Chapter 17

Competition and Complementarity in Diffusion: The Case of Octane

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17.1 Introduction

The standard ontogenic (*life-cycle*) model of technological evolution can be characterized briefly as follows (Ayres, 1987): (1) a radical invention (**birth**) creates a new technology; (2) it is commercialized on the basis of performance and rapidly developed by a series of improvements and modifications (**infancy**); (3) it is successful enough in the marketplace to attract many variants and imitators who hope to exploit a growing market (**adolescence**); (4) the pace of technological change finally slows down enough to permit standardization and exploitation of economies of scale, and competition on the basis of price rather than performance (**maturity**); and finally a new and better technology supplants it (**senescence**).

The standard model involves substitutions in the adolescent and senescent stages. During the adolescent stage, the new and dynamic technology is gradually penetrating the markets of its predecessor. During the senescent stage it, in turn, is being displaced from its markets by its successor. The substitution of a new technology for an older one is often modeled as a deterministic process, following a simple mathematical formula such as a logistic function or a Gompertz curve (see, for example, Linstone and Sahal, 1976; Mahajan and Peterson, 1985; Mahajan and Wind, 1986).

However, complex social systems – including the system of innovation, adoption and diffusion of technology – are inherently nonlinear. As such, they must be expected to exhibit the characteristics of nonlinear dynamical systems. Among these characteristics is the occurrence of **non-equilibrium** steady-state behaviors (such as limit cycles and quasi-periodic motion) that temporarily emulate the behavior of simpler systems, but eventually depart from it (Crutchfield *et al.*, 1986). In short, social systems cannot be expected to always behave in accordance with any given simple model. Indeed, simple behavior, when it does occur, is likely to be an example of non-equilibrium steady state. Hence, from the standpoint of fundamental dynamical theory it seems likely that more can be learned by analyzing cases where the simple models fail than cases where they seem to work well (e.g., Fisher and Pry, 1971).

In particular, the simple deterministic substitution model that is normally assumed assumes that a substitution process, once it has proceeded past a certain threshold, inevitably proceeds to completion (unless it is interrupted by a further substitution). This implies the existence of an underlying self-reinforcing (*lock-in*) mechanism of some sort. Such mechanisms are intrinsically nonlinear in nature. A number of examples have been examined by Arthur (1983, 1988a, and 1988b). Obviously, the large number of cases where the substitution process has proceeded according to this script can be regarded as indirect evidence of the pervasiveness of self-reinforcing mechanisms. Yet, there are significant exceptions. Such a case is the subject of this chapter. We examine the technological evolution of fuels for spark-ignition internal combustion engines (e.g., automobile engines) since the beginning of the present century. The chapter concludes with a discussion of some possible explanations for the failure of "antiknock" additives to displace cracking as a means of raising gasoline octane, or conversely.

17.2 Historical Background

The automobile had no single inventor. It is usually traced to early models by Gottlieb Daimler and Wilhelm Maybach, and Karl Benz (*ca.* 1885). For the next twenty years and more, automobiles were essentially toys for the rich and adventurous. It was not until after 1905 (the year Ford Motor Co. was founded) that automobiles were technologically developed enough to be useful for simple transportation purposes. Even then, for many years, they remained expensive, unreliable and uncomfortable. However, by 1908 the dominant technological *trajectory* had been determined and the industry, led by Ford, began to standardize. The enormously successful *Model T* was introduced in 1908, which symbolically marks the end of the "childhood" phase of the auto industry and the beginning of **adolescence** and consolidation.

This chapter is not about autos, however, but about motor fuel. The relevance of the previous paragraph is simply that after 1908 demand for cars – and, consequently for gasoline – began to rise rapidly. It is important to note that in the earliest days automotive fuel was so-called *natural gasoline*, a medium volatility product of crude oil refining, consisting of fractions boiling in the range between 0–70° C and an octane of 72–75. But this light fraction averages only about 2.4% (by weight) of North American crude and no more than 4.7% of middle-Eastern crude.[1] To increase the output of motor fuel, early refineries blended natural gasoline with the next heavier fraction, *naphtha*, boiling in the range 70–140° C, but with less desirable combustion properties. The blend had an octane level of around 50. For North American crude oils the naphtha fraction averages 6.5% by weight (7.9% for middle-Eastern crude). Thus, while local details differed, petroleum refiners in the USA *ca.* 1910 could only utilize around 9% of their crude oil, by weight, directly for motor fuel.

At the time (1910), 9% of the crude oil was still adequate to supply the automotive demand, inasmuch as there were as yet relatively few vehicles on the roads. Indeed, the biggest market for petroleum products was still *illuminating oil* (kerosene), which constituted about 15.6% of the weight of the refinery product stream. However the heavier, lower-value fractions, *gas oil* (now known as heavy distillate, diesel oil, or heating oil), and *residual oil* together still constituted 75% of the refinery output. Gas oil, alone, accounted for about 60% of the product. There were already significant incentives to add value to the heavy fractions by somehow converting them into lighter fractions.

