# Unleaded Gasoline in the United States: A Successful Model of System Innovation

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**The introduction of unleaded gasoline and catalyst-equipped vehicles required numerous changes in U.S. transportation and energy systems. Simultaneous technological and operational changes in fuel production, distribution, and end-use systems had to be made, and the inherent resistance to change that characterizes complex sociotechnical systems had to be overcome. The transition to unleaded gasoline was unique in that it was instigated and orchestrated by federal rules and laws; market forces did not play a direct or major role. This government-orchestrated transition serves as a possible model for other countries that are contemplating the phasing out of lead in gasoline and, more generally, as a model for the United States and other countries for the introduction of nonpetroleum fuels.**

The introduction of unleaded gasoline and catalyst-equipped vehicles required numerous changes in U.S. transportation and energy systems. Major changes (and investments) had to be made in oil refinery and storage facilities; transportation technologies had to be modified to separate unleaded gasoline from leaded gasoline; vehicle manufacturers had to invest in the development of new engine systems and retooling of existing factories; and a network of retail fuel outlets had to be established to serve the new single-fuel unleaded vehicles. Also, the "chicken-or-egg" problem of coordinating the production, distribution, and marketing of new fuels, and production and marketing of new vehicles, had somehow to be solved (*1*). The introduction of unleaded gasoline and catalytic converters required simultaneous technological and operational changes in fuel production, distribution, and end-use systems, and faced numerous economic and political barriers, as well as having to overcome the inherent resistance to change that characterizes complex sociotechnical systems. Introduction of unleaded gasoline and catalytic converters faced the same type of obstacles as would any other new fuel, dissimilar to petroleum, such as alcohols, gaseous hydrocarbons, and hydrogen.

The transition to unleaded gasoline in the United States in the 1970s is documented and analyzed. That transition was unique in that it was instigated and orchestrated by federal rules and laws; market forces did not play a direct or major role. This government-orchestrated transition to unleaded gasoline serves as a possible model for other countries as they contemplate the phasing out of lead in gasoline and, more generally, as a model for the United States and other countries for the introduction of nonpetroleum fuels.

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## LEGISLATIVE AND RULE-MAKING HISTORY

Lead has been used as a gasoline additive since the early 1920s, when researchers at General Motors found that adding tetraethyl lead (hereafter referred to simply as "lead") to gasoline reduced "knocking" in engines by slowing the rate at which gasoline burned in the compression chamber (*2*, *3*). Oil refiners found that putting small amounts of lead in gasoline was the cheapest way to boost octane and reduce the knocking characteristic of gasoline; the existence of higher-octane gasoline meant that automobile manufacturers could build larger and more powerful engines. The first leaded gasoline was marketed in 1923. It immediately attracted opposition from scientists and public health officials who were concerned about the health impacts of lead (*4*). General Motors along with Ethyl Corporation, a company set up by General Motors and DuPont to produce and market tetraethyl lead, successfully defused that opposition (without resolving the health issue), and sales of leaded gasoline continued.

The environmental movement of the late 1960s revived the health issue. The 1970 amendments to the Clean Air Act established ambient standards for six pollutants including lead. To attain the ambient standards, the 1970 Clean Air Act amendments imposed emission standards that required automobile makers to reduce hydrocarbon and carbon monoxide exhaust emissions by 90 percent by 1975 and nitrogen oxide emissions by 90 percent by 1976 (*5*); at that time, however, no schedule was established (for either the automobile or oil industry) for reduction of lead emissions. Lead was to be removed principally to achieve other air quality and health goals. [Later, in the 1970s, a lead "phase-down" schedule was imposed on refiners to eliminate lead from "leaded" gasoline. In the early 1980s new scientific studies emphasized the severity of lead's adverse health effects, leading the EPA to accelerate the lead phase-down schedule.] Despite not being a principal objective, the replacement of leaded gasoline took place quickly and rather smoothly.

Congress recognized in 1970 that emissions are related to the composition of fuel, and that the automobile industry's probable means of achieving the emissions standards was with catalytic converters; accordingly, it inserted language in the Clean Air Act that was subsequently to provide the basis for regulating fuel quality and lead levels. Congress specified two conditions under which the newly established Environmental Protection Agency (EPA) could control or prohibit fuels or fuel

additives: (a) if the fuel or additive endangered health or welfare or (b) if the fuel or additive impaired the performance of emission control devices (*6*). The second condition was to allow the EPA to mandate the elimination of lead. [U.S. Senate Report 91-1196, p. 34, noted that "The effect of lead on catalysts can reduce the effectiveness of such mufflers by up to 90 percent. Since the use of catalytic mufflers may be essential for compliance with standards established under section 202, the Committee has adopted language permitting the secretary to control fuels in order to facilitate the use of emission control systems."] Lead removal was of concern to automobile makers because the catalytic converter, which automobile makers perceived to be the most advanced and feasible technological option for achieving large vehicle emission reductions, was poisoned by tetraethyl lead.

