Potential Barriers to Lead Reduction and Elimination

Because many countries have aged vehicle fleets, a key concern has been the perception that older cars and trucks need leaded gasoline.

Two primary barriers have been noted to the elimination of leaded gasoline, despite clear evidence of the toxic risks posed by its continued use. The first concerns the fuel requirements of existing vehicle fleets and the perception that some vehicles require leaded gasoline. This is an issue of particular concern to poorer nations, where fleets contain a significantly greater proportion of old vehicles and median vehicle age is considerably higher than in developed nations. The second is the presumably higher costs associated with unleaded fuel. A third objection, that unleaded fuel poses health risks as great or greater than leaded fuel, has never been substantiated in the scientific literature.

Vehicle Fuel Requirements

While vehicles with catalytic converters *must* use unleaded gasoline, vehicles do *not* have to have catalytic converters to use unleaded gasoline.

The perception that older vehicles cannot be operated on unleaded gas, but actually require leaded gas, actually combines three distinct issues. One of these is a frank misconception about the role of lead in gasoline and the catalytic converters used to control automotive hydrocarbon emissions. Another involves a considerable number of assumptions about vehicle usage and the lubrication provided by lead. The third involves more fundamental issues of engine design, gasoline octane, and fuel efficiency.

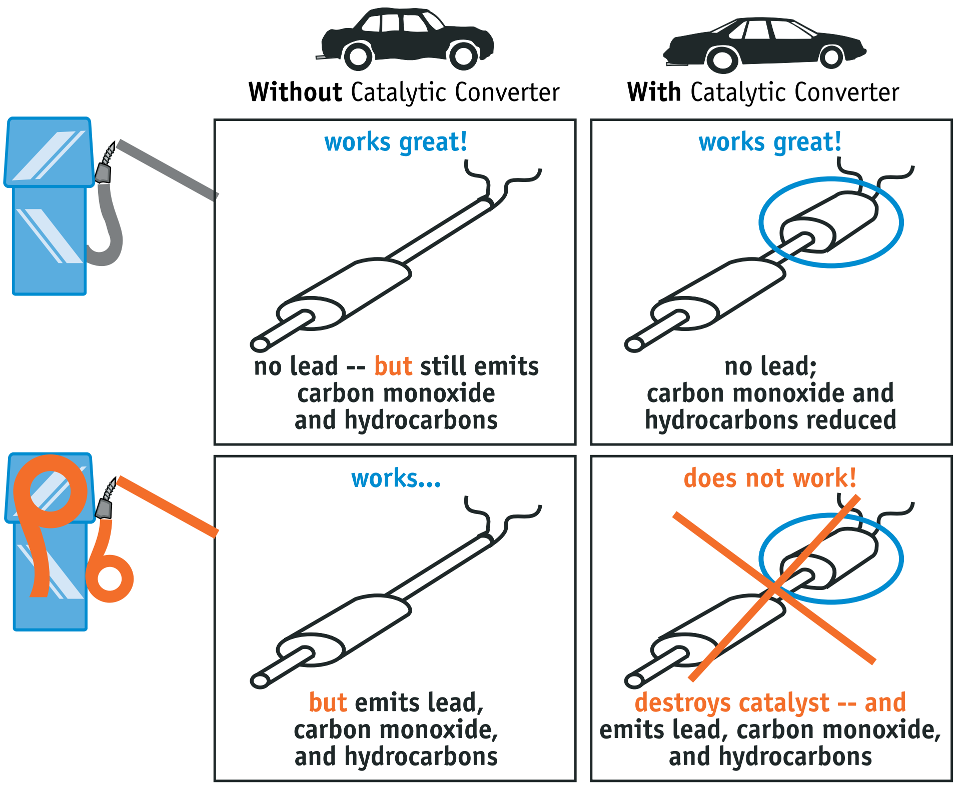
Misconceptions—Catalytic Converters and Unleaded Gasoline

Some publications on lead in gasoline assert that cars without catalytic converters (used to reduce hydrocarbon emissions from incomplete combustion) cannot or should not use unleaded fuel. More than one national environmental official, for example, made statements to this effect in discussing progress towards reducing lead exposure under Agenda 21 (10).

