An examination of the potential for methanol and other alternative transportation fuels to compete with petroleum-based fuels should not assume that the existing fuel supply network is a stationary target. Current investors in this network may be expected to compete vigorously for market share with the new fuels, rather than see their existing investment in gasoline supply lose value. And to the extent that Federal and State support for alternative fuels takes the form of requirements for low-emission vehicles or other requirements tied to improving urban air quality, gasoline refiners can be expected to reformulate their product (see box 8-A) to obtain similar emissions benefits and avoid a mandated switch to the new fuels.

Until recently, with the important exception of the lead phasedown, there has been relatively little incentive, and little effort, to improve gasoline’s performance in terms of reducing vehicle emissions. Governments had exerted limited pressure to improve this performance: on the Federal level, the past pressure has on the whole been limited to requirements for lead reduction and elimination and, more recently, to controls on fuel volatility to control smog-causing evaporative emissions; at the State and local levels, pressure has been limited to a few areas requiring addition of oxygenates to reduce carbon monoxide emissions and to California’s requirement for a ceiling on gasoline volatility (more stringent than the Federal requirements) and sulfur content (and the South Coast Air Quality Management District’s reduction in olefinicity). With this limited pressure, the oil industry generally has avoided changing the composition of gasoline to reduce emissions, because such changes are expensive and unlikely to have market value. Instead, the

Box-8-A—What Is Reformulated Gasoline?

Unlike methanol or hydrogen, which are composed wholly of single chemical compounds, or even natural gas, which is composed of several compounds but is predominantly methane, gasoline is a complex mixture of flammable liquid hydrocarbons made from petroleum and natural gas. Some of these hydrocarbons are present in the oil and gas and are obtained by separating them from the oil and gas using distillation and other separation technologies. Others are created by a variety of physical and chemical transformation processes, often in the presence of catalysts, in a modern refinery. For example, aromatics are obtained from catalytic reforming; olefins from catalytic cracking or catalytic polymerization; and isoparaffins from distillation (separation) or by isomerization of normal paraffins, or in the alkylation process.1

In order to be a practical fuel for a modern automobile, gasoline must satisfy a number of requirements pertaining to its volatility, octane level, tendency to form engine deposits, and other characteristics. Refiners can satisfy these requirements using a variety of different combinations of chemical components, with their selection dependent on relative costs of the different components, market prices for other products, refinery capability, and quality of the crude oil feedstocks available. The production of reformulated gasoline simply accentuates the importance of a particular fuel characteristic—the fuel’s effect on emissions—in the selection of gasoline components, and possibly also in the degree of purification applied to the fuel. For example, the addition of oxygenates—ethanol, methanol, methyl tertiary butyl ether, and so forth—to the gasoline blend can reduce exhaust carbon monoxide emissions and may serve to reduce the reactivity of exhaust hydrocarbon emissions, yielding a net reduction in ambient ozone concentrations. Reducing the more volatile components of the fuel will reduce overall volatility and yield lower evaporative emissions. Removing sulfur impurities will reduce emissions of sulfur oxides and hydrogen sulfide. Because the gasoline components undergo radical chemical transformations inside the engine, and then the exhaust emissions undergo still more transformations inside the catalytic converter, the precise form that a reformulated gasoline must take can only be learned through extensive testing.


industry has focused its production and marketing efforts on changes to achieve better vehicle performance and drivability and lower maintenance—attributes that are valued by gasoline purchasers and thus provide market advantage.

ARCO’S “EMISSION CONTROL 1“ GASOLINE

In August of 1989, Atlantic Richfield Oil Co. (ARCO), fired the opening salvo in the new competition for the future light-duty fuel market by introducing a so-called ‘reformulated gasoline’ to replace leaded regular gasoline at its southern California stations. This gasoline, named EC-1 (“Emission Control 1”), contains one-third less olefins and aromatics and 50 percent less benzene, no lead, and 80 percent less sulfur than regular gasoline. It has low volatility—its vapor pressure (RVP) is 1 psi lower than the South Coast standard. It contains methyl tertiary butyl ether, or MTBE, an octane-raising additive derived from methanol that raises the oxygen content of the fuel and provides emission benefits, especially in reducing carbon monoxide emissions, without the volatility increase—and increase in evaporative emissions—normally associated with adding oxygenates.