The breakup of Standard Oil Co. of New Jersey (NJ) in 1911 triggered a major innovation, the thermal cracking process. The chief inventor and innovator of the process was William Burton, a vice president of one of the spinoffs from Standard Oil, Standard Oil Co. of Indiana (now renamed Amoco). With its refineries on the shores of Lake Michigan, and its major market the rapidly growing Chicago metropolitan area, Indiana Standard was faced with an exceptionally rapidly growing market area, together with a rather limited access to crude oil.[2] A new technology promising to increase the fraction of crude oil that could be used for motor fuel was very welcome.

Burton's thermal cracking process – heating a batch of heavy gas oil in a closed tank or retort – effectively converted about 20% of the gas oil into a light fraction suitable for blending with natural gasoline and naphtha. This effectively doubled the output of motor gasoline from about 9% to around 21%, while simultaneously increasing its *research octane* (RON) rating from 50 to 55. The Burton process was first introduced in 1913–1914 and was enormously profitable to refiners. For this reason it was rapidly adopted by others (*Figure 17.1*). It also set off a great wave of competitive invention and innovation, since other oil companies did not like paying the high royalties demanded by Indiana Standard for what was, essentially a very simple invention. Burton and his colleagues began to improve their first crude batch process. Meanwhile, others entered the field with ideas for continuous thermal processes and (later) catalytic processes.

Table 17.1 summarizes the major innovations in refining after 1913 and *Figure 17.2* indicates the succession of substitutions in refinery technology in quantitative terms, as each technology replaced its predecessor and was, in turn, replaced. (Data for these exhibits has been taken primarily from Enos, 1962, and Lakhani, 1975). It is noteworthy that the substitutions displayed in *Figure 17.2* do seem to fit the standard ontogenic model reasonably well.

From the standpoint of the *octane* industry, Burton's radical innovation of 1913 marks the date of birth. But, what makes this case complicated (and interesting) is that there were two different – and noncomplementary – market interests and consequently two *driving forces* involved. The first, as suggested above, was the petroleum refineries' direct economic interest in increasing the output of high-value motor fuel per barrel of crude oil. Doubling the output of motor fuel per barrel from 9% to 20–21% meant, in effect, that less than half the amount of crude oil had to be discovered, pumped, shipped, and distilled to yield the same amount of salable product.

The second market interest – which created a demand for higher octane *per se* – was shared by the automobile users and manufacturers, but was

**Table 17.1.** Summary of major cracking technologies.

Name	Specific economic advantage over predecessor	Factors driving innovation
Burton batch thermal cracking process, Indiana Standard, 1913–1914	Increased octane to about 60 and motor gasoline yield per bbl of petroleum from about 9% to 21% or so.	Indiana Standard was created by the court ordered breakup of Jersey Standard; it was left with refining and distribution, but little crude supply. Demand in Chicago area was rising imperative to *stretch* each barrel.
Continuous *tube & tank* thermal cracking process (Clark, ESSO, 1922). Dubbs process (UOP, 1922). Cross process (1922).	Better suited to scale-up than batch process; increased octane to 72, mpg by 22% and output per unit of capital by 50%. Reduced process energy by 20%.	ESSO wanted to invent around Indiana Standard's processes and to invalidate other patents (e.g., Cross). Universal Oil Products (UOP) was created by a group of regional refiners to invent around Indiana Standard's patents because they were unable to license because they were in the same marketing area. UOP sued Indiana Standard to preempt.
Houdry fixed bed (batch) catalytic cracking process (Sun Oil, Socony-Vacuum, 1938)	Increased gasoline yield to 40% of crude, octane to 72. Cut process energy by 2/3.	Initial research in France was prompted by fears of shortages and lack of crude oil in Europe: Backing by Sun Oil Co. was due to a glut of heavy fuel oil and Sun's market niche with a single grade gasoline of higher octane than its competitors.
Continuous fluidized bed catalytic cracking process (ESSO *et al.*, Mobil, Houdry)	Better suited to scale-up than batch process; increased octane to 93–95.	Catalytic Research Associates was formed by Esso, with BP, Shell, Texaco, UOP, MW Kellogg and IG Farben to invent around the Houdry fixed bed process. Members of the syndicate could avoid royalties on the process. Mobil developed its own process for the same reason.
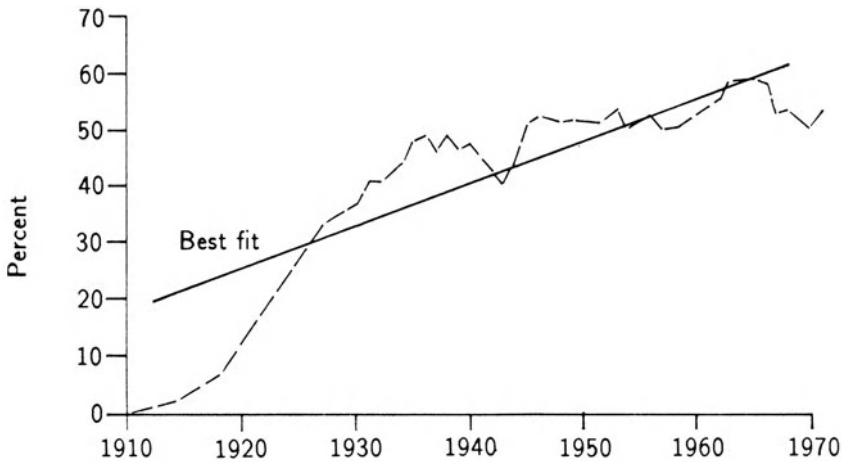
Figure 17.1. Cracking capacity as percent of total crude oil production capacity. (Source: Lakhani, 1975, p. 54.)