Vehicle emission standards, which were the principal motivation for introducing unleaded gasoline, were resisted by the automobile industry. Beginning in early 1972 the major domestic automobile manufacturers and several foreign manufacturers filed for extensions. After extensive litigation, EPA Administrator Ruckelshaus granted an extension and established two sets of interim 1975 standards—one for California and one for the rest of the nation. Ruckelshaus believed that the stricter California standards (imposed by the more activist California regulators) would require the use of catalytic converters in all new cars for that state, but that the weaker national standards would result in few catalytic converters being used elsewhere. He believed that these interim standards eased sufficiently the technological and economic challenge of having to design and build the new catalytic converters on short notice (*7*, *8*).

Although the imposition of emission standards was delayed, the introduction of unleaded gasoline was not. In early 1973, the EPA adopted a series of regulations that forced the oil industry "to provide for the general availability of lead-free gasoline" (*9*). These regulations attempted to minimize any necessary changes in consumer behavior and placed the burden of implementation on the oil and automobile industries. The EPA thought that economic incentives by themselves would not be sufficient to assure that adequate supplies of unleaded gasoline would be available in 1975 when catalyst-equipped vehicles would first be marketed in large numbers. These regulations were premised on the conviction that not having unleaded gasoline generally available would "defeat the purpose" of the emission standards, because leaded fuel would destroy the emissions reduction capability of the converters (*10*).

One set of regulations required all retail outlets that sold 200,000 gal or more of gasoline per year to sell at least one grade of 91-octane (RON) unleaded gasoline by July 1, 1974 (*11*). [In the United States during the 1970s, gasoline octane was rated according to research octane number (RON). RON ratings did not accurately reflect operating conditions, so a motor octane number (MON) scale began to be used; gasoline is now rated as (RON + MON)/2, which gives a numerical rating somewhat less than the RON scale. All octane ratings in this paper use the RON scale.]

To prevent misfueling (i.e., putting leaded fuel in a catalyst-equipped car), the EPA promulgated a second set of regulations that required automobile manufacturers to build narrower tank inlets on cars that require unleaded gasoline and ordered fuel stations to use correspondingly smaller nozzles on their unleaded fuel pumps (*12*).

Also, signs were required on car tanks, instrument panels, and gasoline pumps (*13*). Retailers were prohibited from putting leaded gasoline into tanks of unleaded vehicles, with penalties of up to $10,000 per day (*14*). [EPA had also proposed, but then abandoned, requirements that unleaded fuels be dyed or conspicuously colored to help prevent misfueling (*15*).]

In summary, the drafters and implementers of the Clean Air Act were extraordinary in their determination to improve air quality dramatically and quickly. Even though the EPA delayed implementation of emission standards to ease the economic and technological burden on the automobile industry, the agency nonetheless was intent on aggressively implementing the intent of the law. Supported by enabling legislation, the EPA assumed responsibility for orchestrating the introduction of unleaded gasoline and catalytic converters, and took an activist stance by ordering the concurrent changes in the automotive, oil refining, and oil marketing industries that were necessary to ensure a smooth transition.

## AUTOMOTIVE INDUSTRY

The automotive industry did not have a favorable image around the beginning of the 1970s and was therefore vulnerable to governmental regulation. For instance, in response to a February 1971 nationwide Harris poll, 50 percent of those queried stated that the quality of automobiles was worse than it had been 10 years before; only 30 percent said quality had improved (*16*). Another nationwide Harris poll in February 1970 found that people were especially critical of automobile manufacturers' efforts to control air pollution: four times more people said that the manufacturers had done poorly (41 percent) or fair (27 percent) than said that they had done pretty well (15 percent) or excellent (2 percent) (*17*).

This skepticism about the performance of the automobile industry led many people to believe that clean air could only be achieved with a new power system that was not based on the well-known internal combustion engine. A poll in 1969 found that 62 percent of respondents favored outlawing the internal combustion engine in order to force automobile makers to produce cleaner burning cars (*18–20*).

The technology-forcing nature of the 90 percent emission reduction mandate and the numerical specificity of the standards were a manifestation of the distrust in which the public held the industry. Thus the decision by motor vehicle manufacturers to meet those standards by using conventional engines and catalytic converters (which required unleaded gasoline) was controversial—but it was not an unexpected decision. That decision was based on the industry's belief that research and development of a new type of engine would take too long and probably prove unsuccessful. Mobil Oil presented a statement to the Senate Committee on Public Works in 1972 that said, "The basic premise upon which IIEC [Inter-Industry Emission Control program, which comprised major automotive and oil companies] research has been conducted is that the gasoline-powered internal-combustion engine will be the dominant automotive power plant for some years to come" (*20*, p. 95).

