Legislative and Technical Perspectives for Advanced Ground Transportation Systems

This paper analyzes from legislative and technical perspectives 10 different scenarios for advanced ground transportation systems using natural gas to supplement oil. It is first shown that previous legislative efforts to promote the use of alternative fuels by incentives have failed because of a lack of infrastructure to store and distribute the fuels. The paper then compares the efficiencies of various fuel-vehicle options by means of a well-to-wheel fuel cycle that starts with the well at which the feedstock is extracted from the ground and ends with the power delivered to the wheels of the vehicle. The complete cycle includes feedstock production; feedstock transportation and storage; fuel production; fuel transportation, storage, and distribution; and finally the vehicle operations. Such an all-inclusive comparison is essential in order to accurately and fairly compare the efficiency of transportation fuel options. This approach indicates that at the present time hybrid-electric vehicles, particularly those using diesel engines, can achieve the highest efficiency among available technologies. Hydrogen spark ignition, all-electric battery-powered, and methanol fuel cell vehicles rank lowest in well-to-wheel efficiency because of their poor fuel production efficiencies. The study also examines various options to reduce air pollution and concludes that any significant reduction requires repairing the worst 10% of polluting vehicles or removing them from the national transportation fleet.

by Frank Kreith, R.E. West, and Beth Isler

An efficient and economically viable transportation system is an essential part of a modern industrial society. This is particularly true in the United States, where the growth of suburbia requires the average American worker to commute daily a considerable distance between home and work. The situation is exacerbated in many locations by a lack of adequate public transport, which requires most commuters to travel by private automobile. The use of single occupancy vehicles not only causes congestion, delays, and air pollution, but also imposes a severe economic penalty on many Americans.

A recent Consumer Expenditure Survey (U.S. Bureau of Labor Statistics, 1999) showed that transportation for most Americans is an expense second only to housing (Figure 1). For example, the average U.S. household devotes 19¢ out of every dollar it spends just to get around. The vast majority of the transportation spending (98%) is for the purchase, operation, and maintenance of automobiles. In fact, most families spend more on driving their cars than on health care, education, or food.

The situation is becoming more serious because as population increases, so do the vehicle miles of travel (Figure 2). Since World
Figure 1: Household Expenditures

<table>
<thead>
<tr>
<th>Category</th>
<th>Expenditure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Housing</td>
<td>32.6c</td>
</tr>
<tr>
<td>Transportation</td>
<td>19.0c</td>
</tr>
<tr>
<td>Food</td>
<td>13.6c</td>
</tr>
<tr>
<td>Other expenditures</td>
<td>10.5c</td>
</tr>
<tr>
<td>Personal insurance and pensions</td>
<td>9.3c</td>
</tr>
<tr>
<td>Health care</td>
<td>5.3c</td>
</tr>
<tr>
<td>Entertainment</td>
<td>5.1c</td>
</tr>
<tr>
<td>Apparel and services</td>
<td>4.7c</td>
</tr>
</tbody>
</table>

Note: The 1999 distribution of total annual household expenditures by major category, showing both total expenditure by category and cents per dollar spent on each.

Figure 2: Increase in Vehicle Miles Traveled, 1990–2000

War II, a booming population aided by federal taxpayer subsidies has encouraged migration from cities into sprawling suburbs. According to a study by the Sierra Club Foundation, most of the tax dollars available for transportation have been spent on building and maintaining highways to sustain these suburbs (Haddow and Silverman, 2000). Without adequate mass transport, the urban sprawl has increased our dependence on an automobile way of life, which is costly, unhealthy, and not sustainable for the long haul. The transportation pattern imposed by urban sprawl impacts particularly lower income households. Figure 3, based upon a 1999 Consumer Expenditure Survey, shows the percentage of income before taxes spent by Americans in different income brackets on transportation. The results of this survey clearly indicate that poorer Americans use a much higher portion of their income on transportation than wealthier Americans. In households earning less than $25,000, often more than one-third of the total income goes to transportation. It is obvious that an economically viable transportation system is imperative for a healthy economy.

Fuel Supply Options

Future world oil prices and the potential for new transportation fuels are topics of great interest on a state and national level, and extensive studies of these topics have
Figure 3: Percentage of Income Spent on Transportation by Income Bracket

![Bar chart showing percentage of income spent on transportation by income bracket.]


been made by various organizations. The demand for transportation fuels is rapidly growing all over the world. From 1990 to 1996, energy use in the U.S. transportation sector increased at a rate of 1.6% per year, culminating in the year 2000 at about 13 million barrels of oil equivalent per day. Energy use in the rest of the world during the same period increased 22%, compared to 10% in the U.S. Today, the rest of the world uses 30 million barrels of oil per day, and it is expected that within the next decade, transportation demands will require more than 50% of the total worldwide petroleum production. The Energy Information Administration (EIA) projects that energy use in the U.S. transportation sector will grow 36% in the next 20 years, whereas the demand in the rest of the world will increase by 74% (U.S. Department of Energy, 1999).

Known petroleum resources worldwide are being consumed rapidly and future availability of oil resources is uncertain. After the oil crisis of 1973, reliance on imported oil has been a persistent security problem for the United States, and since the 1980s urban air pollution has been a health problem for residents in many metropolitan areas. Most recently, the effect of carbon emissions on climate change and global warming has become a growing global concern. As a result, substantial resources have been invested in research to improve the end use efficiency of fossil fuels from both energy and pollution standpoints and develop cost competitive alternatives and clean transportation fuels to meet the domestic and global demand.

At the present time, more than 97% of the fuel used for ground transportation in the U.S. is petroleum-based and over 50% is imported. During the past three years, the cost of gas and oil has become a growing concern to governments. In 1999, the U.S. Department of Energy presented three oil price scenarios with predictions through the
year 2020. In the low price case, the price remained level at just over $14 per barrel in 1997 dollars, whereas in the reference case, prices were expected to rise slowly to less than $23 per barrel by 2020. In the high price scenario, the U.S. Department of Energy predicted an increase to about $30 per barrel by 2020. These predictions were based on various supply and demand assumptions that are obviously questionable because the price of oil is already close to $30 per barrel (Greene and Tischishyna, 2001). Moreover, current predictions indicate that the demand for oil will continue to grow, and barring a worldwide recession there is no reason to expect a long-term drop in crude oil prices in the future.

