuji 1994

Steam

Early steam carriage experiments used coal fuel and the vehicles were heavy and difficult to manoeuvre. Hancock's steam omnibus, that carried passengers for a few months between the City and Paddington in 1833 is illustrative. Later traction engines were more reliable but their great weight made them more suitable as mobile power sources than as means of personal transport. Perhaps 8000 traction engined threshers trundled over British roads during the 1890s (Barker 1987 p8).

What transformed the possibilities of personal transport powered by steam was the introduction of liquid fuel. Pictures of the American light steamers at the turn of the century, such as the Stanley show a design metamorphosis only possible because petrol (or paraffin) was employed to heat the water that drove the car. So it is quite incorrect to distinguish between steam and petrol powered cars. The most successful steamers were powered by the same fuel as internal combustion engined cars. Consequently they were less thermally efficient. Instead of driving the engine directly by explosion, as in the internal combustion engine, the petrol was only an indirect power source and therefore was burned more extravagantly. In the US, where petrol was abundant, this made a good deal of sense because the steam engine was simpler than the internal combustion power unit; it did not require a gear box for instance. Steam cars could therefore be made more cheaply than any other type to compensate for their higher running costs, which in any case were lower in the US than in Europe. Among those running costs for early steamers were the very heavy consumption of water, unacceptable in Europe (Worby Beaumont 1900 p458). This was not an intrinsic drawback of the steamer, for they could be fitted with condensers, as was the later White car. But it added to the first cost of the vehicle.

Lady Bracknell's principle ("To lose one parent...may be regarded as a misfortune; to lose both looks like carelessness") may be generalised to appraise the unique importance of steam in the US by contrast with Europe. If engineering in each market developed broadly independently and if steam had a probability p of ultimately dominating the market, then the chances of not actually taking over any one of the four markets is p^4. If p were 50 per cent then the probability of the observed defeat is 6.25 per cent- rather low. The US economy, that most enthusiastically embraced mass production of internal combustion engine powered cars, also at first showed the strongest interest in steam vehicles. French individualism, unguided by visible hands of established corporations, earliest made the best long term technological choices, according to Table 2.

Steam entrants to the US industry increased radically, from 8 in 1898 to 34 in 1901 - the heyday of the flash boiler and liquid fuel- and then fell over the next three years to 6 in 1904 (Hayafuji 1994). Britain shows a similar but less dramatic pattern with a two year lag, peaking with 11 entrants in 1902 and 1903. France's even lower profile more closely matches the US in timing (a peak of 5 in 1901 and zero for 1902-4) whereas Germany, with a total of two entrants, remained virtually terra incognito for the steam car maker.

The fall of internal combustion and the rise of steam in 1897-8 is apparent from the proportions of entrants by power source. In 1897 40 per cent of US new entrants adopted steam[1] (Hayafuji 1994). Though the 'lock-in' doctrine requires reference to particular historical events for it to have any substance, another necessary condition is some form of positive feedback which might indicate that if (because, say, of the diffusion of the flash boiler and liquid fuel), steam was increasing its share, it should go on doing so. Yet it did not. Equally difficult for the lock-in doctrine is that electricity was not 'locked out' simultaneously.

Internal Combustion Engines

Internal combustion entrants were always more abundant in the US than steam, but in 1897 only just so. With the exception of the unusual year 1914 (125 new models), US internal combustion entrants reach a peak (of 107) in 1908 (Hayafuji 1994). Also in 1908 Ford moved to large batch production with the Model T, giving some credibility to lock-in for the internal combustion engine. Less committed to steam, UK internal combustion entrants peaked earlier than the US in 1901 (92), but with another local maximum (60) in 1913. French and German internal combustion entrants peak in the same year as Britain, consistent with their industries being subject to similar technological forces.