ARCO has claimed significant emissions reductions when EC-1 is used in place of regular leaded gasoline in pre-1975 model-year cars:

<table>
<thead>
<tr>
<th>Emission Type</th>
<th>Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaporative emissions</td>
<td>−21</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>−9</td>
</tr>
<tr>
<td>Nitrogen oxides</td>
<td>−5</td>
</tr>
<tr>
<td>Hydrocarbons (exhaust)</td>
<td>−4</td>
</tr>
<tr>
<td>Sulfur dioxides</td>
<td>−80</td>
</tr>
</tbody>
</table>

ARCO redirects the olefin and aromatic streams removed from EC-1 into its unleaded grades, however, so there maybe some increase in emissions, or in the reactivity of emissions, from vehicles using these grades. Because the catalytic controls of the vehicles using these fuel grades are designed to handle such emissions, it is likely that any increase will be relatively small—but they should be accounted for in an assessment of costs and benefits.

The emission benefits of EC-1-type gasolines can, in theory, be gained immediately by a substantial part of the fleet—ARCO claims that pre-1975 vehicles made up about 15 percent of the vehicles in California’s South Coast air basin in 1989, and emitted more than 30 percent of total vehicle emissions. If environment-conscious drivers give ARCO additional market share, or if California’s legislators turn ARCO’s voluntary emission reduction into a requirement, other refiners will follow ARCO’s lead, probably within a short time. Reformulated versions of unleaded gas for catalyst-equipped vehicles are expected to appear as well, although not until the early 1990s.

REFORMULATION POTENTIAL

Gasoline is made from crude oil by mixing natural constituents of the crude with constituents formed from the crude during the refining process, as well as other nonpetroleum-based constituents such as alcohols or ethers made from alcohols. The four major groups of petroleum-based constituents of gasoline are:

- **olefins**: high-octane chemicals produced from crude during refining, and also occurring naturally in the crude in very low concentrations. Many of the olefins are both highly volatile (they evaporate easily) and highly reactive (in the presence of sunlight, they react with nitrogen oxides and other atmospheric constituents to form ozone);
- **aromatics**: even higher octane constituents, occurring naturally in crude in moderate to high concentrations. Aromatics are reactive, though not as much as olefins;
- **paraffins**: consisting of two groups, “highly branched” paraffins that are both high in octane and low in reactivity, and “straight chain” paraffins that also are low in reactivity but are very low octane. Paraffins, like aromatics, are present in crude at moderate to high concentrations, depending on crude type; and
- **benzene**: a strong-smelling, colorless liquid that is highly flammable and toxic. Benzene is a known carcinogen.

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3Olefins and some aromatics are significant smog-producers; benzene is carcinogenic.

4“ARCO’s To Market Low-Emission Regular Gasoline,” *Oil and Gas Journal*, vol. 87, No. 34, Aug. 21, 1989, p. 31.

5Pre-1975 cars do not have catalytic converters.

6Oil and Gas Journal, op. cit., footnote 4.
\textit{naphthenes:} between paraffins and olefins in octane; present in crude in moderate to high concentrations.

The combination of Federal emission control and lead phaseout requirements, higher crude prices, and the growing demand for gasoline have caused major changes in the makeup of gasoline. These changes, in turn, had some negative effects on gasoline environmental quality. For example, refiners expanded cracking capacity and severity to increase gasoline yields and octane, thereby increasing production of light olefins, which are highly reactive and volatile. Refiners also channeled increasing supplies of butane into gasoline to increase yields, at the cost of higher vapor pressure and thus higher evaporative emissions.\footnote{W.J. Piel, ARCO Chemical Co., "The Role of Ethers in Low-Emission Gasoline," National Conference on Motor Fuels & Air Quality, Oct. 3-5, 1989, Washington, DC.}

Federal requirements to reduce and eliminate lead content created a need for additional octane enhancement, because lead had been a key octane-raising constituent of gasoline. To replace lead, refiners increased the conversion of paraffins and naphthenes into higher octane branched paraffins, olefins, and aromatics. Ironically, these changes, designed to allow the use of catalytic converters that would reduce tailpipe mass emissions, increased the reactivity of the fuels and presumably their emissions (thus increasing their impact per unit mass on ozone formation) and, by increasing gasoline volatility, lessened the effectiveness of new controls on evaporative emissions introduced at the same time. Although the \textit{net} effect of the vehicle and fuel changes was a reduction in effective ozone-causing emissions, the fuel reactivity and volatility increases reduced the overall air quality benefit.