In a seminal analysis of the growth, peaking, and subsequent decline of a finite non-renewable resource, the oil geologist M.K. Hubbert (1974) formulated in 1956 the behavior of oil production in the United States analytically. Based upon oil production data combined with the typical behavior of oil wells, Hubbert predicted that oil production in the United States would peak about 1973. His prediction has been borne out and oil production in this country has declined since that time. A.A. Bartlett applied in 1999 the same approach that Hubbert had used to predict worldwide oil production, using available data as shown in Figure 4 (Bartlett, 2000). Based on estimates of the total worldwide oil reserves, that bracket maximum and minimum estimates of experts, Bartlett predicted both the worldwide oil production in billion barrels per year and the date at which this production would peak. The results of this analysis are shown in Figure 4, where the oil production as a function of time is shown for three total amounts of recoverable oil. Oil production can be expected to peak somewhere between 2010 and 2030. It is apparent that as supplies decline the price of oil is likely to escalate and that planning for a transportation system does not depend entirely on petroleum resources is imperative.

Alternative fuels available to supplement oil as well as their feedstocks are shown in Table 1. Except for ethanol, natural gas is a primary feedstock for all these options. Because of its relative abundance, and because it offers significant environmental advantages, natural gas has been promoted by various groups as a near term supplement for gasoline and diesel fuel in the transportation sector, particularly for use in automobiles and trucks. Natural gas can be used directly in liquefied or compressed form for internal combustion engines, or it can be

Figure 4: Estimates of Peak Production of World Oil for Various Ultimate Recovery Scenarios

![Figure 4: Estimates of Peak Production of World Oil for Various Ultimate Recovery Scenarios](image)

Source: Bartlett, 2000

Table 1: Feedstocks for Alternative Fuels

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Feedstock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propane (LPG)</td>
<td>Natural Gas (NG), Petroleum</td>
</tr>
<tr>
<td>Compressed NG</td>
<td>NG</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>NG or Water + Electricity</td>
</tr>
<tr>
<td>FT Diesel</td>
<td>NG or Coal</td>
</tr>
<tr>
<td>Methanol (M85)</td>
<td>NG or Coal</td>
</tr>
<tr>
<td>Ethanol (E85)</td>
<td>Corn or Sugar Cane</td>
</tr>
<tr>
<td>Electricity</td>
<td>NG, Coal or Uranium</td>
</tr>
</tbody>
</table>
used as the feedstock to produce other fuels, including methanol, hydrogen, and Fischer-Tropsch (FT) diesel. Although natural gas is also a nonrenewable and finite resource, conservative estimates at present indicate that there are sufficient gas resources in the ground to last at least 30 years and many of them are in North America (Wang and Huang, 1999; Kreith, 1998; Cochener, 2000; Borbely and Kreider, 2001). Since the time horizon of this study is the next 20 or so years and natural gas is the primary feedstock for most alternatives, it is chosen as the baseline feedstock/fuel for this study.

During the past few years, visionaries all over the world have claimed that as the liquid fuel era comes to an end and oil resources are being depleted, a new fuel era based on hydrogen will develop. Large amounts of money are being spent on R&D to develop a so-called "hydrogen economy," and environmentalists are fascinated with hydrogen as a "green" fuel for cars because it does not contain carbon. With hydrogen as the fuel in fuel cells or internal combustion (IC) engines, there are no unburned hydrocarbons, no carbon monoxide or carbon dioxide in the exhaust, and it is widely believed that this will automatically reduce air pollution. However, hydrogen does not occur spontaneously in nature; it has to be produced, and the production of hydrogen requires energy and creates pollution. Today, about 80% of hydrogen is obtained from natural gas by a process called steam reforming. Hydrogen can also be produced by electrolysis of water, but this process requires large amounts of electrical energy and costs approximately three times as much as hydrogen from steam reforming of natural gas (Howe-Grant, 1994). If large scale development of nuclear or wind power generation would occur, excess capacity could be used to make hydrogen, but the cost would be considerably higher than with steam reforming. If solar energy were used to power the electrolysis, the cost of hydrogen would be even higher because the cost of electricity produced from solar radiation with photovoltaic (PV) cells is several times the cost of electric power from nuclear or fossil fuels (Block, 1997).

Assessment of Previous Alternative Fuel Incentives

Following the passage of the Federal Energy Policy Act of 1992, many states created alternative fuel vehicle initiatives in order to reduce America's reliance on foreign oil imports and to reduce the air pollution from the use of gasoline and diesel fuel for ground transportation. The results of these actions have been documented by Brown and Breckenridge, 2001. The overall conclusion of this study is that after 10 years of efforts to stimulate use of alternative fuels for transportation, incentives have not achieved the desired results. Despite large financial expenditures, incentives, both on a federal and state level, have failed to increase the use of alternative fuels appreciably, did not significantly reduce the nation's dependence of foreign oil and have not reduced air pollution measurably.

After President Bush signed the Energy Policy Act in 1992, 46 states initiated their own incentives for alternative fuels by subsidizing alternative fuel vehicles with tax incentives and rebates and buying alternative fuel vehicles for their own fleet. Alternative fuels comprised a mere 0.17% of the total U.S. fuel consumption for ground transportation in 1992, and by 1999 that proportion had increased only 0.05%; today alternative fuels still comprise less than one-quarter of 1% of the total fuel consumption. Data on the number of vehicles capable of operating on alternative fuels are available, but they are not meaningful because few of the vehicles actually use an alternative fuel. Most of the state initiatives provided incentives for vehicles capable of
using alternative fuels, but very few of them were actually operated on anything but gasoline or diesel fuel because of a lack of available storage and distribution infrastructure for alternative fuels. Despite efforts on the state and federal levels, by the year 2001 there were only approximately 5,000 fueling stations dispensing alternative fuels in the entire country, and over 3,000 of them were for propane. This compares to approximately 180,000 fueling stations dispensing gasoline and/or diesel fuel (Alternative Fuels Data Center, 2001). There may be several reasons for the failure of the alternative fuel vehicle incentives. But the most significant reason for the failure is the lack of an infrastructure that can dispense alternative fuels conveniently for the average driver.