It might be argued, as it was at the time, that Congress set the deadlines too soon (and the standards too low), precluding any

possibility of innovation in engine design and assuring the widespread use of catalysts. This argument is undermined by evidence that the automobile industry may have committed itself to the catalytic technology even before the Clean Air Act amendments were passed in 1970. A Senate committee print (*20*, p. 95) states:

> A review of the minutes of G.M. policymaking meetings held shortly after enactment of the Clean Air Act [1970] also reveals that the decision to continue prime emphasis on the present engine was made not because the Clean Air Act foreclosed other options but simply because G.M. thought the present engine the best one.

Subsequent studies support the industry's position that a long time is needed to develop, test, and commercialize new engine designs. The realization that catalyst technology required less technological change (and less research and development) than the development of new engine designs presumably was the underlying reason for the industry's quick commitment to the catalyst option. The converters were especially attractive because they were added on, not integral, to the engine itself. Indeed, a decade and a half later, western European nations were debating the same issue: whether to reduce vehicle emissions by requiring catalytic converters and unleaded fuel or by redesigning engines (using in this case lean-burn technology) (*21*, p. 159).

To smooth the transition to catalytic converters and unleaded gasoline in 1975 models, the automobile makers made plans to produce pre-1975 cars that could run on either unleaded or leaded gasoline. These "dual-fuel" cars required lower compression ratios to accommodate the lower octane of unleaded fuel, and changes in valves so that they no longer needed lead as a lubricant. The decision to produce dual-fuel vehicles was made in part to allay fears on the part of the petroleum industry that it would make large capital investments to produce unleaded gasoline and then find there was little demand for it. All 1971 General Motors (GM) cars were designed to run on either unleaded or leaded gasoline with a RON rating of 91 octane or higher (*22*, Part 2). [The conversion to unleaded gasoline in 1971 cars further supports the case that GM was committed to catalytic converters very early, probably by late 1969.] The initial decision by GM in February 1970 to make their cars compatible with unleaded fuel was editorialized by the *New York Times* as "the most dramatic action by any industry in the new environmental movement" (*22*, Part 3, p. 1058). The other automobile makers followed suit; all domestically produced 1972 cars were designed to use unleaded fuel. Ford estimated in early 1970 that 40 percent of the total 1975 vehicle population would be able to operate on unleaded gasoline (instead of only 10 percent if 1975 models were the first to be compatible with unleaded fuel) (*22*, Part 3, p. 1020).

Despite the 1-year extension of emission standards granted in 1973, and claims by Ruckelshaus that most 1975 model year cars would be able to meet the less stringent emission standards without catalysts, the industry equipped between 85 and 90 percent of its 1975 models with catalytic devices (*23*, *24*). GM led the way when they announced, less than 2 months after the extension was granted, that all 1975 models would be catalyst equipped (*25*). Ford used the converter on 70 percent of its automobiles and Chrysler on 75 percent; American Motor Company only needed it on one-third of their cars because of their smaller engines and correspondingly lower emissions (*26*). Because of the more restrictive emission standards in California, all 1975 domestically manufactured automobiles sold in that state were equipped with catalytic converters (*27*, EPA Statement, p. 42).

By the end of 1975 there were more than 6 million catalyst-equipped vehicles on the road; most imported 1976 model year automobiles and all U.S. models, except about 10 percent of Chrysler's cars, were equipped with catalytic converters (*28*).

Automobile makers were supportive of the elimination of lead not only because lead poisoned the catalysts but also because lead-free gasoline was expected to lower vehicle maintenance costs and increase fuel economy. An American Oil (Amoco) study (*29*) claimed that

> Eliminating the lead antiknock compounds unquestionably reduces or postpones the need for exhaust system repairs, spark plug replacement, carburetor service and other gasoline-related maintenance. Moreover, no adverse side effects such as valve seat wear have been observed.

The reduction in vehicle maintenance costs was estimated in that study at 4 to 5 cents per gallon, or about 0.3 cents per mile at that time. In addition, it was found that chemicals that accompany lead additives, such as hydrobromic and hydrochloric acids, caused deterioration in a car's engine, muffler, and tailpipe.

Automobile makers also expected cars to have better fuel economy with the catalytic converters. During the 5 years before 1975, automobile makers had "detuned" cars, sacrificing driveability, power, and efficiency to meet emission standards. With the new devices, automobile makers could tune engines to run more efficiently and rely on the catalytic converter to control pollutants. GM expected 1975 models (with catalysts) to be 13 percent more efficient than 1974 models, and Ford and Chrysler estimated lesser gains of 8 and 5 percent, respectively (*30*). (GM acknowledged later that part of the gain was due to changes in sales weighting. GM was apparently exaggerating fuel efficiency to promote sales of 1975 cars and possibly to defuse mounting pressure from Congress to legislate improved automotive fuel efficiency.)