Internal combustion powered motor car technical development is particularly amenable to study because the series of public trials, initiated by the French, created performance data for the public domain. There can be no question of large corporations determining the pattern of technological evolution by suppressing information for this product. Each trial indicates a different point on the technological trajectory of the French, and to a lesser extent European, internal combustion engine as a power source for the motor car. The rise in average, maximum and minimum speeds over the years 1895 to 1900 is a fair indication of the rapid improvement in the effective power output, and reliability, of the internal combustion engine (Table 3). Each year's observation may not be exactly comparable with the next, because the distance travelled differs. But maximum and average speed rise inexorably. The UK TT of 1905, run over a different type of road system, brought down average and maximum speed, but the minimum speed of finishing cars was the highest in the sample. Two years before, the first powered flight by Flyer I, or the Kitty Hawk, in the US, demonstrated how the power to weight ratio of the internal combustion engine had been raised[2].

Table 3 Technological Trajectory of the Internal Combustion Engine 1895-1905 from French Motor Car Races

	av. speed	max speed	no of finishers	dist. miles	min speed
June 1895	11.8*	15.25	9++	744	9.0
Sept 1896	14.3	15.9	9	1077	12.8
July 1897	20.4+	23.1	15x	106	16.5
July 1898	21.8	27.0	17	895	15.2
May 1899	25.4	29.9	12	351	22.1
July 1899	26.5	31.9	11	1440	18.8
March 1900	30.8	37.0	16**	125	17.3
TT(UK) 1905	28.4	33.9	18xx	208	23.0

Source: calculated from W Worby Beaumont Motor Vehicles and Motors: Their Design, Construction and Working by Steam, Oil and Electricity, Constable, London 2 vols 1900,1906 vol 2 p685, vol 1 p388 vol 1 pp380-1.

Notes: * Bollee steamer 8.23 ++ 8 int. comb.
+ DeDion Bouton Steamer 24.6 x 14 int comb
** excl Werner bicycle 21.4
xx 54 started including 2 steamers

The French data also demonstrate the odd position of steam power. Only two steam vehicles completed their courses, the first as the slowest in 1895, the second as the fastest in 1897. Despite this last success, the decision of the technological selection process was conveyed early in the sequence of trials by so few steamers finishing.

Electricity

The earlier diffusion of the electric tram, did not prevent the electric road vehicle carrying its own power source being a latecomer to the competition. Experiments were made in 1887 but not until a decade later was a really practical electrical road vehicle entered for a race in France. Such vehicles were clean and quiet but the batteries needed recharging every 16 miles, they were extremely heavy, they were vulnerable to the inevitable vibrations of road vehicles and their recharging was very time consuming. Engineers calculated that the final efficiency of electric vehicles was halfway between steam and internal combustion cars and a variety of innovations shortly after the turn of the century suggested a bright future for the electric (Jenkins 1902 p811). Still, batteries needed replacing at least every other year, maintenance costs and tyre wear were high, and the vehicles were restricted to cities where recharging was possible.

The first US electrical vehicle (a Morrison) dates from 1891-2. H G Morris and P G Salom built an electric car in Philadelphia in 1894 that performed well in the Chicago Times-Herald race of 1895. The electric attained average speeds of 18.72 and 36.72 km/hr, whereas the Duryea averaged just under 8 km per hour and the Benz engined de la Vergne achieved 11.23 and 18.36 km per hour (Hasluck 1902 p766). At the Mechanics Fair, Boston in 1898, of the four cars exhibited, two were electric and one was steam powered.

Because electric cars were poor hill climbers, their manufacturers were based in towns on plains, such as Cleveland and Chicago. Electric cars also sold well in New York from 1905 until 1914 or later. Laux (1976 p94) explains this demand by the greater number of women drivers in New York than anywhere else and by the poor state of the roads outside the city, on which few cars could hope to drive even if they had the range. US entry into electric cars, such as by Rausch and Lang in 1905, thus continued until the First World War. Electric entrant series confirm the niche market in the US until 1917. This contrasted strongly with

Europe, as did the precocious boom in 1899 and 1901. US entry peaked in 1901 with 13. Whereas there was apparently no British or French entry between 1906 and 1914, US entrants averaged four a year (Hayafuji 1994).