Quite apart from the failure of incentives and mandates for alternative fuel vehicles to increase use of alternative fuels, efforts to force a technology that is not ready for the marketplace upon consumers has been an enormous waste of taxpayers’ money and resources. Moreover, some of the programs have created financial strains for state governments that were forced by federal regulation to purchase a certain percentage of alternative fuel vehicles for their governmental fleets. In view of the fact that no adequate infrastructure exists for alternative fuel vehicles, most state governments met the mandate of the Federal Energy Policy Act by purchasing so-called “dual fuel vehicles” that could run on an alternative fuel such as ethanol, methanol, natural gas, or LPG as well as conventional gasoline. The extra cost of buying such a vehicle was approximately $5,000. Currently 400,000 such vehicles, most of them state-owned, are approaching their normal fleet life span and are for sale. A market analysis indicated that there are virtually no buyers for dedicated alternative fuel vehicles, except possibly for natural gas vehicles by New York taxicab companies that have a natural gas infrastructure (Flax, 2000). When dual fuel vehicles are placed on the market, they barely bring the price of similar conventional vehicles. But since the excess purchase cost of each was $5,000, the federal regulation under the Energy Policy Act requiring that alternative fuel vehicles be purchased by state fleets will eventually cost the states approximately $2 billion for an experiment that attempted to generate a market for alternative automotive fuels. This experience should serve as a warning to future programs such as efforts to stimulate the use of hydrogen-powered vehicles for ground transportation without having an adequate hydrogen fuel infrastructure in place.

Efforts by state governments to promote alternative fuel vehicles have also been failures. For example, Arizona enacted legislation in 1995 that was intended to improve air quality by offering incentives to consumers for purchasing dedicated alternative fuel vehicles. During the initial four years of the law less than 200 people availed themselves of the tax rebates. But amendments to the original law were passed in the 1999 and 2000 legislative sessions to make the incentives more attractive. The 1999 change provided that as long as a vehicle were capable of running on an alternative fuel, the consumer qualified for a tax rebate (potentially up to $15,000) even if he or she did not actually use an alternative fuel. Furthermore, in the year 2000 the Arizona legislature changed the structure of the incentives into refundable tax credits which were similar to grants. This meant that a purchaser could receive a check for the entire tax rebate (approximately $15,000) for a vehicle capable of using an alternative fuel, including small electric vehicles. These changes in the law enabled about 21,000 consumers to apply for approximately $500 million in rebates in the year 2000, according to a study by the Arizona Departments of Commerce, Alternative Fuel Recovery, and Revenue. Obviously, state governments want to avoid repeating similar mistakes and there-
fore need complete and unbiased information about transportation issues.

Comparison of Advanced Vehicle Systems

In order to provide information that would enable policymakers to assess transportation options, including the need for a new infrastructure, we have evaluated the efficiency of using natural gas to generate hydrogen for a fuel cell or to use natural gas directly in a spark-ignition or diesel engine, or to use natural gas to generate electric power for an electric battery-driven vehicle or to use hydrogen as a fuel in an internal combustion engine. Our comparative analysis, which is described in detail in “Efficiency of Advanced Transportation Technologies” by F. Kreith et al. (2001), avoids speculation about future prospects for new technologies on the basis of demonstration programs and R&D targets, such as those set periodically by the U.S. Department of Energy or by the U.S. Department of Transportation. Instead, this comparison relies as much as possible on engineering data, analyses in peer-reviewed articles, and information from engineers who are currently working on vehicles that are already undergoing tests in the public domain or have entered the market.

To obtain objective comparisons, we performed complete well-to-wheel analyses of 10 realistic scenarios for using natural gas to power motor vehicles. This approach starts with the well at which the feedstock is first extracted from the ground and ends with the power finally delivered to the wheels of the vehicle. As shown in Figure 5, this cycle includes feedstock production, feedstock transportation and storage (T&S), fuel production, fuel transportation, storage, and distribution (T&S&D), and finally the vehicle operations. This all-inclusive comparison is essential in order to accurately and fairly compare the transportation options. For example, while a hydrogen fuel cell performs well in terms of vehicle operations, the low fuel production efficiency of the hydrogen makes it a less efficient choice compared to some hybrid vehicle propulsion systems.

The 10 technologies considered include using natural gas in a conventional spark ignition engine both directly and combined with an electric motor in hybrid-electric configuration, using natural gas as the feedstock to generate diesel by the Fischer-Tropsch process for conventional and high compression diesel engines and diesel hybrid-electrics, generating hydrogen or methanol from natural gas for use in a fuel cell, or hydrogen in a spark-ignition engine, and finally generating electricity in a natural gas combined cycle power plant for an all-electric battery-powered vehicle. The 10 technologies listed in Table 2 and described in Figure 6 are then compared in order to decide whether or not, given the current state of knowledge about internal combustion, hybrid, electric and fuel cell vehicles, a hydrogen distribution system would be useful in alleviating the anticipated shortage of

Figure 5: Schematic Diagram for a Complete Well-to-Wheel Vehicle Efficiency Analysis
oil for ground transportation. It is hoped that this comparison will be valuable to policymakers in developing environmentally compatible and economically feasible transportation options that can supplement conventional petroleum-based vehicles.

It has been suggested that reforming gasoline to hydrogen for use in a fuel cell onboard would eliminate the need for a new hydrogen infrastructure. However, one of the principal reasons for considering alternative options is that as the supply of oil dwindles and the cost of gasoline increases, a different transportation fuel will be required for an economically and environmentally sustainable energy plan. Furthermore, while gasoline may be a convenient feedstock (in terms of infrastructure) with which to generate hydrogen, the technology needed to efficiently execute the reforming process onboard the vehicle is not available and likely would be expensive and inefficient according to a study for the California Air Resources Board (Kalhammer, et al., 1998; see also Lovins and Williams, 1999). Therefore, this option has not been included in our study.