As a general rule, environmental reformulation of gasoline will lower volatility, lower the concentrations of aromatics and volatile olefins, and add oxygenates. A primary holdup in gasoline reformulation, however, is a significant lack of knowledge about the \textit{precise} role that each gasoline constituent plays in vehicle emissions, and (to a lesser extent) the role of the emissions in ozone formation. The lack of understanding about vehicle emissions is more severe with cars equipped with catalytic controls, because sophisticated controls tend to further complicate the relationship between gasoline makeup and emissions, by destroying some hydrocarbons and converting others into new compounds with different reactivities. Directionally, refiners know that they need to reduce aromatic and olefin content, but they can’t as yet quantify the effects of these reductions, and emissions benefits may be strongly nonlinear. Also, aromatics and olefins are produced during combustion and in the catalyst, so even elimination of these compounds in the fuel will not eliminate their presence in the exhaust. Further, refiners do not yet understand the potential emissions impact of switching the makeup of gasoline in subtler ways, for example, in replacing certain aromatics with other aromatics. And refiners will have to figure out how to deal with excess aromatics and olefins, since the option to move them to another product pool will vanish as reformulation requirements expand to cover a larger share of the gasoline pool.

The oil and automobile industries recently began a joint research program to better define the impact of changes in the major gasoline constituents on emissions levels, as well as to examine alternatives to gasoline.

The frost phase of the program, for completion by 1990, will test a variety of reformulated gasolines in 1989 vehicles and 1983-85 vehicles (the program will test methanol fuels in flexible fuel vehicles, as well).\footnote{American Petroleum Institute and General Motors Corp., "Auto/Oil Air Quality Improvement Research Program," news release of Oct. 17, 1989.} The gasolines will be restricted to those producible in volumes from existing refineries. A critical aspect of the tests is that they will measure specific chemical constituents of the emissions, and then use the results in air quality models to estimate urban ozone levels that would result from use of the fuels. Collection of this type of speciated data has been extremely limited thus far.

The second phase of the program will conduct research on advanced technology gasoline and alternative fuel vehicles. The reformulated gasoline research will examine future gasolines including those requiring significant refinery changes, and will explore the potential to optimize the fuel-vehicle system by simultaneously reformulating gasoline and changing vehicle emission control parameters.\footnote{Ibid.}
Given the general direction in which they must move, however, refiners appear to have several options. One important option is the use of ethers, produced by combining various alcohols with olefins (examples: MTBE, made from methanol and isobutylene; ETBE, made from ethanol and isobutylene, and TAME, made from methanol and isoamylenes) to displace light olefins (primarily the C_4 olefins) and aromatics as octane boosters. Ethers have the triple advantage of being oxygenates, which tend to lean out engine combustion and reduce carbon monoxide emissions (especially in older vehicles, but recent test have shown they reduce CO in new vehicles as well), of being high in octane, and of having a low volatility effect. In addition, ether manufacture, by providing an alternative use for C_4 and possibly C_5 olefins, will dilute the concentration of these reactive compounds in gasoline. Also, butane can be used to produce isobutylene, needed for MTBE or ETBE production, potentially providing an alternative use for this compound as well.

Refiners may also be able to increase catalytic cracking severities and selectively favor the formation of lighter components, e.g., isobutane and butylenes, and then use alkylation or other polymerization processes to combine these into highly branched paraffins. And refiners could increase the removal of benzene from gasoline using extraction, and hydrogenate the benzene to cyclohexane, which is less reactive but still moderate octane. A key question here, as elsewhere, is the expense of lowering benzene concentrations, or concentrations of other aromatics such as xylenes.