In the late 1890s, speed or distance records could be obtained by special vehicles with little implication for commercial viability. Camille Jenatzy's La Jamais Contente, a streamlined development of a Paris electric taxicab, held the world land speed record for a flying kilometre in 1898. But it was no practical guide for vehicle design (Worby Beaumont 1900 p397). Similarly, electric vehicles had travelled 180-190 miles on a single charge without employing commercially practical arrangements (Worby Beaumont 1906 p538). By 1900, Trials results for standing and flying miles showed steam and electricity could not match the best internal combustion engined cars, even in these performance characteristics, though in some cases they came very close.

Table 4 Comparative UK costs of different power sources for personal transport in pence per day 1900

	2 seater			4 seater		
miles p.a.	Horse	£200 i.c. Voiturette	Electric	Horse	i.c. solid tyres	pneu. tyres
3000	5.98	6.5	n.a.	n.a.	n.a.	n.a.
6000	7.55	3.95	7.1x	12.06	5.71	7.39

x 5000 miles p.a., excl depreciation

Notes: Driver not included. Interest at 4%. Horse depreciation at 20%. Solid tyres with life of 15000 miles. Internal combustion engine depreciation at 15%.
Source: Worby Beaumont 1900 ch 36

The message conveyed by trials was supported by cost data (Table 4). Electrics were much more costly as well as less reliable. One higher cost was that US street tramways required very large tyres on electric taxis. Servicing electrics needed expensive equipment, as the 1898 depot at 1684 Broadway, New York showed. There were hydraulic lifts for raising cabs for battery removal and claw arms for taking out the heavy batteries.

Across the Atlantic, electric vehicles met with less commercial success. The London Electric Cab Co began operating also in 1898 and ceased trading the following year. In 1903 the City and Suburban Electric Carriage Co tried to re-introduce a service. This business, like the US equivalent, operated a central garage and charging station (at Westminster).

The Sources of Comparative Advantage

Why did each of the four countries considered here adopt different mixes of power sources and rates of industry entry? German lethargy in developing the car they invented has surprised many observers (Laux 1976 p77). Table 2 shows the German environment was not particularly favourable to any kind of motor cars. The authorities considered Germany's well developed railway system supplied adequate transport (Beasley 1988). But there was little overt discrimination against steam to account for the paucity of steam cars in Germany. Each Lander possessed its own rules, and from the 1890s each implemented special laws and ordinances. The 1902 Bavarian police regulations for instance did not discriminate, apart from the requirement that cars with a fully loaded weight of more than 4 metric tons needed special permission from local authorities before being put on the road[3]. Within the low total of car models innovated, disproportionate German interest in electrical vehicles may be traced to the strong development of electricity supply infrastructure, and also of electrical engineering firms.

British concern with public safety during the 1860s and 1870s so restricted the use of motor vehicles on the road that the incentive to invent in Britain was markedly reduced until the repeal of the 'Red Flag Act' in 1896. Although when agitation against the 1878 Highways and Locomotives Act arose, the legislation was quickly repealed, the Act constrained innovation while in force. An entrepreneur is not inclined to consider supplying a new market tightly restricted by law unless that market has been clearly identified. By that time, entrepreneurs in other countries will have achieved a lead[4]. Average speeds of the French trials suggest the continuing inhibiting effects of legislation on British development. The 1896 Locomotive on the Highway Act specified a 14 mph maximum speed, which could be reduced by local authorities.