The results of the overall well-to-wheel efficiency for the technologies listed in Table 2 and depicted in Figure 6 are summarized in Table 3. As fuel production involves several steps (e.g., recovery, processing, transmission and distribution, etc.), the efficiencies of each step are multiplied together for a total fuel production efficiency, similar to the GREET Model developed at the Argonne National Laboratory (Wang, 1999). The most important lesson to be learned from the study is the importance of considering all the steps of the fuel cycle in an efficiency analysis. For example, it may be seen that while hydrogen fuel cells equal or slightly outrank conventional

<table>
<thead>
<tr>
<th>Engine Configuration Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spark Ignition (SI) Internal Combustion (IC) Engine</td>
</tr>
<tr>
<td>SI-IC Hybrid-Electric</td>
</tr>
<tr>
<td>Fischer-Tropsch (FT) Diesel Engine</td>
</tr>
<tr>
<td>High Compression Diesel Engine</td>
</tr>
<tr>
<td>FT Diesel Hybrid-Electric</td>
</tr>
<tr>
<td>High Compression Diesel Hybrid-Electric</td>
</tr>
<tr>
<td>Methanol Fuel Cell</td>
</tr>
<tr>
<td>Hydrogen Fuel Cell</td>
</tr>
<tr>
<td>All-Electric Battery-Powered</td>
</tr>
<tr>
<td>Hydrogen SI-IC Engine</td>
</tr>
</tbody>
</table>

58
technologies in operating efficiency, their total cycle efficiency is lower than that of hybrid technologies. The reason for the low overall performance of a hydrogen fuel cell vehicle is its low fuel production efficiency. Although fuel cells are very efficient once hydrogen is available, the process of obtaining hydrogen is inefficient and eradicates any advantages gained by a high operating efficiency. The same is true for battery all-electric vehicles, which have the highest operating efficiency (49%); however, the generation of electricity to recharge the batteries of such a vehicle has the lowest fuel production efficiency (37%). Hence, the total cycle efficiency is extremely low.

Similarly, methanol fuel cell vehicles have a low well-to-wheel efficiency due to the low efficiency of the fuel processor (Chalk et al., 1998), which is included here as part of the efficiency. For comparison, the well-to-wheel efficiency of a conventional gasoline-powered Chevrolet Silverado, tank-to-wheel full-size pickup truck is of the order of 13% (General Motors Corporation, 2001).

Hybrid-electric vehicles use a small internal combustion engine in combination with an electric motor and battery storage. They can be arranged in a series or parallel configuration. This analysis is based on a parallel configuration, as shown schematically in Figure 7, because it is the arrangement used by Toyota in the Prius and by Honda in the Insight. These are the only hybrid-electric automobiles commercially available at this time.

As shown in Table 3, the efficiency of fuel production for conventional and hybrid technologies using natural gas or diesel is much higher than the production of electric-

Table 3: Summary of Natural Gas Well-to-Wheel Efficiencies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Engine</th>
<th>Fuel</th>
<th>Well-to-Tank Efficiency</th>
<th>Tank-to-Wheel Efficiency</th>
<th>Well-to-Wheel Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conventional SI</td>
<td>Natural Gas</td>
<td>87.5%</td>
<td>22%</td>
<td>19%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hydrogen</td>
<td>59%</td>
<td>13%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Conventional Diesel</td>
<td>F-T Diesel</td>
<td>67%</td>
<td>29%</td>
<td>20%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High Compression</td>
<td>86%</td>
<td>26%</td>
<td>22.5%</td>
</tr>
<tr>
<td></td>
<td>Hybrid SI</td>
<td>Natural Gas</td>
<td>87.5%</td>
<td>36%</td>
<td>31%</td>
</tr>
<tr>
<td></td>
<td>Hybrid Diesel</td>
<td>F-T Diesel</td>
<td>67%</td>
<td>45%</td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High Compression</td>
<td>86%</td>
<td>37.5%</td>
<td>32%</td>
</tr>
<tr>
<td></td>
<td>Battery All-Electric</td>
<td>Electricity</td>
<td>37%</td>
<td>44%</td>
<td>16%</td>
</tr>
<tr>
<td></td>
<td>Fuel Cell</td>
<td>Methanol</td>
<td>57.5%</td>
<td>24%</td>
<td>14%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hydrogen</td>
<td>59%</td>
<td>42%</td>
<td>24.5%</td>
</tr>
</tbody>
</table>

b. Values are for large vehicles currently on the road from manufacturers Volvo and Mack.
c. Calculated from data provided by Caterpillar (2000) for the C-12 Electronic Dual-Fuel Truck Engine.
d. Electric Motor and Controller efficiency=85%; Battery Pack efficiency=68%; Battery Charger efficiency=95%; Drive Train efficiency=90% (McCoy and Lyons, 1983): Multiplying 0.85x0.68x0.85x0.90=0.44 results in 0.49 for peak brake engine efficiency.
e. Includes on-board fuel processor efficiency (Chalk et al., 1999).
f. Tank-to-wheel efficiency uses stack efficiency at peak load (Thomas et al., 1998).
g. Billings (1997) provides experimental data which essentially demonstrated the vehicle tank-to-wheel efficiency.
Figure 6: Schematic Depiction of the Four Basic Well-to-Wheel Configurations Analyzed

Internal Combustion

- NG or F-T Diesel, Dual Fuel, H₂ → ENGINE → DRIVE TRAIN → ROAD LOAD

Hybrid-Electric

- NG or F-T Diesel, Dual Fuel
  - ENGINE
  - MOTOR
  - GENERATOR → BATTERY → INVERTER
  → DRIVE TRAIN → ROAD LOAD

Methanol Fuel Cell System with On-Board Reformer

- Methanol → FUEL REFORMER → H₂ → FUEL CELL SYSTEM
  - INVERTER
  - AC MOTOR → DRIVE TRAIN → ROAD LOAD
  - BATTERY

Hydrogen Fuel Cell System

- H₂ → FUEL CELL SYSTEM
  - INVERTER
  - AC MOTOR → DRIVE TRAIN → ROAD LOAD
  - BATTERY

Note: The configurations examined are variations on these basic concepts.

It is clear that unless one performs a complete well-to-wheel efficiency analysis, one might arrive at erroneous conclusions regarding the potential of advanced vehicle options. The total cycle efficiency not only affects the resource utilization, but also the carbon dioxide emissions since the amount of carbon dioxide emission is inversely proportional to the well-to-wheel efficiency.

Hence, the largest amount of greenhouse gas emission results from hydrogen or methanol fuel cells or hydrogen-SI engines, followed closely by the all-electric battery vehicle. For the electric battery vehicle, which has no tailpipe emission, the emissions are largely the result of the power plant needed to recharge the battery even though concerns have also been raised about pollution from disposal or recycling of batteries (Passell, 1995).