to some extent contrary to the interests of the petroleum companies. The conflict and its resolution are part of this story. The inherent characteristics of internal combustion engines are such that both output power and thermodynamic efficiency are functions of the compression ratio of the engine. Thus, high compression engines offer better performance for the car. The compression ratio is the ratio of the volume of combustion products after expansion (exhaust gases) to the volume of the fuel-air mixture at the point of ignition. Since the exhaust gases must be at atmospheric pressure, this is also a measure of the amount of compression in the engine.

For a spark-ignition engine – in contrast to a Diesel engine – the maximum compression is not limited by the geometry of the cylinder and crankshaft, or the tightness of the piston-rings, as might be expected, but by the tendency of the engine to *knock* or *ping*, which cuts power output sharply and can cause damage. Knocking means the octane level of the fuel being used is not high enough to operate at the design compression ratio. The attribute that permits higher compression is called the research octane number or RON, or simply *octane*. It varies considerably from fuel to fuel, depending on its chemical structure, oxygen content and other factors. In general, higher octane fuels permitted higher compression engines, which permitted better automotive performance as well as fuel economy. *Figure 17.3* shows
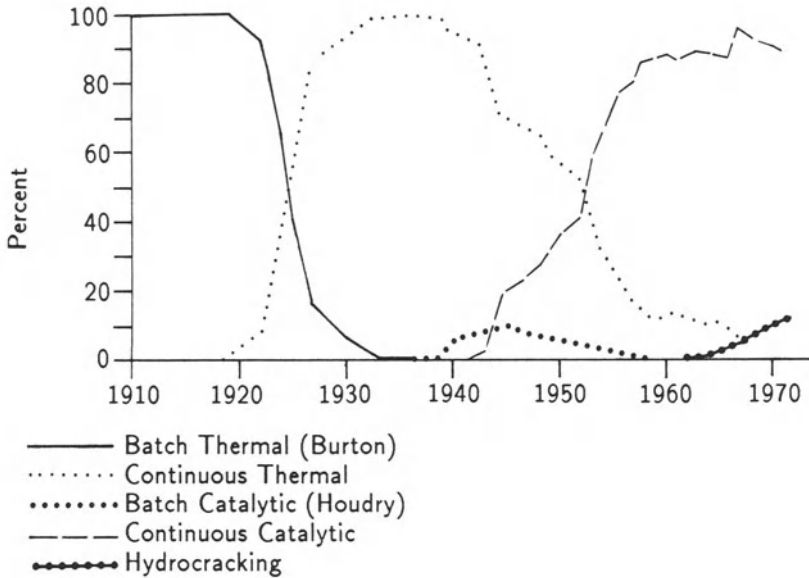
Figure 17.2. Petroleum cracking processes. (Sources: Data prior to 1958 from Ayres, 1987; data from 1958 on from Lakhani, 1975, p. 54.)

the historical progression of octanes from 1930 until 1970, while *Figure 17.4* shows the close parallel with increasing engine compression ratios.

Increasing fuel economy (due to increased octane levels) meant that gasoline sales in volume terms did not increase as fast as automobile usage. On the other hand, every increase in automotive performance attracted more first-time buyers of automobiles, and each additional vehicle in the fleet meant a guaranteed demand for gasoline throughout the life of the car. Thus, the petroleum industry had a somewhat contradictory interest in the *octane race*. On the one hand, as long as petroleum supplies were ample, better fuel economy was not in its direct economic interest. On the other hand, it did share the interest of the automobile manufacturers in attracting more and more people to buy cars, because the more cars people bought the more motor fuel the refiners could sell.

This conflict between short- and long-term interests on the part of the petroleum refiners had one direct implication, however. Given the possibility of increasing octane levels **independently** of changes in refining technology,
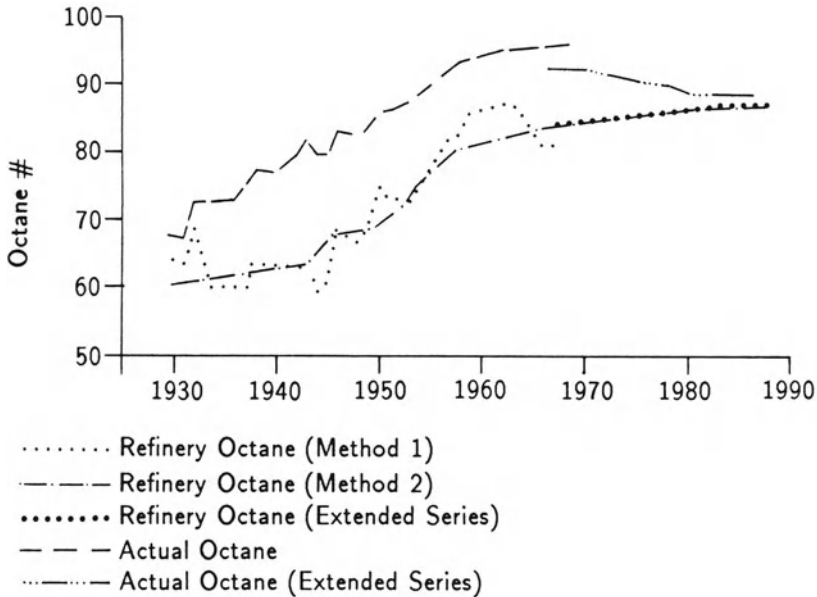
Figure 17.3. Average octane numbers.