Comparing electric vehicle innovation in Britain and Germany, Germany's relatively strong (but absolutely weaker) performance (Table 2) may be traced to Britain's inability to supply cheap electric power after 1890 (Hughes 1983 p257). By 1905 London used only one fifth of the electric power per head of Berlin (Hughes 1983 p252). Five years later operating costs per kwh were 19 per cent lower in Berlin. Chicago's operating costs were then 46 per cent of London's. Local authority obstructiveness appears to underlie Britain's shortcomings in electricity supply.

State policy may explain differences within Europe but understanding why United States and European motor vehicle development trajectories differed requires reference to the long debate on British and American technology in the nineteenth century. Scarcity of labour, the interest in mechanisation, the intensive use of natural resources in the United States, and localised learning, were key elements (Habbakuk 1962, David 1975, Wright 1990, Nelson and Wright 1992). America's dalliance with the steam car exemplifies her resource-intensive choices. US gasoline prices were around 11-14 cents a gallon between 1899 and 1910 (Williamson et al 1963 p172) whereas in England, Germany and France they were perhaps double[5]. By 1913, when US prices reached 17 cents, motorists in London and Paris were paying 50 (Yergin 1991 p112). Karslake and Pomeroy (1956) consider the use of coke fuel held back European steamers in the 1890s, but coke was cheaper in Europe as well as more available than 'motor spirit', though far less convenient.

Abundant American endowments of oil at the turn of the century, explain why Europeans regarded European internal combustion cars as superior to American products (Oliver 1966). In Britain the only US motor products that were competitive in 1902 were steamers (Table 5). Moreover the pattern of US internal combustion engined car use confirms a European comparative advantage. European cars accounted for half the internal combustion engined cars in the 1902 US Autoclub Trial (Table 6).

Against higher fuel costs had to be weighed the US steamer's mechanical simplicity. When coupled with American production and design this meant that the Locomobile's initial low cost in Europe placed the steamer in a price class of its own. Hence it is not surprising that in trials the Locomobile did not always score highly. In the Glasgow Trials of 1901 over 535 miles the Locomobile was third from bottom in the marks awarded (Hasluck 1902 p779). The heavy fuel consumption of the Locomobile and the marked improvement of the White steamer was amply demonstrated in the US 100 miles non-stop USA Auto Club trial of May 1902 (Hasluck 1902 p780). For that US sample however steamers as a whole averaged 8.4 miles per gallon of fuel and internal combustion engined cars fuel consumption was almost half that at 16.1 mpg (Table 6). If foreign makes are eliminated, on the grounds they were designed for a less egalitarian market, then the fuel economy discrepancy is widened.

Even more suitable for examining the competitive selection of efficient product types is the (UK) Auto Club Reliability Trials over 650 miles in 1902 (Table 5). This event classified competitors cars by price bracket (Hasluck 1902 p792). In the £150-200 range Locomobiles were the only vehicles to complete the course. In the next class there were four European internal combustion engined cars against four US steamers - US internal combustion cars are notable for their absence. Grouping the price classes together, the average fuel consumption of the six steamers was 18 mpg and for the four internal combustion engined cars, 35.5mpg (Table 6). On average steamers also performed less well on a broad range of criteria within the price class. Average total marks scored by steamers was 2696, 100 marks or 3.5 per cent less than the internal combustion average.

The French Gardner Serpollet four cylinder steamers were in a much higher price class, the £500-600 range. Their consumption was 10.3mpg and 8.4 mpg compared with their internal combustion engined competitors, Peugeot with 25.2mpg, and Brush with 24.2mpg.

Under some conditions the greater fuel consumption of American steamers would offset their lower American first costs. Running cost differentials depended on the annual mileage, the life of the car, fuel consumption per mile, and fuel price; certain expenses such as tyres were common to all motor vehicles[6]. Survival of steam or internal combustion then turned on the market assessment of the performance characteristics of the two power sources, having controlled for their generalised costs. The running costs formula suggests that as reliability, and therefore annual mileage and car life, increased, fuel prices and fuel consumption assume greater importance in full car costs. For low lifetime mileages, first costs dominated, but as mileages increased, the balance tipped against the fuel-intensive steamer. In Europe higher fuel prices militated against steamers earlier.