Our analysis is based on the highest efficiency of a fuel cell for which experimental data could be found, as well as the maximum efficiency of a diesel engine on the road. Although the level of maturity of fuel cells and diesel engines is not the same, it should
be noted that even if the R&D efficiency target set by the Department of Energy (Chalk et al., 1998) were used for the fuel cell in this analysis, the ranking would not be affected significantly. The reason for this is the low efficiency of the production of hydrogen fuel compared to most other fuels. Since this step in the cycle is based on well-established commercial processes, it is not expected that any substantial improvements can be achieved.

**Hydrogen Fuel Issues**

One of the questions confronting policymakers is whether or not the country should expand the existing natural gas infrastructure or build an entirely new hydrogen infrastructure. At the present time, government policymakers are receiving information about possible futures for transportation fuels from at least two groups. One group believes that natural gas vehicles are most likely to supplement the spark-ignition gasoline engines which currently constitute a majority of the vehicles on the road. Another group believes that the fuel of the future is hydrogen and that the fuel cell is the most promising prime mover for automobiles in the transportation sector. Having experienced the failure of previous incentives for alternative fuels, largely due to a lack of infrastructure, policymakers need adequate and unbiased information to evaluate the options for any future paradigm shift in transportation fuel.

For the hydrogen to be available in locations where it is needed, an expensive nationwide hydrogen distribution system would have to be built. Estimates of the cost of building a nationwide hydrogen storage and distribution system vary widely since no real-world data are available. Argonne National Laboratory has made an extensive study of the comparative costs of fuel distribution systems (Mintz, 2001). The analysis assumed that the fuel economy of vehicles will increase between 2.25 and 2.75 times to between 52 and 63 mpg for cars and 40 to 49 mpg for light trucks. Based on this projection, the Argonne engineering analysis
estimates that the cost of a hydrogen infrastructure for a modest market penetration of only 2% in 2020 would be about $60 billion. To achieve a penetration of 12% in the year 2030 would cost about $180 billion, but it could be more than $500 billion for a high market penetration in which 40% of the stock is hydrogen-fueled with cars having a fuel economy of 50 mpg.

Once hydrogen is available, it could be stored in a tank onboard the vehicle as a cryogenic liquid or as a compressed gas. Hydrogen fuel could also be generated onboard the vehicle by reforming methanol or some other hydrocarbon liquid fuel, but any hydrogen storage and transportation system requires special alloys for pipes, valves, and tanks because hydrogen embrit-tles steel. Hydrogen can also be ignited easily by a spark and cause an explosion. Although it is possible that future research may someday provide solutions to these and all other problems for using hydrogen as a transportation fuel, at this time neither is the technology ready for commercialization, nor is funding for an infrastructure available.

Despite these engineering problems in using hydrogen, proponents of a hydrogen economy claim that the answer to our future transportation system is in the use of fuel cells that are powered by hydrogen. For example, in a report titled “Automotive Fuel Cells—The Future is Here,” the Allied Business Intelligence (2000) predicts that by the year 2010 millions of fuel cell-powered vehicles will be on the road. The report also claims that by the second decade of this century the mass production of automotive fuel cells will ultimately result in a total rejection of oil as a transportation fuel. In a similar vein, a recent study by the Freedonia Group (2000) titled “Fuel Cells” claims that explosive growth in fuel cell demand will result in a market reaching $7 billion by the year 2009. An article titled “The Fuel-Cell Sell” in the November 6, 2000 issue of The New Yorker (Surowiecki, 2000) claims that “by the middle of this decade, people driving fuel cell cars will be sitting in traffic with the rest of us” and that “fuel cells will first reach a mass market as replacements for traditional automobile engines.” Doug Nelson, director of the Center for Automotive Fuel Cell Research (the Center is sponsored by the U.S. Department of Energy at Virginia Tech), claimed in the June 11, 2001 issue of Insight (Maier, 2001) “in 10 years the general public will be driving fuel cell vehicles.”

At the other side of the opinion spectrum is a report of the Fuel Cell Technical Advisory Panel prepared in July 1998 for the California Air Resources Board—CARB (Kalhammer et al., 1998). The report concludes, “hydrogen is not considered a techni-cally and economically feasible fuel for private automobiles now nor in the foreseeable future.” This conclusion is buttressed by a comparative study of fuel cell vehicles and vehicles with internal combustion engines conducted by the Umwelt Bundes Amt, Germany’s Federal Environmental Agency (Kolke, 1999), which also concludes that “it will be considerably less expensive to cut emissions and save resources in the foreseeable future by focusing on ultra-low emission vehicles . . . rather than by pressing ahead with fuel cell vehicles.” The report further states that “hydrogen is an inappropriate choice [for transportation applications] because of the high losses incurred in the production and processing stages.”

Despite the many unanswered questions that have been raised about the efficiency, safety, and cost of hydrogen fuel vehicles, several R&D programs with large sums of money are moving ahead on the assumption that hydrogen will become a major transportation fuel in the near future. The CARB Advisory Panel (Kalhammer et al., 1998) estimated that R&D investments to date and commitments for the next few years by major fuel cell developers and some automobile companies are already in excess of $1.5 billion. CARB is considering a program for Zero-Emission Vehicles (ZEV) incentives
that will provide a total of $18 million in grants for the purchase or lease of ZEVs. The South Coast Air Quality Management District is soliciting proposals to develop and demonstrate hydrogen-refueling stations. The U.S. DOE has awarded an additional contract to IMPCO Technologies to test its 5,000 psi hydrogen, crash-resistant in-tank regulator “H2R5000” and develop concepts to extend the ultra-weight, tri-shield hydrogen storage tank technology to 10,000 psi. Although basic research designed to overcome the hurdles of using hydrogen as a transportation fuel should of course be continued, it is important for policymakers to be aware of the major technical and financial problems concerning the use of hydrogen as a transportation fuel and not to assume that the R&D will be able to solve them anytime soon.