vis-à-vis the possibility of increasing octane levels **in conjunction with** increasing the fraction of the crude oil that could be utilized for motor fuel, the latter was vastly preferable for the refiners. This preference explains much of the history of the octane race. Of course, the technology of increasing octane levels independently of refinery practice was introduced in the early 1920s. We discuss this next.

17.3   The Introduction of Tetraethyl Lead

The search for an antiknock additive for gasoline began in 1916, when engine compression ratios averaged only 4:1, yet *knocking* was a pervasive problem due to the low octane level of the motor fuels then available. At the time, however, the cause was not known. Charles Kettering's battery ignition system had been introduced only a few years earlier, and rival magneto ignition system manufacturers blamed it for knock. To counter this ploy (and find the real explanation, and a solution to the problem), Kettering and his colleagues Thomas Midgley, Thomas Boyd, and Carroll Hochwalt launched a research program at his Dayton Engineering Laboratories. It was subsidized
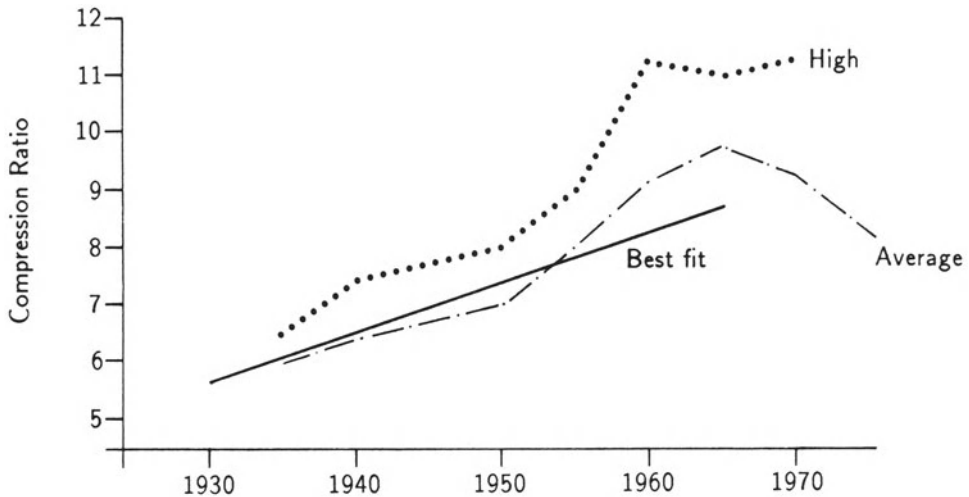
Figure 17.4. Automobile engine compression ratios.

by General Motors Corporation (GM), which later purchased Dayton Engineering Labs., (now known as DELCO Division) and made Kettering Vice President and chief scientist.

The first step was to test Midgley's theory that fuel volatility was the cause of the problem. (This had seemed plausible because increased demand for motor fuel had been met by increased blending of natural gasoline with less volatile naphtha). Volatility was ruled out by the end of 1916. Next, Kettering had a hunch that fuel color[3] might have an influence on knocking. This was quickly tested by adding various coloring agents to the fuel. The *color theory* was quickly discarded, but one of the chemical agents tested was iodine, which did have a measurably beneficial effect on knocking. For the next five years hundreds of compounds were tested, and some possible antiknock compounds were found, including aniline, selenium, and tellurium. They were all rejected for various reasons (such as odor). Finally, in December 1921, tetraethyl lead (TEL) was synthesized by Hochwalt. As an antiknock additive it has never been equalled, despite many millions of dollars of subsequent research by the German chemical cartel IG Farben.

For TEL to become a practical fuel additive, a manufacturing process was needed. This was developed by Charles Kraus, whose research was supported by Standard Oil Co., NJ. The GM patents on TEL and the Standard Oil Co., NJ manufacturing patents were consolidated by the formation of Ethyl Corporation in 1924, jointly owned by GM and Standard Oil Co., NJ.

Another problem that had to be overcome was the corrosion of spark plugs by lead oxide deposits. This was finally overcome by the addition of ethylene dichloride and ethylene dibromide in the additive. The latter, in turn, required a large and reliable source of bromine, which was finally achieved by the commercialization of the Dow process to extract bromine from seawater (1931).

From 1924 to 1930 the Ethyl Corporation was primarily involved in R&D, testing, advertising and marketing *premium* or *Ethyl* gasoline and building up its distribution network. Meanwhile, GM was actively promoting the higher performance cars that the new fuel made possible. Whether for this reason, or others, it was during this period that GM overtook Ford as the major US auto manufacturer.