GM was more enthusiastic about the switch to unleaded fuel than were other vehicle manufacturers. Before 1975 both Ford and Chrysler feared that unleaded gasoline shortages would encourage fuel switching or misfueling (use of leaded gasoline in unleaded tanks) (*31*, p. 1). Both companies had supported the proposal to delay the tightening of emission standards and the planned introduction of catalytic converters in 1975 (*8*, Part 1). Ford and Chrysler emphasized that the extra crude oil used to produce unleaded gasoline would easily offset any projected gains in fuel economy (*27*, p. 185). GM, however, citing an Arthur D. Little report that they had commissioned, stated that "up to 50 percent of gasoline production could be unleaded at 91 research octane number . . . without a crude oil utilization penalty" (*27*, p. 194). After assurances from the petroleum industry, GM believed that unleaded fuel would be available in adequate quantities for 1975 models (*27*, pp. 195, 314).

The apparent contradiction of the automobile industry vigorously fighting emission standards, while at the same time embracing unleaded gasoline, is readily explained. The industry knew that it would have to reduce emissions significantly; fighting imposition of emission standards would delay and

perhaps lessen, but not eliminate, the standards. That delay was valuable; it allowed the companies time to further test and improve what to them was a major technological change. This was important because the reputation and future sales of a company depend on vehicle reliability. The industry required, and still requires, long lead times in which to design, test, and manufacture a new technological component. From this perspective, it was in the automobile industry's interest to have unleaded fuel on the market as soon as possible, in anticipation of catalytic converters. Because most of the initial (pre-1975) cost burden of accelerating the introduction of unleaded gasoline fell on the oil industry—the automobile industry had only to make cars compatible with unleaded gasoline—and because unleaded gasoline was necessary if catalytic converters were to be used, it is not surprising that the automobile industry proved to be enthusiastic proponents of unleaded gasoline.

## PETROLEUM INDUSTRY

The petroleum industry played a relatively passive role in the transition to unleaded gasoline. The industry obviously had a deep interest in the debate, but it was not unduly threatened by the transition. Principal reasons for this passivity were the absence of technical challenges and, after late 1973, abundant revenues.

Clearly, though, the transition to unleaded gasoline represented a major change in the oil-refining industry. Through the late 1960s refiners had steadily increased lead content of gasoline in order to serve growing demand for higher engine compression ratios (to get more power). The oil industry became highly dependent on lead. By the late 1960s, refiners were using about 2.5 g/gal of gasoline (Ethyl Corp. estimates, March 1984), which was enough to boost octane ratings six to nine points. They did not use more because larger doses had a diminishing effect on octane.

Refiners had (and still have) two basic options besides lead for increasing octane: they may refine petroleum more intensively or they may use hydrocarbon chemicals or oxygenated hydrocarbons (e.g., alcohol) as additives. These options were, and are, more expensive than lead. In almost all cases, refiners chose more intensive processing.

Until 1970 only one company, Amoco, had consistently offered unleaded gasoline. Their "white gas" had been on the market since 1915. Although it comprised less than 2 percent of the total gasoline market, Amoco's lead-free 100-octane Super Premium generally out-sold its regular leaded brand by a 2-to-1 margin in the 25 southern and eastern states where it was offered. In 1970 Amoco introduced a 91-octane unleaded fuel, which reduced Super Premium's sales to 55 percent of Amoco sales (*22*, Part 3, p. 1092).

By late 1970 several companies had introduced, or planned to introduce, low-lead or no-lead gasoline (Table 1). Oil marketers were interested in unleaded and low-lead gasoline because they thought the new environmental consciousness would motivate demand for these fuels, even though unleaded gasolines were priced 1 to 4 cents per gallon higher than equivalent leaded gasoline (*32*). They also hoped that longer engine life and lower maintenance costs would attract customers. But sales were poor. In 1971 only 2 to 3 percent of all gasoline sales were low-lead or no-lead (*22*, Part 3, p. 1063). One petroleum industry executive called the marketing of unleaded gasoline in the early 1970s premature and "a lesson in mass hysteria and panic marketing" (*33*). To overcome consumer reluctance, some companies raised the octane of unleaded gasoline.