This assertion is simply false (Figure 9). While it is certainly true that automobiles equipped with catalytic converters *cannot use leaded gasoline*, the absence of a catalytic converter presents no problem what-

Catalytic Converters with Unleaded and Leaded Fuels

Figure 9



ever for the use of unleaded gasoline. The use of unleaded fuel in a vehicle without a catalytic converter has not been shown to lead to any increase in pollutant emissions, but only with the elimination of lead emissions.

Valve Seat Recession

A more realistic argument for retaining lead in gasoline, although not at the levels used in many nations, is that lead provides lubrication for valves made of soft metal. Generally, these are cars manufactured in the 1970s, early 1980s, and earlier decades.

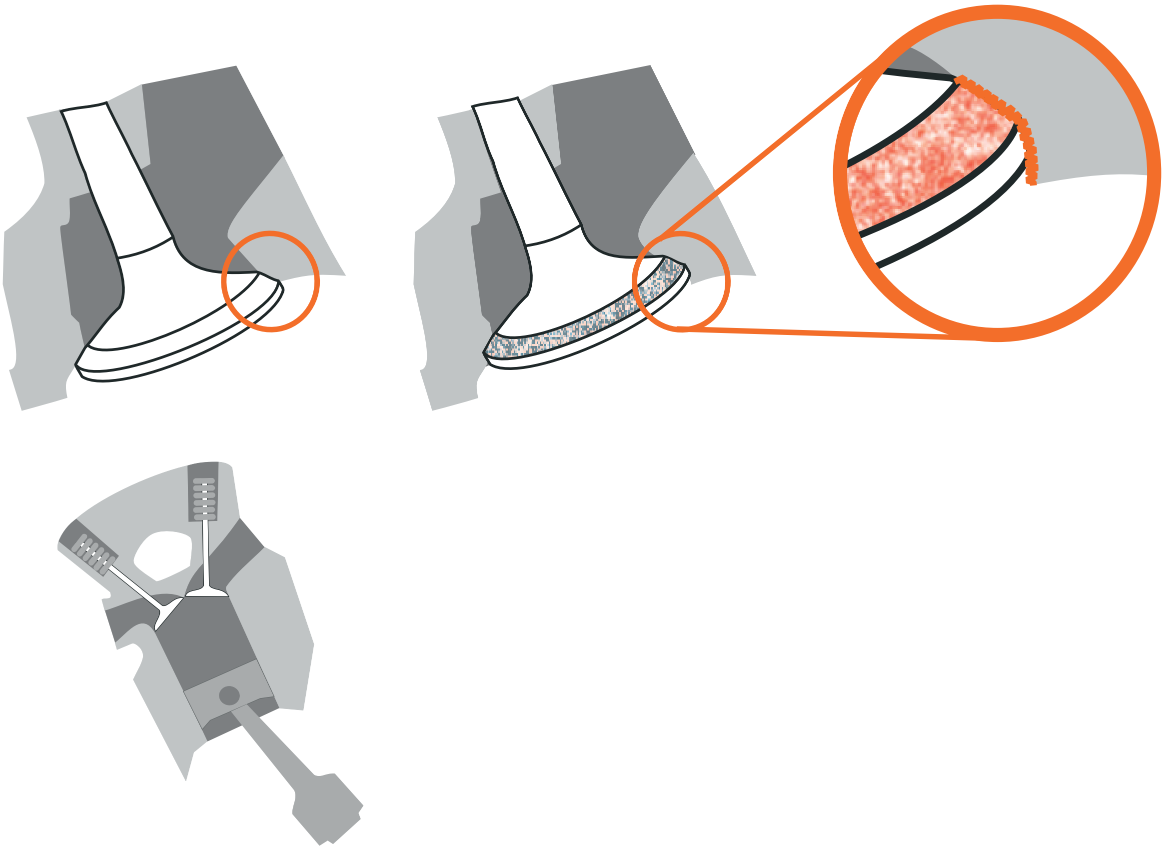
In the absence of lubrication provided by lead (or a substitute additive), the edges of the valves become worn away as small amounts of metal adhere between the valves and the valve seats, a phenomenon known as valve seat recession (Figure 10). Cars designed to operate on unleaded fuel (including, but not limited to, those equipped with catalytic converters) use hardened metal for valves and valve seats, eliminating the problem of recession. US manufacturers introduced hardened valve seats in 1971. In many other parts of the world, they were introduced in the late 1980s.