There is also evidence that some aromatics are less reactive for smog formation than others. With proper identification of reactivity levels, refiners will be able to convert highly reactive aromatics to less reactive aromatics. Again, the presence of the catalytic converter complicates these relationships.

Another option for some refiners is to increase their use of deposit control additives to reduce deterioration of vehicle exhaust emission control systems. There is substantial evidence that differences between exhaust emissions levels in on-the-road vehicles and levels achieved during EPA vehicle certification testing—the on-the-road levels are significantly higher—are caused in part by insufficient deposit control additives. A 1986 survey by Chevron concluded that only 16 percent of California gasolines contained high concentrations of such additives. Advertising campaigns by several of the major oil companies state that they have increased the level of detergents in their fuel formulations, primarily due to complaints from owners of cars with fuel-injected engines, so that the remaining margin for improvement may have shrunk considerably.

We cannot overstress the uncertainty associated with projecting the emissions-reduction potential of reformulated gasoline. With the exception of EC-1 and perhaps one or two more recent market entries, reformulated gasoline is a concept, not a reality. The potential effect on newer, catalyst-equipped cars is particularly uncertain. Although discussions of reformulated gasoline tend to presume that it would likely be able to match M85 in emissions performance, but not M100, there appears to be little basis for such assumptions.

**COSTS**

The long-term costs of gasoline reformulation cannot be predicted accurately until the nature of the reformulation is better defined. However, some basic aspects of reformulation costs can be projected.

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11 Ibid.
12 Catalytic cracking subjects the feedstock to high temperature in the presence of a catalyst, producing lighter constituents by breaking down heavier ones.
13 In many areas, benzene is already being extracted for sale as a chemical, but this market is limited.
15 Ibid.
16 The January 1990 issue of C-Sum Review presents the results of a survey of gasoline marketers. The survey indicates that, while 6 major brands had passed a widely accepted test for deposit control for all 3 grades of their gasoline, 17 others had either not passed the test or had passed it for only 1 or 2 grades.
EC-1 will cost ARCO an additional 2 cents per gallon to manufacture. These costs represent only changes in operating costs (for example, refinery energy costs are about 10 percent higher in producing EC-118), byproduct credits, and feedstock costs rather than capital costs. ARCO’s existing Carson, California refinery has the necessary equipment to produce 36 million gallons/month of EC-1, which is more than the 23 million gallons/month of leaded regular that ARCO previously sold in southern California, so ARCO did not incur significant capital costs. Also, ARCO can use the aromatics removed from EC-1 in its other unleaded gasolines for catalyst-equipped vehicles, where the added emissions potential of these components will be controlled. However, with the current limited understanding of the relationship between fuel properties and vehicle emissions, it is not clear how much additional use ARCO can make of this fleet as a “sink” for aromatics. The ability of refiners nationwide to repeat ARCO’s experience will depend on the particular configurations and processing capabilities of their refineries. Refineries oriented to premium, high octane fuels with high aromatics contents may have a difficult time producing reformulated fuels without major processing reconfiguration and capital investment. Many other refiners—especially those with modern, complex refineries—are likely to be able to repeat ARCO’s experience at similar costs if the quantities of reformulated gasoline demanded are moderate—up to perhaps 20 percent of total production.

Producing much larger quantities of EC-1 or other gasoline reformulations will have significantly higher costs. Manufacturers will need to revamp or replace refinery equipment at substantial capital cost, because existing refineries will not have the necessary capabilities. Blending of byproducts such as aromatics will be market limited, and refiners will have to convert excess aromatics and other byproducts to more desirable components, at added energy and cost. Supply limitations for key materials, e.g., isobutylene (needed for MTBE and ETBE production) must be overcome, presumably at added cost. And with greater competition for crude feedstocks, most suited for producing “EC-1 ‘type gasolines, refiners will be forced to use less desirable feedstocks that require more processing.

ARCO estimates the added costs to manufacture large quantities of EC-1 at 5 to 15 cents per gallon. These costs incorporate refinery capital charges, higher feedstock costs or additional processing requirements, and higher processing costs for byproduct conversion, in addition to the costs presently being incurred for EC-1. This cost range should serve as a first-order estimate for the costs of large-scale gasoline reformulations aimed at newer vehicles but similar in severity to the EC-1/leaded regular reformulation. Higher severity reformulations may be more expensive; for example, the cost of reducing aromatics to or below 20 to 25 percent by volume may exceed 15 cents per gallon.