TABLE 1 OIL COMPANIES PRODUCING LOW-LEAD OR NO-LEAD GASOLINE IN 1970

| Company | Low-Lead | No-Lead | Octane (RON) |
|---|---|---|---|
| American Oil Company | | X | 100 |
| | | X | 91 |
| Ashland Oil Company | X | | 91 |
| Atlantic Richfield Company | | X | 91 |
| Gulf Oil Company | X | | 91 |
| Humble Oil and Refining Company | X | | 96 |
| Mobil Oil | X | | 91 |
| Murphy Oil Corporation | | X | 91 |
| Phillips Petroleum | X | | 93.5 |
| Powerline Oil Company | X | | 91.5 |
| Shell Oil | | X | 91 |
| Standard Oil of California | X | | 94 |
| | | X | 91 |
| Sun Oil Company | X | | 91 |
| Texaco | | X | 91 |
| Union Oil of California | X | | 93.5 |

SOURCE: Tax Recommendations of the President: Hearings Before the House Committee on Ways and Means, Sept. 1970, p. 341.

Even so, unleaded gasoline sales remained quite low until catalytic converters were introduced. As late as 1974 unleaded gasoline had only about a 5 percent market share (*34*, p. 38). Several factors contributed to this failure. The most important was that motorists could freely choose between unleaded and leaded gasoline—either fuel could be used in their cars. In addition, unleaded gasoline was for consumers a new, unfamiliar, and more expensive fuel. Cleaner engines and air did not provide enough motivation because motorists often were unaware of the air quality benefits, and, even if they were, those benefits were vague and intangible. The benefits of longer engine life and lower maintenance costs were also not obvious. Lack of immediate feedback information left people uncertain about (and in many cases unaware of) the benefits of unleaded gasoline.

When Congress and the EPA attempted to regulate the oil industry and force it to produce unleaded gasoline, the oil company arguments centered not on technology but on costs. Producing unleaded gasoline on such a widespread basis required major investments in refinery equipment and changes in certain operating procedures in distribution and marketing. A 1971 consultant study for the EPA pointed out that "the most significant impact of a lead removal program on the domestic petroleum industry is the requirement that more capital be spent on refineries over the next 10 years . . . ." (*35*). However, the report also noted that cost estimates were quite uncertain because of the flexibility with which equipment could be used to refine oil products. During the drafting of the 1970 Clean Air Act amendments, the American Petroleum Institute (API), trade organization of the oil industry, had projected that producing unleaded gasoline would cost about 2 cents per gallon more than producing leaded gasoline (*36*, p. 106).

Estimates of total additional capital costs varied from about $4 billion to $6 billion (*37*).

Unleaded gasoline was more of a threat to small oil refiners than to large refiners because their simpler facilities were less flexible and more difficult to modify. In the early 1970s, unleaded gasoline was not perceived as a disaster for small refiners, however, because leaded gasoline sales were expected to be large enough for a long enough time to allow small refiners to survive (*31*, p. 1).

The cost of adapting the gasoline distribution and marketing system was another concern. Precautions had to be taken to assure that lead levels in unleaded gasoline did not exceed EPA standards. Pipeline operating procedures had to be modified to minimize contamination, and separate storage facilities were needed throughout the distribution system, including retail service stations. Most companies found it necessary to institute test procedures to monitor lead levels (*31*, p. 18). The total cost of adapting the distribution system to unleaded gasoline was large but never specified; however, because thousands of companies were involved, the costs were widely distributed.

Costs incurred at retail stations were estimated in 1978 at $5,951 per outlet (*34*, p. 125). Many outlets kept costs down by eliminating leaded premium gasoline and converting the leaded premium pump and tank to unleaded gasoline. This conversion, which continued into the 1980s as the number of pre-1975 cars on the road diminished, mitigated the burden placed on fuel station operators.

The oil industry was alarmed more by the government's interventionist approach than by the concept of unleaded gasoline. Initially, several of the major oil companies urged Congress to let the market, not government, guide the introduction and use of unleaded gasoline (*31*, p. 18). As part of their opposition to government intervention, most oil companies supported the automobile makers' request for delays and changes in emission standards (*8*, p. 188). For instance, Mobil placed full-page advertisements in at least five major newspapers, referring to the emission standards in the Clean Air Act as "the $66 billion mistake." The industry was not unified, however, in taking a belligerent and active role in opposing unleaded gasoline (and emission standards). The American Petroleum Institute, for instance, meekly argued that a "systems approach must be taken, that it is not enough to look at just one aspect of the problem and decide on a specific cure for it . . . it is unwise to base a decision on the [still unproved] catalytic muffler alone" (*37*).

The transition to unleaded gasoline was not disruptive to the oil industry; indeed, it was accomplished with relatively little conflict. There were several reasons for the smoothness of the transition and relative lack of rancor between the oil industry and government: (a) uncertainty was minimized because a fairly firm timetable was imposed by the federal government; (b) the industry was already regulated and, despite its misgivings, already accustomed to dealing with government regulators; (c) demand for unleaded gasoline increased at a rather modest pace because of the slow turnover of vehicles (Table 2); (d) the dramatic oil price increases in 1973–1974 mitigated concerns about increased refinery costs; (e) the industry faced no major technological difficulties; (f) the unpopular image of the oil companies in the 1970s (as illustrated by the continuing attempts of Congress to divest the large companies of their vertically integrated operations) encouraged the industry to acquiesce rather than fight; and (g) much of the additional cost could be passed through to the consumer.