Sales of TEL (in the form of *ethyl* fluid sold by Ethyl Corporation to refineries, and blended by the latter into commercial gasoline) took off. Motor fuel (gasoline) sales more than quadrupled from 1929 to 1967, with only a slight decline even in the worst year of the depression. Meanwhile, the average content of lead in grams per gallon of gasoline increased ten-fold and almost monotonically during the depression years (from 0.17 gm/gal. in 1929 to 1.75 gm/gal. in 1939) and reached an all-time peak of 4.71 gm/gal. in the wartime year of 1944. It hovered in the 3.5–3.9 range in the late 1960s before the first restrictions on TEL use – for environmental reasons – became effective. The average lead use, per gallon of gasoline used on highways, is shown in *Figure 17.5*.

17.4   Relative Contributions of Refining and TEL

In terms of the life-cycle model referred to briefly at the beginning of this chapter, one would expect the long-term competition between refinery technology and additives (notably TEL) to result in a clear superiority of one over the other, resulting in a well-defined displacement or substitution process. Before this hypothesis can be tested, however, we need a methodology for allocating the apparent *octane added* in each year (defined as octane per gallon above the base level of 50) among the various sources. From 1929 to 1970, roughly, the competition was strictly between refining and TEL. Since the environmental constraints on TEL have been gradually implemented, a new set of additives – basically alcohols – have appeared on the scene. These will be discussed later.
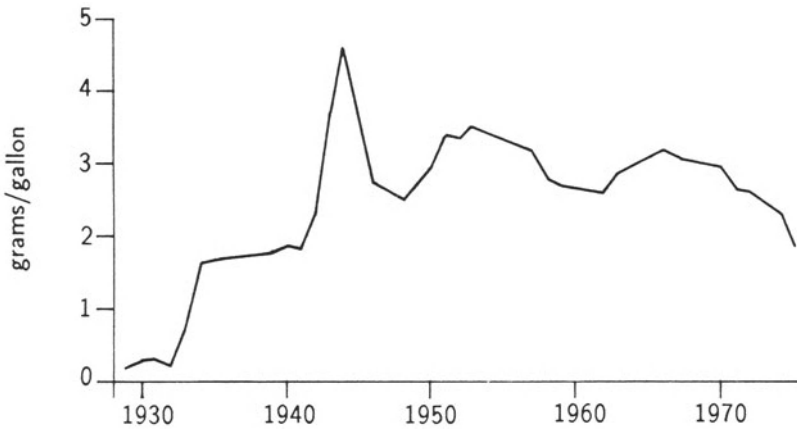
Figure 17.5. Lead use rate (grams/gallon). (Sources: Lead use: US Bureau of Mines, *Minerals Yearbook*, var. vols.; fuel consumption: US Federal Highway Administration, *Highway Statistics*, var. vols.)

There are two straightforward methodologies for estimating the octane-added, as defined above. Both start from the average octane level of fuel sold in a given year (see *Figure 17.3*). One approach is to use a *lead susceptibility* chart prepared by the Ethyl Corporation to determine the octane gain from a given amount of lead additive, based on the octane level of the *base fuel*, i.e., the gasoline as obtained from the refinery process alone. The chart in question is shown as *Figure 17.6*. It can be used to estimate the base fuel octane from the quantity of lead added (in grams per gallon). This method assumes, of course, that lead is added to *average* base fuel. In reality, high octane gasoline from some refineries has always been sold as *unleaded premium*, as long ago as the late 1930s.[4] This tends to lower the average octane level of the base fuel to which TEL *was* added, distorting the average picture somewhat.