Although safety issues are not a primary focus of this study, a preliminary survey was conducted among insurance companies regarding their willingness to insure hydrogen-powered vehicles. Of all the companies contacted, only one responded positively indicating that the company would be willing to consider insuring a hydrogen vehicle, although at a much higher premium than gasoline or natural gas vehicles (Haddock Insurance Agency, 2000). The reluctance of insurance companies to provide insurance for hydrogen vehicles suggests that there is a perception in the insurance industry that hydrogen is a more hazardous fuel than gasoline or natural gas.

**Fischer-Tropsch Technology**

The Fischer-Tropsch (FT) process is the chemical conversion of a synthesis gas into a synthetic liquid fuel. The feedstock can be natural gas, methane from landfills or coal mines, petroleum fractions, or coal. The FT process was invented by two German scientists in 1923. It was subsequently employed in full-scale industrial plants to manufacture synfuels, principally motor diesel, for use by the Hitler war machine during World War II. FT was critical for Germany because the country has substantial coal reserves, but virtually no crude oil. The fuel produced by FT was used for tanks, planes, and motor vehicles. The German FT plants were dismantled after the war, and one of them was actually reassembled in the USA and produced 100 barrels per day in Missouri. In the 1950s, FT technology was further developed and used in South Africa through the South African Coal, Oil and Gas Corporation (SASOL) when the rest of the world embargoed the import of oil during the Apartheid regime. The FT industry in South Africa produced virtually all the fuel needed in the country. Further development of the FT process is currently in progress in many parts of the world.

Rentech, one of the foremost companies in the Fischer Tropsch business, supplied schematic diagrams and efficiency data for diesel fuel production with the Fischer Tropsch process by steam methane reforming and partial oxidation. Although partial oxidation is perhaps more efficient, in view of the fact that steam methane reforming is by far the more advanced and widely used process, we used this method of FT diesel production in our analysis. The schematic diagram for the steam methane-reforming process is shown in Figure 8.

For the purpose of this analysis, we defined the overall thermal efficiency as the energy in all the C5+ (organic compounds with five or more carbon atoms) products, divided by the energy content of the natural gas feedstock, minus the amount of electric power produced from the waste heat available from the process. Using this definition, the efficiency of conversion of natural gas feed by the steam methane reforming is 72%. However, the C5+ products contain not only diesel but also lighter petroleum fractions. According to Dr. Mark Bohn, vice president of Rentech, the C5+ product consists of 75%
diesel fuel and 25% of other products. It is difficult to assign an energy content to the diesel and other fraction, but we have assumed that the diesel fuel portion contains 75% of the energy of the product stream.

According to George Sverdrup of NREL, FT fuels used in diesel engines emit 10% less NOx and 25% less particular matter (PM) than typical California diesel (Sverdrup, 2001). The cost of FT diesel is difficult to determine because there are only two relatively small commercial plants in operation: one in South Africa owned by SASOL and one in Malaysia owned by Shell. According to Gary Grimes (1999), a consultant for Paramount Petroleum, FT diesel from Malaysia can be mixed with conventional diesel to meet the chemical composition requirement of CARB (Sec. 2282 of Title 13 of CA Code of Regulations). Grimes estimates that the value of the FT diesel for blending is 1.77 times the cost of crude oil. For example, if crude oil sells for $25 per barrel, the price it brings in California is ($25/barrel)/(42 gallons/barrel) x 1.77 or $1.05/gallon. In comparison, Hart’s Diesel Fuel News of March 30, 2001 quotes a price of $0.89/gallon for CARB low sulfur diesel in Los Angeles. Hence in California the value of FT diesel is higher than that of regular diesel because it can be used for blending to meet California Standards, but cost for a commercial operation in the U.S. is uncertain.

Air Pollution Remedies

The scientific community as well as most industries has recognized that burning fossil fuels emits CO2 and other greenhouse gases
into the atmosphere and contributes to global warming. It is therefore useful to subdivide air pollution from cars and trucks into two categories (see Figure 9). The first consists of greenhouse gases that trap solar radiation and cause global warming. In the second category are the EPA criteria pollutants, which cause smog and eye irritation and are considered health hazards. The reason for subdividing air pollution from vehicles in this manner is that the remedies to the two types of pollutants are quite different.

When analyzing the energy efficiency of a transportation technology or calculating the pollution from its deployment, it is important to use a well-to-wheel analysis for an accurate evaluation. Otherwise, if the energy needed and the pollution created from the preparation of the fuel is omitted from the analysis, false impressions can be created and legislative efforts to reduce fuel consumption and air pollution can end up in failure. For example, in the preparation of the zero-emission standards for California, the staff of CARB stated in 1994 “the average electric vehicle in 1998 will have a fuel efficiency equivalent to over 100 miles per gallon.” Similarly, a senior scientist at the National Renewable Energy Laboratory (NREL), in an interview with Mitzi Perdue (2000) of Scripps-Howard, claimed, “a car based on fuel cell technology will give you 80 to 90 miles per gallon.” Both of these claims, while technically not untrue, fail to include the inefficiencies in producing the electricity for the batteries or the fuel for the fuel cells. The CARB estimate is based on the electric energy necessary to recharge the batteries as the fuel input, but neglects the efficiency of the power plants required to produce and distribute that energy and the air pollution created in that process. Similarly, the NREL estimate is based on the assumption that hydrogen is available as the fuel for a fuel cell-driven vehicle, but does not consider the energy required to generate the hydrogen. As shown by a subsequent study (Austin and Caretto, 1995), if the CARB analysis were based on the fuel necessary for the electric power production to charge the batteries, the mileage of an electric vehicle is no better than that of an average vehicle with an internal combustion engine, a conclusion that is in agreement with the analysis presented by Kreith et al., 2001.

We shall first consider the pollution from greenhouse gases, which include carbon dioxide, methane, and nitrous oxide. As shown in Table 4, irrespective of what kind of fuel is used, the net amount of CO₂ equivalent pollution is within ± 25% the same for combustion of any major automotive fuels. Although natural gas is cleaner than gasoline or diesel fuel, the only way to reduce the emission of greenhouse gases substantially is to burn less fossil fuels. Unless electricity is generated from nuclear or renewable sources for all-electric battery-powered vehicles, the reduction of greenhouse gases emitted from ground transportation requires cars with better mileage, use of mass transportation, and/or a change in lifestyle that reduces the use of automobiles, particularly single occupancy vehicles. It should be emphasized, however, that mileage must be based on well-to-wheel efficiency.