Manufacturing vehicles that do not require lead to lubricate valves is fairly simple and inexpensive; rather, the key issue is fleet turnover. It has been argued that in developing nations, vehicle replacement rates are much lower than are those in developed nations (that is, vehicles are retained for a much longer service life). The argument has been simplified to the inaccurate assertion that these older vehicles cannot operate on unleaded gasoline.

Occurrence and Prevention of Valve Seat Recession

Most parties agree that valve seat recession can occur in vehicles designed to use leaded fuel when they are operated exclusively on unleaded fuel. There appears to be little or no consensus, however, on the conditions under which valve seat recession occurs, the level of lead (and frequency of fueling with leaded gas) needed to prevent it, and the extent to which the risk of valve seat recession is offset by lower

Figure 10 **Valve Seat Recession**



maintenance costs in other areas of vehicle operation that result from the use of unleaded gas. Also subject to debate is the adequacy of substitute lubricants developed to address the problem.

Even for older cars *potentially* subject to valve seat recession, complete protection can be obtained with as little as 0.08 g/l lead.

The conditions under which valve seat recession occurs appear to have been the subject of more argument than study, and a variety of positions have been advanced (for example, 8, 14, 32, 33). Studies in the United States, and subsequently in Europe, indicated that valve seat recession was not a significant problem with unleaded gasoline, except under extreme driving conditions (high speed / heavy load), a finding that also applied to studies of Lada automobiles in Eastern Europe. In contrast, the Australian automobile industry determined that only 30 percent of pre-1986 cars can run entirely on unleaded gasoline, while an additional 30 percent require occasional fueling with leaded fuel (Australian cars manufactured or imported after 1986 are all designed to run on unleaded fuel). Studies in the Slovak Republic indicate a need for replacement lubricant in older Skodas.

Similarly, the levels of lead needed for valve seat protection have been debated (14, 31, 33, 47, 55). The 1996 Transatlantic Automotive Industry Conference on International Regulatory Harmonization argued for retaining leaded gasoline for a limited time for those vehicles subject to valve seat recession. The assertion was made that levels of lead below 0.08 g/l may not offer older vehicles adequate protection. Various US studies, however, indicate that levels between 0.02 and 0.03 g/l were sufficient. European tests indicated that 0.05 g/l protects valve seats in extreme conditions and 0.02 g/l in moderate conditions.

Despite ongoing disagreements, however, a clear minimum consensus can be drawn from these studies:

Even for older cars that can be said to require protection from the *possibility* of valve seat recession, complete protection can be obtained with a gasoline lead content of only 0.08 g/l, a level approximately *one-half* the current EU standard for lead in gasoline. This level represents less than *one-tenth* of the amount of lead currently added to gasoline in many countries.

Octane Requirements

As noted earlier, the lubricant properties of lead (which prevent valve seat recession) were not the original motivation for its introduction into gasoline. Rather, its purpose was to increase the octane rating, allowing higher compression ratios without problems of preignition ("knocking" or "pinging"). In the absence of lead additives, some other approach must be taken to obtain the desired octane. Alternatively, engines can be designed to use gasoline with a lower octane rating. Communications from automobile manufacturers (see below) indicated that in many cases vehicles can be run on fuels with much lower octane than that for which they were designed, by virtue of relatively simple adjustments.

To enhance gasoline octane requires either redesigning refinery processes (with capital outlays) or purchasing alternative octane-enhancing agents. To obtain optimal performance with low-octane gasoline requires redesigning automobile engines. Clearly, in the near term, the large amounts of capital invested in existing vehicle fleets suggests that fuel with enhanced octane (comparable to the octane rating provided by leaded fuel) is a preferable approach. In the longer term, either option may prove useful for a given country.

The design of an automobile and its fuel octane range ideally reflects trade-offs between energy consumption at the refinery to produce fuel and motor vehicle fuel use (for example, 35, 55). From a total energy viewpoint, the optimal octane is considered to be 94.5 Research Octane Number (RON) with a Motor Octane Number (MON) ranging from 82.5 to 84.5. These numbers are laboratory indices of resistance to preignition. (MON reflects conditions at higher engine speed and temperature and is invariably lower than the former.)