On the other hand, the alternative approach – which can be termed "process accounting" – is to calculate the average octane of the base fuel from the fraction of gasoline produced by each refinery process in each year and the octane produced by that process. For purposes of this analysis we have assumed the octane levels indicated in *Table 17.1*, namely, Burton batch thermal cracking (55 RON), continuous thermal cracking (73 RON), Houdry batch catalytic (87 RON), continuous catalytic or fluidic (95 RON).
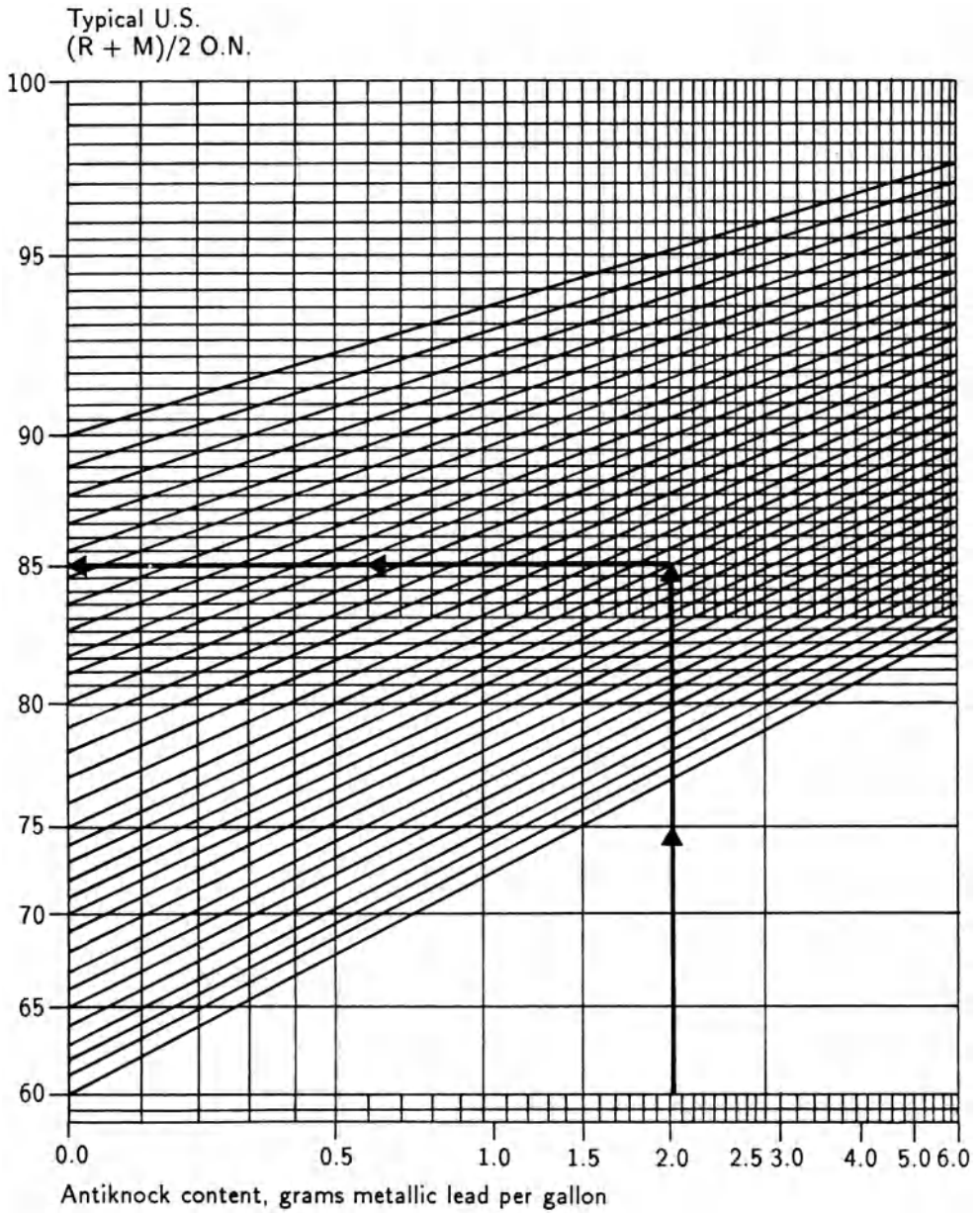
Figure 17.6. Ethyl Corporation lead alkyl antiknock susceptibility chart.

Here there are three difficulties. The first is the same as the one noted above, *viz.*, some high octane refinery products fuels have been sold directly as lead-free premium gasoline without added lead. The second problem is that the *average* octane number associated with each process is only approximate. Moreover, apart from the four main types of cracking process, refiners have had, since the 1930s, a variety of other octane-enhancing processes available, including hydrogenation, polymerization, alkylation, hydrogen reforming and catalytic reforming. In fact, each refinery is unique in its mix of processes and products. The third problem is that we do not have published data on production by process, but only on *capacity* by process. On the average, over a long period of time, the two probably track together roughly, but on a year-to-year basis there are likely to be significant variations as some types of capacity are more highly utilized than others.[5] Apart from wartime distortions, during the early years of penetration of a new process one might expect some *debugging* troubles to reduce capacity utilization; this is the pattern observed in other cases of new process introduction. By contrast, in the late stages of a displacement, a refiner might keep an old depreciated plant on-stream and available, but operating at a low level *just in case* of a sudden upsurge in demand. Thus, one would tend to expect capacity utilization levels for a new process technology to start at moderate levels, rising gradually due to *learning by doing* until fairly late in the life of that technology, before dropping to rather low levels immediately prior to being phased out.

For the several reasons given above, the two ways of estimating base fuel octane levels would not be expected to agree exactly. Of the two, the *lead susceptibility* method would appear to be more reliable. In fact, the agreement between the two methods is not remarkably close (*Table 17.2*). Using both methods of calculating refinery octane, the share of *added octane* attributable to refining technology versus that attributable to the addition of TEL is plotted in *Figure 17.7*. The results are very interesting, especially when the lead susceptibility chart is used to calculate base octane level. Starting in the late 1920s, the TEL share began to rise rapidly (except for the single relapse in 1932) to the 50% level, or more, which it held throughout the 1930s and even increased to a peak of 66% in the war year of 1944. Thereafter the TEL share began to drop, falling to 36% in 1950, with a slight pickup to 40% in 1953, followed by a further fall to a low point of 17% in 1963. Yet it rebounded once again to the 32% level in 1967.

Table 17.2. Refinery and actual octane plus additive share.