The California Air Resources Board (ARB) has been examining a number of gasoline quality-control measures that would require changes in gasoline composition that would likely be similar to those selected as part of a reformulation program. ARB’s cost estimates are as follows (these are not necessarily additive):

- Reducing Reid Vapor Pressure from 9 psi to 8 psi: $0.01 to $0.02/gallon
- Benzene content reductions from 2 to 0.8 percent: $0.025/gallon
- Reduction of aromatics: $0.08 to $0.20/gallon
- Oxygenate blending: $0.005 to $0.03/gallon

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17Wald, op. cit., footnote 2, and confirmed by personal communication, Dwayne Smith, ARCO, Los Angeles, CA.
18Dwayne Smith, ARCO, Los Angeles, CA, personal communication.
19Oil and Gas Journal, op. cit., footnote 4.
21Daniel Townsend, ARCO Products Co., Anaheim, CA, personal communication.
22The option of making capital changes until capital turnover is required anyway is not available here because of the longevity of major refinery components and the shift in building new refinery capacity to overseas.
23Dwayne Smith, ARCO, personal communication.
25Nationwide, RVP averages about 11 psi. California already requires a 5 summertime reduction to 9 psi.
• Addition of gasoline detergents/additives: not known\textsuperscript{26}

An additional cost for some gasolines will be that of olefin reduction, not addressed in these estimates.

The potential availability of moderate quantities of reformulated gasoline at low cost, and the sharp escalation in costs when larger quantities are demanded, point to a possible strategy of promoting sale of such gasolines only in urban areas with significant air quality problems. This type of strategy can work well because the reformulations can be aimed at achieving emission reductions without vehicle modifications; vehicles can be used, unmodified, outside of the areas where reformulated gasoline is sold, and emissions benefits can be achieved for all or most vehicles in the fleet without waiting for vehicle turnover.

**SECONDARY IMPACTS**

Given the uncertainty associated with the nature of the changes that will be made to gasoline formulations and to refining processes, it is premature to attempt quantitative assessments of the impact of broad reformulation of the gasoline pool. However, the following qualitative impacts are plausible:

1. increases in processing energy required to produce gasoline, with some adverse consequences for emissions of greenhouse gases;
2. economic difficulties for some refiners, particularly the small independents;
3. changes in the import balance between crude and gasoline, with the direction (more or less product imports) and magnitude speculative;
4. changes in the relative desirability of different crude oil feedstocks, with accompanying shifts in the mix of supplier countries; and
5. changes in the ability of refiners to accept a range of feedstocks, and thus changes in the United States’ flexibility in shifting its sources of supply (direction depends on the type of refinery process shifts adopted).

Impacts 3 through 5 may involve changes in energy security. Such changes, coupled with the substantial economic impacts that widespread reformulation may involve, demand careful analysis as research on reformulation proceeds and as the likely physical character of reformulation becomes clearer.

**ADDITION OF OXYGENATES**

Although it is not yet clear what perfected reformulated gasolines will look like, they most likely will contain significant quantities of oxygenates such as ethanol, ETBE, and MTBE. Concentrations as high as 15 percent are possible with some of the oxygenates, so that the energy security and other impacts of reformulated gasoline must account for this presence of gasoline constituents that are produced largely from non-oil components. For example, a large increase in either ethanol or ETBE use will affect energy security by simultaneously increasing the percentage of gasoline volume produced from domestic components (e.g., domestic corn), exposing this gasoline component to the vagaries of crop production uncertainties, and changing the economics of gasoline production. With the United States’ relatively secure system of crop stockpiles, the risk of feedstock shortages should be small until ethanol production becomes quite large—but if all U.S. gasoline, or a large percentage of it, is reformulated with a high ethanol or ETBE content, this risk may become non-trivial. Similarly, large-scale use of MTBE or methanol as oxygenates would shift some supply risks from the oil supply system to the methanol supply system, probably with positive consequences as discussed in chapter 3.