The remedy for reducing EPA criteria pollutants such as carbon monoxide (CO), NOₓ, SOₓ, and VOC (Volatile

![Figure 9: Subdivision of Air Pollutants](image-url)
Organic Compounds) is quite different. Criteria pollution can be reduced by technological means, such as improved combustion by direct injection engines, efficient catalytic converters, and better engine maintenance. However, no substantial reduction in air pollution, particularly in metropolitan areas, can be achieved without first recognizing the main sources of air pollution. As shown from the tail pipe emissions data of vehicles in cities all over the country, including California cities, most air pollution comes from a small portion of vehicles. This is demonstrated in Figure 10 by CO emissions measured by remote sensing at an intersection between a major cross street (Speer Blvd.) and a highway (I-25) in Denver (Stedman, 1995). The data show that the worst polluting 10% of cars and trucks emit 65% of the CO pollution while the 50% of clean, new cars emit less than 6%. The "gross polluters" are older, poorly maintained automobiles.

Hence, reducing the emissions from virtually clean new cars, as mandated in California and New York, will not significantly alleviate air pollution since they are not the major source of the problem. A similar conclusion was reached by a committee of the National Research Council who, according to the Associated Press (2001), stated that state vehicle emission inspection programs are wasting much of their effort and recommended that they should refocus on older, malfunctioning vehicles that produce most of the pollution.

Figure 10: Percent of Total CO

![Denver 1998 CO Emissions Plot](image-url)

Source: Stedman, March 1995
Based on experiments conducted by Professor D. Stedman (Stedman et al., 1995), the inventor of vehicular-emission remote sensing, the cost effectiveness of various emission reduction strategies for the California fleet is shown in Table 5. Repairing the worst 20% of vehicles is by far the most cost effective strategy. An effective and inexpensive way to reduce air pollution caused by carbon monoxide (CO) and hydrocarbons (HC) anywhere is by identifying the worst polluting vehicles with remote sensing and then repairing them. Reducing the pollution of the worst offenders by 50% could reduce air pollution by 25% or more, according to Bishop and Stedman (1998). On the other hand, reducing the pollution of all new cars by 50% the next year will reduce the total carbon monoxide pollution by less than 3%. It is therefore obvious that no substantial reduction in air pollution can be achieved without repairing the gross polluters or removing them from the road. Legislative measures aimed at new cars, such as the California and New York requirements that a certain percentage of all new cars sold in the state be zero-emission vehicles or the initiatives for alternative fueled-vehicles in Arizona, can result in large expenditures without reducing air pollution significantly.

If the past experience has shown anything, it is that mandates are a poor way to introduce a new technology, especially when the technology is not ready and affordable at the time the mandate is put in place. A good example of this is the ZEV mandate in California, which was put in place in the expectation that advanced battery technology with higher energy densities and lower lifetime costs would be available soon. The projections and expectations did not materialize and CARB subsequently withdrew the mandate that by 1998, 2% of all vehicles must be zero-emission. However,

Table 5: Estimated Costs and Benefits of Various Mobile-Source HC and CO Emission Reduction Strategies (as applied to the California fleet measured in 1991)

<table>
<thead>
<tr>
<th>Action</th>
<th>Millions of Vehicles Affected</th>
<th>Percent Reduction</th>
<th>Estimated Cost (billions of dollars)*</th>
<th>Percent Reduction per Billion Dollars Spent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>HC CO</td>
<td></td>
</tr>
<tr>
<td>Switch to reformulated fuels*</td>
<td>20 (100%)</td>
<td>17 11</td>
<td>1.5</td>
<td>11 7.3</td>
</tr>
<tr>
<td>Scrap pre-1980 vehicles</td>
<td>3.2 (16%)</td>
<td>33 42</td>
<td>2.2</td>
<td>15 19</td>
</tr>
<tr>
<td>Scrap pre-1988 vehicles</td>
<td>14.6 (73%)</td>
<td>44 67</td>
<td>17</td>
<td>2.6 3.9</td>
</tr>
<tr>
<td>Repair worst 20% of vehicles</td>
<td>4 (20%)</td>
<td>50 61</td>
<td>0.88</td>
<td>57 69</td>
</tr>
<tr>
<td>Repair worst 40% of vehicles</td>
<td>8 (40%)</td>
<td>68 83</td>
<td>1.76</td>
<td>39 47</td>
</tr>
</tbody>
</table>

*Reformulated fuels were estimated to cost consumers an extra $0.15 per gallon, or $75 per year for a 20-mpg car driven 10,000 miles per year. Scrappage costs per vehicle were conservatively estimated at $700 for pre-1980 cars and $1,000 to $2,000 for cars built from 1980 to 1988. Average repair costs were estimated at $200 per vehicle.
some states still have mandates backed by incentives in place that by 2003 10% of all vehicles sold in the state must be zero-emission vehicles. These mandates could cost taxpayers a lot of money and also exacerbate any electric power shortages resulting from deregulation.

A new approach to effectively improve air quality by reducing pollution from motor vehicles is under consideration in Colorado. Under the Clean Screen Bill (HB-01-1091), which was introduced in 2000 in the Colorado legislature, vehicles would be screened randomly by a remote sensing technique (Hartman, 2000). The remote sensing system measures the carbon monoxide and hydrocarbons in the exhaust by passing an infrared beam of radiation through the exhaust as shown schematically in Figure 11. The beam, stationed approximately 10 inches above the road surface, is directed into a detector on the opposite side of the road and can determine emissions from vehicles at speeds between 2.5 and 150 mph in less than one second per vehicle. At the same time, the system takes a photograph of the license plate on the car and a computer writes the date, time, and calculated exhaust CO, HC, NOx and CO2 percentage concentrations at the bottom of the image. These images are then stored on videotape or a digital system.