	Refinery octane[a]	Refinery octane[b]	Refinery octane[c]	Actual octane	Actual octane[c]	Additive share[a]	Additive share[b]	Additive share[c]
1930	64.0	60.50		67.5		0.200	0.400	
1931	63.5	60.88		67.0		0.206	0.360	
1932	69.0	61.00		72.0		0.136	0.500	
1933	63.5	61.25		72.0		0.386	0.489	
1934	60.0	61.50		72.5		0.556	0.489	
1935	60.0	61.75		72.5		0.556	0.478	
1936	60.0	61.88		73.0		0.565	0.483	
1937	60.0	62.00		75.0		0.600	0.520	
1938	63.0	62.13		77.0		0.519	0.551	
1939	63.0	62.38		77.0		0.519	0.541	
1940	62.0	62.63		77.0		0.556	0.532	
1941	63.0	62.75		78.2		0.539	0.548	
1942	63.0	63.00		79.2		0.555	0.555	
1943	63.0	63.38		81.5		0.587	0.575	
1944	60.0	65.75		79.6		0.662	0.468	
1945	61.0	66.98		79.5		0.627	0.424	
1946	68.0	67.75		82.7		0.450	0.457	
1948	66.5	68.25		82.5		0.492	0.438	
1949	69.0	69.00		83.8		0.438	0.438	
1950	74.0	70.25		85.88		0.331	0.436	
1951	73.0	71.00		85.95		0.360	0.416	
1952	73.0	71.75		86.75		0.374	0.408	
1953	73.0	74.25		87.50		0.387	0.353	
1957	82.0	79.75		92.20		0.242	0.295	
1958	83.0	80.38		93.45		0.241	0.301	
1959	85.0	80.82		94.00		0.205	0.300	
1962	87.0	82.13		94.90		0.176	0.284	
1963	87.0	82.50		95.10		0.180	0.279	
1966	81.0	83.75		95.65		0.321	0.261	
1967	81.0	83.50	84.1	95.83	92.25	0.324	0.269	0.193
1970			84.6		92.25			0.181
1975			85.4		90.63			0.129
1978			85.8		90.00			0.105
1979			86.0		89.60			0.091
1980			86.2		88.72			0.065
1981			86.3		88.60			0.060
1982			86.5		88.50			0.052
1983			86.6		88.55			0.051
1984			86.7		88.60			0.049
1985			86.7		88.50			0.047
1986			86.7		88.67			0.051
1987			86.8		88.61			0.047

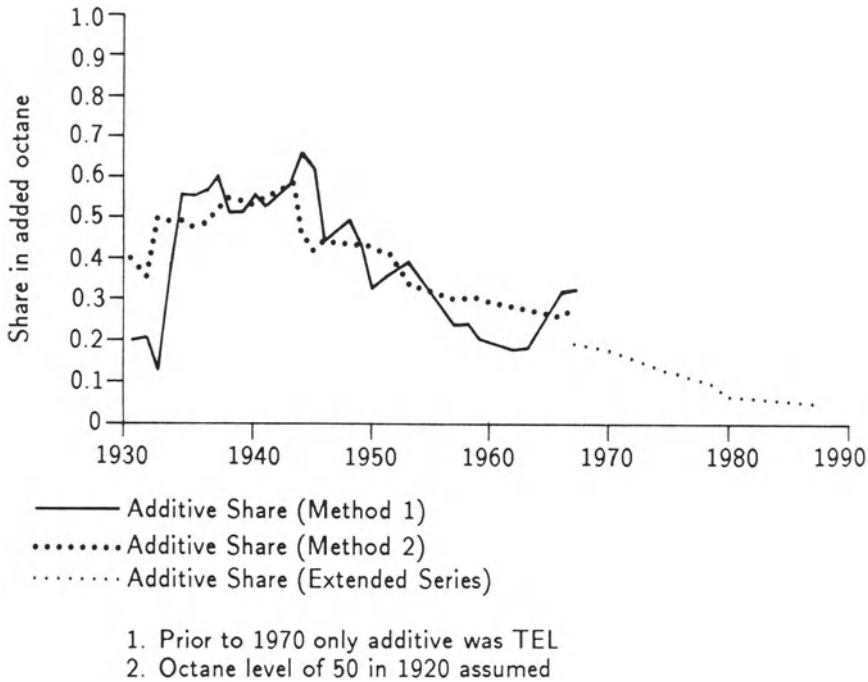[a]Method 1. [b]Method 2. [c]Extended series.

Figure 17.7. Contribution of additives to added octane.

17.5   Discussion and Conclusions

How can this behavior be explained at all, still less fitted into the conventional *substitution* picture? As noted earlier, one normally expects the *superior* technology to gradually displace the *inferior* one, following an S-curve or some similar path. In the present case, TEL became dominant rather soon after its introduction, but did not replace cracking, or even slow down its rate of adoption. In fact, since the 1940s the trend has been the other way. TEL has subsequently been displaced very largely by more advanced cracking and other refining technologies and new additives (*Figure 17.8*). This trend was well advanced even before the environmental regulations restricting the use of TEL.