TABLE 2 LEADED AND UNLEADED GASOLINE SALES IN THE UNITED STATES

| Year | Total Gasoline | Unleaded | Percentage Unleaded |
|---|---|---|---|
| 1974 | 6,537 | ~300 | 5 |
| 1975 | 6,675 | ~870 | 13 |
| 1976 | 6,978 | ~1,400 | 19–22 |
| 1977 | 7,176 | 1,976 | 27.5 |
| 1978 | 7,412 | 2,521 | 34.0 |
| 1979 | 7,034 | 2,798 | 39.8 |
| 1980 | 6,579 | 3,067 | 46.6 |
| 1981 | 6,588 | 3,264 | 49.5 |
| 1982 | 6,539 | 3,409 | 52.1 |
| 1983 | 6,622 | 3,647 | 55.1 |
| 1984 | 6,693 | 3,987 | 59.6 |
| 1985 | 6,815 | 4,395 | 64.5 |

NOTE: Values are thousands of barrels per day.
SOURCE: *Monthly Energy Review*. Energy Information Administration, U.S. Department of Energy, March 1986; Competition in Retail Sales of Motor Gasoline: Hearings Before the Senate Committee on Environment and Natural Resources, March 26, 1979.

The lack of unity in the oil industry and the inability to demonstrate that unleaded gasoline would cause an extraordinary burden undermined the industry's opposition. Thus, unlike the automobile industry, the oil industry was unsuccessful in swaying the EPA from its aggressive posture; the EPA did not relent in ordering the marketing of unleaded gasoline.

## LEAD PRODUCERS

Though not targeted directly through regulation, the lead producers were more directly threatened by the introduction of unleaded gasoline than any other industry group. Because legislation and regulation would eliminate its market, the lead industry was, of course, unequivocally opposed to the introduction of unleaded gasoline. However, the overwhelming public and political mandate for cleaner cars and air and the aggressive actions of the automobile industry in moving toward catalytic converters proved to be dominant.

Only four companies manufactured lead at the time—Ethyl Corporation, DuPont, PPG Industries, and Nalco Chemical Company. DuPont and Ethyl each produced about 40 percent of the lead additives used in the United States (*38*). Except for Ethyl, none of the companies was highly dependent on revenues from lead sales. The effect on these four companies was moderated by the gradual, not precipitous, reduction in demand for lead additives and by continued demand for lead elsewhere in the world.

Of the four companies, Ethyl objected the most strenuously to the regulations. Ethyl Corporation was created in 1924 by DuPont and GM to produce and market lead additives (*4*, p. 344). Because of this historical and financial commitment to lead additives, Ethyl invested heavily in research and development of automobile emission control devices (i.e., thermal reactors), as well as in lead particulate traps that reduce lead emissions. Other firms, including DuPont, also developed thermal reactors and lead trap devices. However, no such devices

were adopted by the automobile makers, apparently because of suspected reliability problems and because the thermal reactors were so bulky (*37*).

The effect of the regulations on Ethyl is evident in the company's sales figures. Lead additives accounted for 90 percent of Ethyl's sales in 1962 (*39*). This percentage dropped to 40 percent ($200 million) in 1970 as the company began its diversification and continued to drop thereafter (*36*, p. 104). In 1973 about half of Ethyl's lead sales were in other countries (*39*). Ethyl stock took a large plunge in 1970 to a low of 15 from a 1969 high of 36¾ (*40*). Between 1967 and 1974, the company's ratio of stock price to earnings fell from 22 to 4 (*39*). During this period Ethyl diversified into plastics, aluminum, coal, other chemicals, and, in 1982, insurance (*41*).

The actions of the lead industry were to be expected. Ethyl, in particular, had much to lose. However, with only four companies selling lead and only one with a large stake in the product, the lead producers' interests received little attention. In any case, decisions by Congress and the EPA did not cause widespread economic distress; even Ethyl had enough time to adapt.

## PRICES AND CONSUMER RESPONSE

Consumer acceptance of any new product is based above all on price. If unleaded gasoline is comparable in quality with but higher in price than leaded gasoline, motorists can be expected to attempt to use leaded gasoline in catalyst-equipped vehicles. That indeed proved to be the case.