Despite a predilection for resource-intensive technology, US engineers did not put all their eggs in one basket. Nor were they irrevocably committed to any particular technology. Once the superiority of the internal combustion engine had emerged, they were willing and able to learn from other engineering traditions that had opted for more progressive trajectories. Early US development internal combustion engine and steam cars concentrated on light, low cost 6-7 BHP 2 seater general runabouts (Worby Beaumont 1906 p268). The heavier, more successful, internal combustion Pierce Arrow however was copied from Europe.

American engineers were broadly aware of developments in Europe both from journals and from imports. But that did not confer the ability at first to match them technically. European car producers could take advantage of local steel and component makers encouraged already to master this technology by demands from other car firms. As late as 1905, Henry Ford was 'reverse engineering' a component of a crashed French car to understand the secret of its strength and lightness. Having discovered the material was French vanadium steel, he was obliged to import an Englishman who knew how to make the steel commercially and to finance considerable experimentation (Ford 1923 p66). European motor car special steels had taken considerable strides by this date; crankshaft nickel steel attained a tensile strength of 60 tons per square inch[7].

Conclusion

With only one throw of the historical dice, a technological outcome might be due to a unique historical event, if coupled with some form of network externality or scale economy. However, where the choice of power source for the motor car was concerned, similar outcomes were obtained virtually independently of each other in different environments. The United States' own technology, at first followed a different course from Europe's, but the eventual similar outcome suggests the internal combustion engine filled a distinctive 'ecological niche'; just as the Tasmanian wolf evolved independently of the European dog but ended up with similar, though not identical, characteristics. Even within Europe, institutional environments were sufficiently different to regard experimentation within the major economies as different realisations of similar innovative processes. Over the longer run, the emergence of the internal combustion engined motor car was not sensitive to small changes in initial conditions, such as the availability or otherwise of horsetrough water. Economies of scale were no source of 'lock-in' to internal combustion engines, for long before Fordism took root, the selection process was complete. Indeed the Locomobile steam car was produced in numbers greater than any contemporary internal combustion engined vehicle, yet that did not serve to lock-in steam.

The ultimate failure of steam is less surprising than its persistence in the US, where it was an example of natural resource-intensive technology too expensive for Europe. Liquid fuel was far cheaper in the US and could be consumed more lavishly, as the steam car required. The early steam car was made at a lower first cost than the more complex internal combustion engined vehicle and, for a brief while, that promised to offset the higher fuel costs[8].

The popularity of the electric car in the US also demonstrates the proposition that distinctive American conditions were not invariably conducive to the emergence of the most appropriate twentieth century technologies. More readily available and cheaper electricity, the early success of the electric tram, greater numbers of women drivers and impassable roads outside the city, created an opportunity for electric cars before 1914 which was hardly to be found in Europe[9]. Once the electric starter became standard and American roads improved, or an internal combustion engined vehicle capable of driving on them was available, the US electric car market disappeared[10].

History mattered for the motor industry over two or three decades but fundamental characteristics of the world economy then reasserted themselves.

Notes

1 There is no comparable rise in the three European countries.

2 France was as receptive to the aeroplane as she was to the motor car. The Wright brother's first public display of flight was in France, not in the United States.

3 Communication from Hartmut Kiehling.

4 In this respect the experience of the late Victorian motor industry was not unique. Vested interests and safety concerns inhibited innovation in a number of other vital new British industries. Similar contemporary hindrances to the development of electricity and the telephone were placed at about the same time, by Parliamentary legislation in 1882 and the Post Office telecommunications monopoly respectively.