An Anti-Knock Index (AKI) averages the RON and MON and is considered a better indication of fuel performance in actual vehicles. The AKI of the optimal octane numbers above would be 88.5 to 89.5. It is important to note that the general design characteristics of US and Western European automobiles differ significantly; a typical US design fuel specification might be an AKI of 87, while European designs more typically would have an AKI of 94. Talks on developing common transatlantic standards are underway.

Adding more and more lead to gasoline results in smaller and smaller increases in octane (for example, 21, 32). That is, much less octane is gained with each increase in lead content. Thus, the octane enhancement obtained by increasing lead content from 0 to 0.1 g/l is significantly greater than that of increasing from 0.1 to 0.2 g/l. The increase in octane rating achieved by adding lead up to the EU limit of 0.15 g/l is nearly as great as the increase seen from increasing from 0.15 to 0.84 g/l. Thus, lead addition beyond the EU limit not only offers no advantage in preventing valve seat recession, but is also relatively ineffective as a means of increasing gasoline octane.

Adding more than the European limit for lead in gasoline (0.15 g/l) offers no advantage in protecting valve seats – and does little to further boost octane.

Concerns about Substitutes

It has been argued that unleaded gasoline presents risks that equal or exceed those of leaded gasoline. No evidence was found to support this assertion.

At a nontechnical level, three generally applicable techniques can be identified for increasing the octane rating of gasoline (further options become available with more sophisticated petroleum refinery equipment) (21, 31). One is to use catalytic reforming to change low-octane "heavy naphtha" derived from petroleum distillation to high-octane constituents suitable for gasoline blending. An alternative approach is to add one of a number of "oxygenates," such as alcohols or ethers. Methanol, ethanol, *tert*-butyl alcohol, or MTBE (methyl *tert*-butyl ether) are commonly used for this purpose. Finally, a variety of non-oxygenate octane enhancers are available for gasoline, including pentacarbonyl iron, tetracarbonyl nickel and methylcyclopentadienyl manganese tricarbonyl (MMT), as well as a range of additives not containing metals.

Catalytic reforming has the disadvantage that the resulting fuel has a higher content of aromatic compounds (for example, benzene). Production of these undesired aromatics is correlated with octane enhancement, such that the greater the octane boost, the greater the aromatic content. This increased production of aromatics has been advanced as an argument against the use of unleaded gasoline, notably by Associated Octel, Ltd., the major producer of lead additives (6). However:

There is no evidence that the risks of unleaded gasoline are comparable to those of leaded gasoline.

- evidence for health effects at the low exposures associated with fuel emissions is better established for lead than for benzene,
- all gasoline contains a significant quantity of benzene (as well as toluene, xylene, and ethylbenzene),
- not all methods of producing unleaded gasoline produce a significant increase in benzene or other aromatics,
- benzene is rapidly destroyed in the atmosphere, unlike lead (in polluted areas, where exposure to gasoline constituents is of greatest concern, the half-life of benzene is as short as 4-6 *hours*), and
- the "scavengers" (EDB and EDC) added to leaded gasoline to avoid corrosion and abrasion from lead deposition in the engine are also carcinogenic.

On a purely practical level, an Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) study of emissions from cars without catalytic converters found fewer hydrocarbon emissions (*including* benzene) with unleaded fuel (8).

No adverse effects of gasoline oxygenates has been clearly substantiated, despite an intensive investigation (34). In the United States, they are mandated as part of "reformulated gasoline" to help prevent regional and seasonal air quality problems, by promoting more complete fuel combustion and reducing emissions of volatile organics (including toxic chemicals). While some loss of fuel economy occurs, it is within the normal range of seasonal variation of gasoline. Major American, European, and Japanese manufacturers have approved the addition of up to 10 percent ethanol (by volume) and even higher levels of MTBE (31). Anecdotal reports of transient ill effects have not been substantiated in either epidemiological or laboratory studies. Gasoline is itself more toxic than any of the oxygenate additives.

The nickel- and manganese-based octane-enhancing additives have raised concerns similar to those prompted by lead, that is, the dispersive use of toxic heavy metals. Each of these metals has well-documented toxic effects at high exposure (data are inadequate at lower exposures) and pose the same issues of environmental persistence, relative to organic constituents of gasoline, as does lead. MMT was banned in US in 1978 and recently in Canada.