On the other hand, neither of the alternatives has ever entirely displaced the other. Even as TEL was phased out, other octane-enhancing additives have begun to replace it (*Figure 17.8, Table 17.3*). If there are economies of scale or economies of adoption favoring *lock-in* to either approach, e.g.,
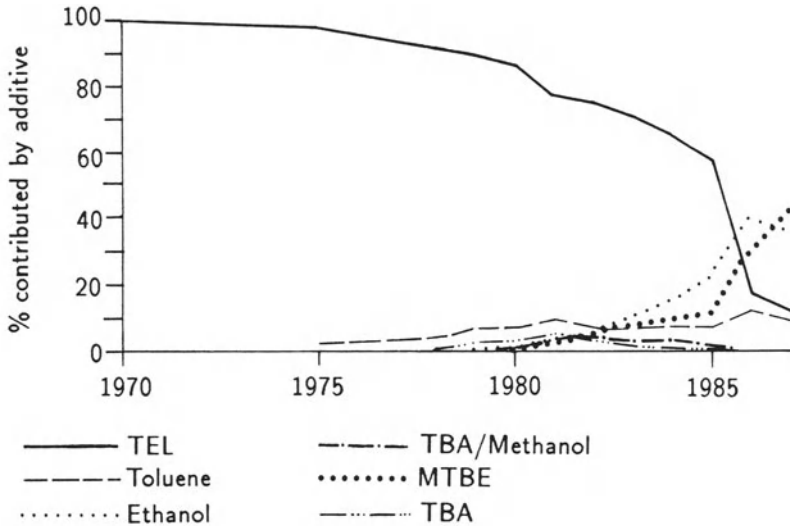
1. Toluene through 1978 includes MMT,
   which was banned in 1978 by the EPA.

Figure 17.8. Percentage contribution of different additives.

Arthur (1988a), they are evidently compensated for by diseconomies (de-clining marginal returns), possibly associated with high-severity petroleum refining. No matter how sophisticated the refinery technology, it is appar-ently always economical (in the narrow sense) to gain additional octane by the addition of some TEL, or one of the alcohols. By the same token, there are also declining marginal returns to the use of TEL, or other additives, beyond a certain point. Thus the two technologies, while somewhat compet-itive, are also to some extent complementary.

Apart from the issue of complementarity, noted above, it is important also to observe that one of the two technologies, cracking, was evolving rapidly while the other remained static until regulation forced a change. In fact TEL is one of the few examples of a technology which essentially did not evolve at all after introduction. Its diffusion process was therefore *pure*, and not the more commonplace combination of technological change and diffusion together. Are there other cases like this one? Quite certainly there are, inasmuch as declining marginal returns and complementarity are not rare phenomena in economics.[6]

Table 17.3. Percentage contribution of different additives.

	TEL	Toluene	Ethanol	TBA	TBA plus Methanol[a]	MTBE
1967	100.0					
1970	100.0					
1975	97.3	2.7				
1978	91.4	3.8[b]		1.0		
1979	89.2	7.2	0.4	2.5	0.1	0.6
1980	86.3	6.8	1.2	2.5	0.8	2.5
1981	76.8	9.3	2.2	3.7	3.1	4.9
1982	74.9	6.9	6.0	2.5	4.0	5.7
1983	71.0	6.6	10.9	1.8	3.0	6.6
1984	65.1	7.2	15.5	1.0	3.3	7.9
1985	57.8	7.3	22.5	0.3	1.4	10.7
1986	17.6	12.0	41.2			29.2
1987	12.2	9.4	36.1			42.2

[a]For methanol, add (TBA plus methanol) to MTBE.
[b]Methyl manganese tricasbonyl (MMT) accounted for 3.8% (or 44% of additives used in unleaded gasoline in 1978). MMT was banned in 1978 by the EPA.

Notes

[1] In fact, for two early Pennsylvania refineries for which data is available – Pratt's and Downer's – the gasoline output was only 1.5% of the output stream (Williamson and Daum, 1959).

[2] Indiana Standard had oil wells in Indiana and Illinois, but the reserves were not large. The breakup of Jersey Standard left the parent company in possession of Humble Oil Co., with its large Texas crude oil reserves.

[3] Kettering was inspired by the red-green natural dyes in plants, such as the trailing arbutus, and an apparent relationship between leaf color and early blooming (Raymond, 1980).

[4] For instance, premium Sunoco "Blue" was made directly from the Houdry catalytic process; in the 1960s Amoco sold a premium lead-free gasoline of very high octane.

[5] During World War II this distorted the picture significantly, inasmuch as the demand for high octane *aviation gasoline* soared, soaking up virtually all of the refinery capacity for catalytic cracking. As a consequence, old thermal cracking plants were kept in service and the base octane level of fuels used by the civilian sector declined sharply. It was made up, in part, by extraordinarily high use of TEL, as shown in *Figure 17.5*.

[6] Another fairly obvious example is the complementarity between the basic oxygen furnace (BOF) and the electric arc furnace (EAF) in steel-making. The one converts pig iron from ore and scrap, but the other converts scrap only. The

balance between them depends on the scrap supply. On reflection, it must be clear that every coproduct relationship corresponds to some complementarity.

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