5 Early references to English petrol prices in the Petroleum Review are from a Liverpool market report. Only in 1911 are there clear indications that prices are from London. In general prices were not too clearly recorded before 1914. Between 1902 and 1910 retail price per gallon (after the tax of 3d imposed April 30 1909 with 50 per cent rebate for commercial vehicles and hackneys), apparently varied between 8.5d and 1s 3d, or between 17 and 30 cents. The first reference to London is in December 1910; 1s. (24 cents) for best quality petrol including tax. Jenkins (1902 p812) cites an 1898 Peugeot estimate of running costs which

assumes petrol costs 17.3d per gallon. I am grateful to Hans-Joachim Voth for German petrol price evidence.

6 The expression for the steam/internal combustion engine running cost differential is

$$RC = \sum^{n} \{(mpg_s^{-1}-mpg_{ic}^{-1})p.a\}/(1+r)n-1$$

where n is the number of years the car is kept on the road, mpg_s, is the miles per gallon of the steamer, mpg_{ic} is the miles per gallon of the internal combustion engined car, p is the fuel price, a is the annual mileage and r is the discount rate.

7 On the other hand this and comparable steels were very expensive in Britain, at 37/--50/- per cwt for bars. Krupp of Essen offered a London catalogue of prices which often undercut Sheffield products (Worby Beaumont 1906 Ch40).

8 Additional evidence that fuel costs determined the national choice of different power source comes from the heavy commercial vehicle sector. British solid fuel steam lorries continued to flourish long after steam cars had disappeared, and diesel engines spread much faster in Europe during the 1930s than in the US (Laux 1987). Heavy internal combustion engined commercial vehicles consumed great quantities of petrol.

9 An Act of 1916 provided Federal aid to states with responsible highway departments.

10 Once the National Grid brought down British electricity prices in the 1930s, the British adopted utility urban delivery vehicles more enthusiastically than elsewhere, as the survival of the British milk float shows (Montagu of Beaulieu 1978).

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Table 5 UK Automobile Club 650 mile Reliability Trial 1902
Class B and C £150-300 price range

	HP	cyl.	marks	price £	weight cwt	fuel gal/cwt	mpg
Locomobile	5.5	2	2753	200	14.25	3.19	14.3
"	5.5	2	2754	200	14.0	3.31	14.0
Star	7	2	2568	300	21.25	1.22	25.1
Locomobile	5.5	2	2279	300	15.07	2.52	17.1
"	5.5	2	2784	300	15.5	3.03	13.8
Renault	4.5	1	2721	245	11.357	1.32	43.3
MMC Voiturette	8	1	2982	255	16.357	1.22	32.6
De Dion Bouton	6	1	2914	245	13.5	1.17	41.15
White steamer	6	2	2749	300	16.07	1.71	23.6
"	6	2	2862	300	16.607	1.56	25.1

Notes: Fuel consumption per cwt load. Weight is laden.
Source: Hasluck (1902 p792)

Table 6 US Autoclub Trial 1902

Fuel consumption in galls per 100 miles

Steamers	HP	Petrol	Water
Grout	4.5	12.75	113.15
Prescott	4.5	13.25	85.5
"	4.5	14	79.5
Lane	10	15.75	93.25
Locomobile	3.5	13.5	114.75
"		10	89.25
		16	103.5
White	6	6.5	6
		5.75	6
		9	9.75
Overman	4.5	10.5	84.75
Locomobile	3.5	16	103.5
Average		11.92 (8.4 mpg)	

Internal Combustion		
Pierce	5.5	4
Long Distance	7	4.5
Darracq	9	5
	9	4.125
Packard	12	6.5
Mors	12	7
Georges Richard	12	8
"	12	7
Autocar	8.5	5
De Dion Bouton	4.5	6
Fournier-Searchmont	8	7
"	8	7.75
Haynes Apperson	9	5
Knox	6	7
"	6	6
"	6	7
Fournier-Searchmont	8?	8.5
average	6.20 (16.1 mpg)	
	(US only 5.625 or 17.8mpg)	

Source: Hasluck (1902) p780