The Extent of the Problem—Existing Vehicle Fleet Composition

While data on vehicle fleet age are available for a number of nations (sometimes only in general terms), the detailed data on octane requirements and susceptibility to valve seat recession that would permit accurate assessment of the best approaches to the introduction of unleaded gasoline do not appear to be readily available for many nations. Automobile manufacturers, however, constitute a potential source of supplemental information.

For this report, 19 major automobile manufacturers, representing a significant fraction of world automotive production, were asked about vehicles sold in Africa, Latin America, or Asia. Questions explicitly addressed:

- vehicles (currently produced or previously sold) requiring leaded gasoline,

- minimum required lead content,
- adaptability to unleaded gasoline, and
- any special procedures required for using unleaded gasoline.

Two manufacturers indicated that they would not be able to respond, while six provided answers to some or all of the questions. These manufacturers included two major automobile producers headquartered in the United States and four headquartered in Europe. None of the Japanese manufacturers responded. Given the early elimination of lead in Japan, the results of this inquiry probably do not fully reflect worldwide manufacturing trends.

Current and Historic Production Practices

All six manufacturers now produce only vehicles designed to run on unleaded fuel. For sales to nations where unleaded fuel is not available, manufacturers are modifying their vehicles to use leaded fuel (for example, by removing catalytic converters).

Indeed, no car produced after 1989 by any of the six companies appeared to be designed to use leaded gasoline, and most had shifted production entirely to engines designed for unleaded fuel much earlier. One European manufacturer had changed all of its engines to run on unleaded fuel by the mid-1970s, and another had changed all but one vehicle model as of 1976 (that model continued in production until 1981). The other two European manufacturers discontinued the production of engines designed for leaded fuel in 1984 and 1987.

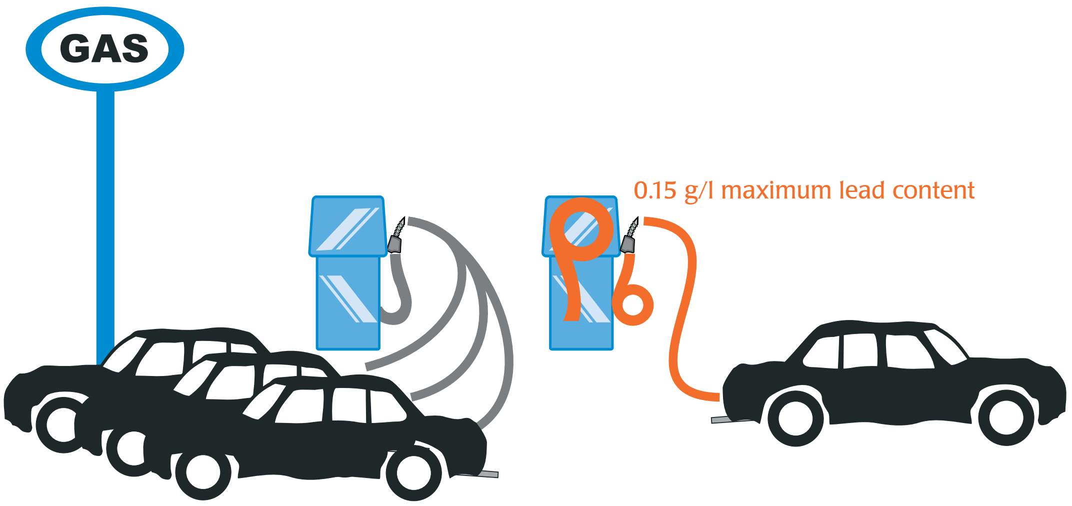
Half of the respondents (one North American manufacturer and two of the European manufacturers) indicated that *none* of the vehicles in service, including those originally designed to operate on leaded gasoline, require leaded gasoline to operate. Regardless of age, their vehicles could be operated entirely on unleaded fuel. The other three respondents indicated that all of their vehicles could be operated without problems using very low levels of lead in fuel. One specified intermittent fueling (every fourth tank, Figure 11), presumably with gasoline containing 0.15 g/l lead (the European Union maximum). The others recommended 0.07 g/l and 0.05 g/l as acceptable lead concentrations for older vehicles. One of these indicated that intermittent fueling to maintain this average level was an acceptable alternative, while the other indicated an unwillingness to impose a "bookkeeping" requirement on the driver.