Before 1975 it was estimated that the additional refining costs of unleaded gasoline were about 2 cents per gallon greater than for leaded regular gasoline. On the basis of these estimates, the EPA expected the retail price differential between unleaded and leaded gasoline also to be about 2 cents per gallon. However, in 1975 the price differential at the pump was considerably more than 2 cents, which encouraged fuel switching. During 1978 hearings on the subject, D. J. Bordin of the U.S. Department of Energy (DOE) stated that 1977 wholesale price differentials were between 2.4 and 2.6 cents per gallon, but that at the retail end the differential at full-service pumps was 3.7 cents for majors and 3.8 cents for independents, and at self-serve pumps, 5.6 cents and 4.1 cents for majors and independents, respectively (*34*, pp. 3–27).

The DOE representative attributed this large retail differential mostly to excess supply of leaded regular gasoline, but also to marketing strategies by stations that were posting lower leaded prices in order to attract customers for the higher-priced fuels.

The EPA believed that these price differentials contributed to an estimated 12 percent fuel switching rate in early 1978 (*34*, p. 47). One reason for such a high rate was the reported ease with which car owners could remove the gasoline tank restricters on their cars and thereby use the larger leaded pump nozzles. Also, it was not illegal initially for motorists to use leaded gasoline in catalyst-equipped vehicles. By 1979, 34 states had passed laws prohibiting such actions, but enforcement was weak (*42*).

During the fuel switching debate, the petroleum industry defended itself by stressing that the lower octane of unleaded gasoline caused cars to knock more. This knocking, not the lower price, they believed, was the prime motivation for using leaded fuel (*34*, pp. 49–63, 123–124). [The National Oil Jobbers Council reported incidents of car owners verbally and physically abusing station employees if they would not pump leaded gasoline into unleaded vehicles. The EPA testified that misfueling rates were almost 15 percent at full-service pumps and 10 percent at self-service pumps (*34*, p. 43).] If car owners found that knocking ceased or decreased after using leaded gasoline, they had considerable incentive to continue using the cheaper fuel, even though it would effectively destroy the catalyst and result in greater pollution. The EPA conceded that knocking was an incentive to misfuel but emphasized that price differentials were the more important factor (*34*, pp. 46–49). However, in a study commissioned by the EPA in 1978, it was claimed that even without a price differential the switching rate would still be about 6 percent (*43*). The study found that fuel switching was more prevalent in the Pacific region and rural areas and among younger, middle-income, and better-educated people, as well as at self-service stations.

The EPA attempted several methods of enforcement including radio announcements, brochures, and a request to 28 oil companies to insert in credit card bills notices that retailers were not allowed to place leaded fuel in unleaded tanks. At least 16 of the companies indicated they would comply (*34*, p. 31). In addition, by 1978 the EPA had prosecuted or was prosecuting 16 fleet owners and 16 owners of retail fuel outlets. Considering that hundreds of thousands of fleets and fuel outlets existed, this enforcement effort was meager. Staffing and funding shortages were blamed for this weak enforcement (*43*).

In addition to greater enforcement, the EPA thought that regulations were needed that explicitly addressed the large price differential between leaded and unleaded gasoline. Such regulations would be more easily enforced than, for instance, the "penny rule" that, as part of the complex fuel price regulations of the 1970s, allowed refiners to charge more for their gasoline (up to 1 additional cent per gallon) if they increased unleaded gasoline production (*34*, p. 31; *42*).

The price differential problem was never solved; indeed, it was aggravated in the early 1980s by deregulation of oil prices. As the market share of leaded gasoline shrank, marketers often reduced leaded gasoline prices relative to regular unleaded—a marketing ploy to lure price-conscious motorists who might not be alert to unleaded gasoline's substantially higher price until they stop alongside the pump. The price differential between leaded and unleaded gasoline increased steadily from about 2.5 cents per gallon in 1976 to 5.4 cents in 1980 and then stabilized at about 8.5 cents from 1983 through 1986 (*44*).

## CONCLUSION

The transition to unleaded gasoline in the United States was extraordinary because of the way it occurred and because of its speed and smoothness. The most extraordinary feature of the transition was the active intervention of the U.S. government in market activities. In this case, despite the fact that market factors were deliberately ignored by government action, the transition was successful. Indeed, the one failing of the transition was the large number of motorists who misfueled their vehicles with leaded gasoline, thereby destroying the effectiveness of the catalytic converters and sharply increasing their

vehicles' emissions. This misfueling was a result of not sending the appropriate price signals to consumers.

An important lesson from the unleaded gasoline experience is that, although it is better to give appropriate market signals to consumers than not to, government may ignore the market but only if it can be certain of enforcing its actions. This nonmarket approach, similar to Charles Schultze's "command-and-control" approach (*45*), is most effective when the smallest number of people (or corporations or other organizations) is involved (*46*). Thus government efforts to enforce the standards for lead in unleaded gasoline were not particularly effective because of the large numbers of businesses and consumers involved. The large number of businesses involved in transporting, storing, and marketing gasoline hindered enforcement of lead levels, and the large number of motorists hindered enforcement of misfueling rules. On the other hand, it was much easier to enforce vehicle design requirements and emission standards because regulators had to deal principally with only three entities: Ford, GM, and Chrysler. Overall, government orchestration was not necessarily efficient and enforcement was sometimes weak, but the net result was a continuing and fairly rapid transition.