Under a proposal submitted by the Regional Air Quality Council (Hartman, 2000), motorists would pay for the remote sensing tests as part of the annual vehicle registration costs, approximately $7. This compares to current requirements of having periodic emissions tests performed which cost about $25 each, and require approximately two hours of the motorist's time. The current emission tests are inconvenient and unnecessarily time-consuming since more than 90% of the vehicles pass. Under the new proposal, those vehicles that pass the test would receive notification with their annual registration card mailed by county clerks and owners would be told that no emission test is needed. Vehicles that marginally fail the remote

Figure 11: Schematic Diagram of the University of Denver On-Road Emissions Monitor

![Diagram of CO, HC, and NO Remote Sensing](image)

*Note: The remote sensing monitor is capable of monitoring emissions at vehicle speeds between 2.5 and 150 mph in less than 1 second per vehicle.*
sensing test would be notified to undergo an emission test similar to the one now in effect at no additional cost. But a third group of vehicles, called gross polluters, would be flagged by the remote sensing devices and owners would be notified that emission tests are needed immediately. It has also been proposed to provide financial assistance for low-income drivers with emission related repairs. At this point it is not clear what steps would be taken if owners would ignore the test and refuse to repair their vehicles.

Conclusions

Well-to-wheel (WTW) energy analyses of the 10 technologies described in Tables 2 and 3 yield the following WTW efficiency rankings: hybrid-electric configurations using high compression diesel, natural gas spark ignition, and FT diesel components can achieve WTW efficiencies between 30% and 32%. Hydrogen fuel cell, high compression diesel, and FT diesel configurations have WTW efficiencies between 20% and 25%. Natural gas spark ignition, all-electric battery-powered, methanol fuel cell, and direct hydrogen spark ignition configurations have WTW efficiencies below 20%. Emission of the greenhouse gas carbon dioxide is inversely proportional to WTW efficiency.

Past efforts by state and national governments to introduce alternative fuel vehicles by legislating incentives and mandates have failed to achieve a measurable reduction in air pollution or a significant increase in the use of alternative fuels to replace gasoline or diesel. The major reason for this failure appears to be that legislative incentives for alternative fuels are not effective without providing first an infrastructure to store and distribute the fuels.

The analysis presented in this paper shows that as long as hydrogen is manufactured from natural gas, there is no valid reason to build a hydrogen distribution infrastructure for ground transportation because the direct use of natural gas in a hybrid spark-ignition or hybrid diesel engine is a more efficient use of natural resources than using hydrogen as the fuel for a vehicle powered by a fuel cell or an internal combustion engine. The reason for this conclusion is that although fuel cells are very efficient once hydrogen fuel is available, a WTW thermodynamic analysis shows that the inefficiencies in producing and transporting hydrogen from a central station cannot be offset by fuel cell technology compared to using natural gas to fuel hybrid vehicles. The WTW efficiency of using methanol with a processor to generate hydrogen onboard the vehicle for a fuel cell is no better than the efficiency of natural gas SI engines.

Battery-powered vehicles have the highest tank-to-wheel efficiency with electricity as the fuel. But the well-to-tank efficiency to produce and distribute the electric power necessary to recharge the batteries is so low that the WTW efficiency of electric vehicles is less than that of vehicles powered by natural gas SI engines. Furthermore, although battery-powered vehicles emit no tailpipe pollution, unless the electricity needed to recharge the batteries is produced from solar, wind, or nuclear sources, with the current mix of electric power plants and the pollution they generate, electric vehicles will not reduce air pollution on a global scale. Also, since the emission of greenhouse gases is the normal result of burning fossil fuels, any significant reduction of greenhouse gas emission from vehicles requires cars with better mileage, convenient mass transport, or a change in lifestyle.

Supplementing petroleum in the transportation sector within the next 20 years by natural gas is more efficient than by hydrogen, because using natural gas directly to power hybrid vehicles is a more efficient use of resources and less expensive than producing hydrogen for use in a fuel cell. This approach can also benefit from the existence of primary distribution lines for natural gas.
and the perception of insurance companies that natural gas is less dangerous than hydrogen. The Fischer-Tropsch methodology for producing diesel fuel is a promising long-term option to make a transportation fuel from natural gas, biomass or coal that can be used in high efficiency diesel engines and hybrid engines without requiring a new fuel infrastructure.

Endnotes

1. For example, Paper #00-1137 by Alicia K. Birky of NREL (presented at the TRB 79th Annual Meeting in January 2000) and Kreith et al. (1999) of NCSL in the book Ground Transportation for the 21st Century, have surveyed projections by experts on the future supply of petroleum resources.

2. The forecasts of the EIA and those of the oil production by Bartlett (as shown in Figure 3) are based on different premises. The EIA forecasts are based on assumed demand and supply scenarios. The forecasts for the oil production are based on sound scientific principles, which were elucidated and verified by Hubbert (1974). Oil geologists predict that although oil will be available for some time to come, the price of oil will increase substantially. For more information see Campbell, C.J., and Laherrere, J.H., 1998, “The End of Cheap Oil,” Scientific American, v. 278, no. 3, pp. 78-83.


4. See Brown and Breckenridge (2001) for more detailed information on the lessons learned from previous incentives.

5. This section is abstracted from the peer-reviewed article “Efficiency of Advanced Transportation Technologies” by Kreith et al. that was presented at the Intersociety Energy Conversion Engineering Conference, July 2001, Savannah, Georgia.


7. Billings et al. (1997) converted a conventional gasoline-powered internal combustion engine to one powered by injecting hydrogen directly into the engine’s cylinders instead of gasoline. The data from their comparative tests were used for Table 2 in “Efficiency of Advanced Transportation Technologies,” F. Kreith et al. (2001).

8. After this paper was presented at the NCSL/TRB Transportation Technology and Policy Symposium on May 10, 2001 in Washington, D.C., Norman Brinkman of the General Motors (GM) Research and Development Center called our attention to a similar study conducted by GM and the Argonne National Laboratory (GM, April 2001). This study considered 75 system configurations, but was restricted to a specific vehicle (full-size pick-up truck as the baseline). In general, the results of both studies showed similar relative results. But GM’s efficiencies for the 10 configurations considered in this paper were lower except for the methanol-fuel cell option. This discrepancy is surprising, particularly since the experimentally measured efficiency for the methanol fueled PEM fuel cell Electrochemical Engine (ECE) developed by General Motors (see page 7 of Chalk et al., 1998) was used in our comparison.

9. Personal information from Dr. Mark Bohn, vice president, Rentech, Denver, Colorado.

10. See “Global Climate Change” by Larry Morandi, National Conference of State Legislatures, Denver, Colorado, 1990, for a broad nontechnical perspective of the issues relevant to global warming.
References


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