None of the manufacturers surveyed indicated a need for regular fueling with leaded gasoline above 0.07 g/l for any vehicle of any age.

Valve-seat recession was predicted for operation of older vehicles on unleaded

For Older Cars: Intermittent Use of Leaded Gasoline

Figure 11



fuel (without substitute lubricants) by two manufacturers, while a third had received reports of recession occurring in heavy duty fleet use. Two other respondents, in contrast, did not anticipate any problem or any need for substitute lubricants.

Manufacturers provided variety of comments on potential substitute fuel additives. One specifically mentioned that MMT or other manganese-containing additives would damage components of the emission control system. Another recommended potassium-based over sodium-based additives, to preclude corrosive damage to turbochargers. Three indicated no need for additives; one of these recommended regular valve inspection when using unleaded fuel in older vehicles.

Octane requirements vary considerably, not only by manufacturer, but also by model. For some of the manufacturers, a significant fraction of the existing fleet can run on octane as low as 91 RON, 82.5 MON (AKI 87). Others more generally specify RON of 93-98, but report that they adjust exported automobiles to fit available fuel stocks, in some cases as low as RON 86. Thus, while there may be some loss of fuel efficiency in eliminating lead from gasoline, none of the manufacturers' data indicated that a resulting reduction in octane rating of available fuel would be a barrier to operating existing vehicles.

Economics

Because technical solutions to both the problem of valve seat recession and to enhancing gasoline octane clearly exist, the complete removal of lead from gasoline stands as an economic, rather than an engineering, problem. In other words, no country needs leaded gasoline, but all face potential costs and benefits in switching to unleaded gasoline. These costs are often quite low and may be entirely offset by benefits, even if the costs of lead toxicity are entirely disregarded.

Fuel Production Costs

The World Bank has examined the economics of alternative approaches to boosting octane of gasoline shipped from various types of refineries existing in different countries (31, 32). Others have made similar estimates for particular countries or regions (for example, 4, 35, 39, 51). The best solution for a given refinery and market varies. In some cases, the need to modernize refineries anyway, for general economic viability, will easily accommodate new technologies for enhancing octane. In others, purchase of octane-enhancing agents such as the oxygenates may be more appropriate, particularly for refineries near the end of their useful economic life.

Experience to date indicates that the direct costs associated with replacing lead in gasoline are often low. In the Slovak Republic, the total cost of phase-out, including developing a non-lead additive for valve lubrication and adding isomerization units to refinery, was approximately $0.02 US/liter. Similarly, complete lead phase-out for Romania has been estimated to cost $0.01- 0.02 US/liter. The price differential for Mexico has been estimated at 0.1 new peso ($0.012 US) per liter.

Net Costs of Vehicle Operation and Maintenance

These data indicate that producing unleaded gasoline is marginally more expensive . However, other costs associated with the use of leaded and unleaded fuels are also important. Leaded fuel is known to be associated with problems of increased friction within the engine, spark plug fouling, and exhaust system corrosion.

Studies in Australia, Canada, and the United States have indicated that savings in vehicle operation and maintenance costs may range from $0.003 - $0.025 US/liter. These expenses include extended spark plug and exhaust system replacement cycles (35). At the high end, the savings more than offset any difference in fuel production costs, as well as any risk of valve seat recession (4, 31, 35, 45). Net costs for eliminating lead in gasoline have thus ranged from modest ($0.02 US per liter) to negative, depending upon the study.