One explanation for the successful transition was the avoidance of too much attention. New technologies are bound to experience problems initially. Because news reporters (for television, newspapers, and magazines) are attracted to and tend to dramatize failings of government-sponsored initiatives and perceived defects in widely used consumer goods, new fuels and vehicles must survive high levels of scrutiny. Exceptionally high levels of quality must be maintained. Unleaded gasoline was not targeted by the media because, unlike other new fuels and engines, it was not vulnerable to consumer-perceived failings. Breakdowns of catalytic converters meant diminished emission control effectiveness, but those breakdowns usually did not affect engine performance; similarly, fuel contamination problems usually affected the catalysts, but not engine performance. Moreover, the use of unleaded gasoline and catalytic converters was essentially invisible to the consumer. No behavioral changes of any type were needed. In contrast, consider the U.S. diesel car case; technical problems with GM's diesel cars in the late 1970s attracted so much attention that it played a major role in causing an almost complete collapse industry-wide of what had been thought to be a highly promising new product (*47*). Similarly, reported technical problems with retrofitted ethanol cars in Brazil in the early 1980s were a major factor in causing sales of factory-produced ethanol cars to collapse (from 73 to 9 percent of new car sales in only 7 months), even though problems with retrofitted vehicles had nothing to do with factory-produced ethanol vehicles (*48*). In the diesel car case, engines and fuel were distinctly different from gasoline and gasoline engines and required special attention; in the Brazilian ethanol case, engine and fuel were also distinct and subject to exceptional scrutiny. Unleaded gasoline, on the other hand, is quite similar to leaded gasoline and the engines are essentially identical; thus unleaded gasoline was not vulnerable to easily observed problems, received virtually no scrutiny from the media, and suffered no public relations setbacks.

A second explanation for the success of unleaded fuel was widespread support for air quality improvements during the 1970s. This national commitment to air quality created a general aura of support for unleaded gasoline, reducing further its vulnerability to devastating exposés.

A third important factor was the concentration of implementation authority and responsibility in one organization—the Environmental Protection Agency. There was no substantive overlap of responsibility or authority with other government agencies; thus the EPA could coordinate the promulgation of all regulations and rules affecting vehicles, fuel production, and fuel distribution and marketing. In contrast, the introduction of ethanol in Brazil involved continual turf battles among various government and quasi-government organizations, including the national petroleum monopoly that controlled fuel marketing and sought to control the entire ethanol program, the Sugar and Alcohol Institute that regulated the sugar cane industry, the National Alcohol Council that reviewed distillery fuel projects, and the National Monetary Council that allocated subsidized credit (*48*). The EPA's autonomy allowed it to develop strategies and coordinate activities effectively.

A fourth factor was luck, although to some extent the EPA must be given credit for taking advantage of situations. Some examples of luck were public antipathy to large corporations, the windfall wealth of oil companies that resulted from the 1973–1974 oil price increases, and the strength of the domestic economy.

Perhaps the most important factor in the success of the transition was the effective reduction of uncertainty and risk to industry and consumers. Several initiatives were crucial: cooperation between the EPA and the automotive and petroleum industries to standardize technologies and to minimize misfueling; incentives to oil refiners to produce unleaded gasoline; mandated sales of unleaded gasoline by retail fuel outlets; and establishment of precise standards and implementation schedules for the oil, automobile, and lead industries. By taking these actions, the EPA reduced uncertainty for all participants including consumers.

Because of government's extraordinary role in orchestrating the transition to unleaded gasoline, uncertainty and risk were a minor consideration for businesses and consumers. All participants (as well as the nonparticipant lead producers) could act with a great deal of certainty—with the knowledge that unleaded gasoline would be widely available, that unleaded gasoline cars would be supported by the automobile and parts industry, and that consumers would have no choice but to purchase unleaded gasoline vehicles (only Honda CVCC cars continued to operate on leaded gasoline in the late 1970s).

The unleaded gasoline experience of the United States is one example, based on government-initiated and government-orchestrated actions, of how to introduce a new transportation fuel. [For an analysis of alternative fuel strategies and options, see Sperling (*49*).] It is the most successful model in the world of government intervention to introduce a new transportation fuel—ironically in a country with a decentralized political system, a market-based economy, and practically no centralized planning.

Although the circumstances of the transition to unleaded gasoline cannot be directly generalized to other times and places, the experience also cannot be dismissed as an aberration or as the result of a crisis situation. It was neither. The U.S. transition to unleaded gasoline provides useful lessons for

countries contemplating the introduction of new transportation fuels.

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