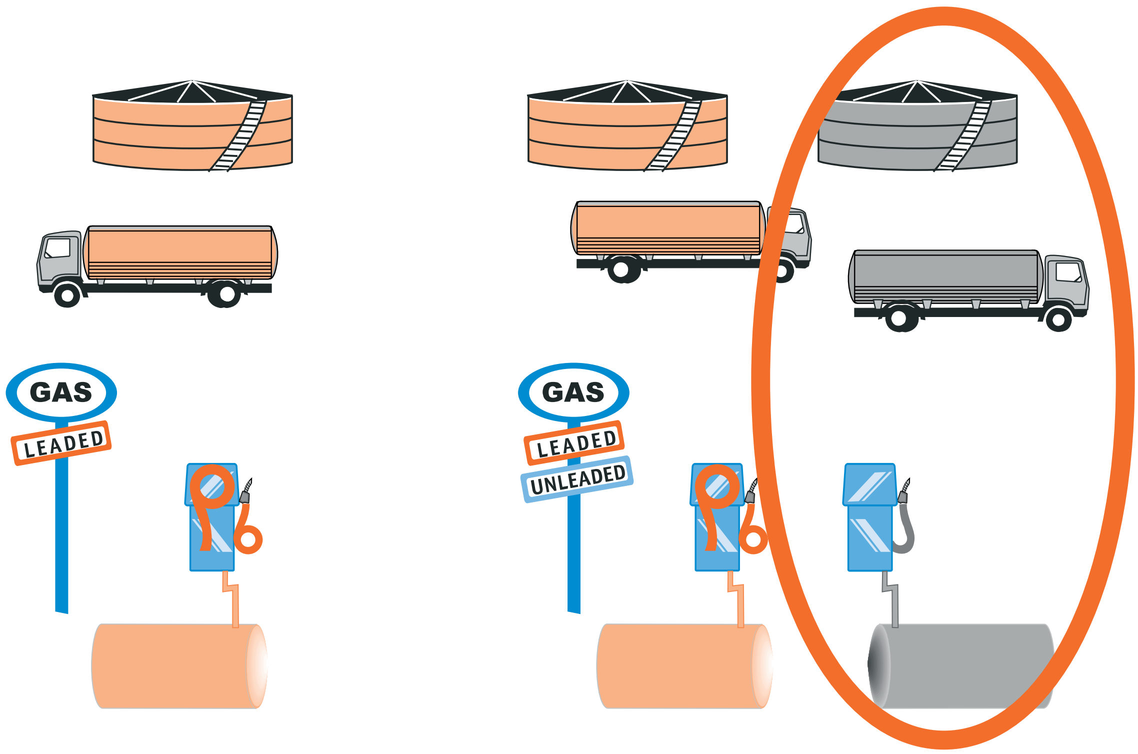
The Dual Fuel Dilemma

It often appears that the least disruptive approach to phasing out the use of lead in gasoline is to supply both leaded and unleaded gasoline, and (with or without government-induced pricing differentials) to allow the market for unleaded gasoline to expand gradually as new vehicles are introduced to the fleet. This has some particular attraction for countries that are expected to increase their vehicle fleets dramatically in the next decades, as fleet expansion with newer vehicles would accelerate the growth of market demand for unleaded fuel (only a tiny fraction of current world automotive production appears geared toward vehicles designed to run on leaded gasoline).

A confounding factor is that concentrations of lead in gasoline greater than 0.01 g/l can lead to catalyst poisoning in automobiles equipped with catalytic converters (35). Mis-fueling with lead at 0.4 g/l or higher can physically block gas passage through a catalytic converter, damaging the engine with excess back-pressure. Accordingly, countries considering a gradual transition from leaded to unleaded gasoline must pay particular attention to separation of the two fuel streams. Separate tankage will be needed for the duration of the phase-out program, if leaded and unleaded gasolines are to be offered simultaneously.

Problems with Dual Fuel Strategy

Figure 12



Single Fuel

Conversion to Dual Fuel May Require Significant Capital Expense

- 35 countries have only one grade of fuel
- many others have two grades (regular, premium) with different octanes
- to use both leaded and unleaded gasolines requires:
  - new parallel distribution system, or
  - loss of an existing grade of gasoline

Capital stocks for fuel distribution represent a key potential problem for such an approach. Octel data on fuel consumption (presented earlier in this report) indicate that 33 nations have only a single grade of (leaded) gasoline; 22 of these nations are in Africa. Another 47 nations (27 in Africa) have two grades of fuel with different octane ratings (both leaded).

Any transition to the use of unleaded fuel that involves the simultaneous marketing of leaded and unleaded fuel in these nations may require a significant capital expansion in the system for gasoline distribution, or the sacrifice of an existing grade of gasoline, or some other, equally disruptive change (Figure 12).