Precursor Systems Analyses of Automated Highway Systems

RESOURCE MATERIALS

Alternative Propulsion Systems Impact

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PRECURSOR SYSTEMS ANALYSES

OF

AUTOMATED HIGHWAY SYSTEMS

Activity Area M

Alternative Propulsion Systems Impact

Results of Research

Conducted By

Delco Systems Operations

FOREWORD

This report was a product of the Federal Highway Administration’s Automated Highway System (AHS) Precursor Systems Analyses (PSA) studies. The AHS Program is part of the larger Department of Transportation (DOT) Intelligent Transportation Systems (ITS) Program and is a multi-year, multi-phase effort to develop the next major upgrade of our nation’s vehicle-highway system.

The PSA studies were part of an initial Analysis Phase of the AHS Program and were initiated to identify the high level issues and risks associated with automated highway systems. Fifteen interdisciplinary contractor teams were selected to conduct these studies. The studies were structured around the following 16 activity areas:

> (A) Urban and Rural AHS Comparison, (B) Automated Check-In, (C) Automated Check-Out, (D) Lateral and Longitudinal Control Analysis, (E) Malfunction Management and Analysis, (F) Commercial and Transit AHS Analysis, (G) Comparable Systems Analysis, (H) AHS Roadway Deployment Analysis, (I) Impact of AHS on Surrounding Non-AHS Roadways, (J) AHS Entry/Exit Implementation, (K) AHS Roadway Operational Analysis, (L) Vehicle Operational Analysis, (M) Alternative Propulsion Systems Impact, (N) AHS Safety Issues, (O) Institutional and Societal Aspects, and (P) Preliminary Cost/Benefit Factors Analysis.

To provide diverse perspectives, each of these 16 activity areas was studied by at least three of the contractor teams. Also, two of the contractor teams studied all 16 activity areas to provide a synergistic approach to their analyses. The combination of the individual activity studies and additional study topics resulted in a total of 69 studies. Individual reports, such as this one, have been prepared for each of these studies. In addition, each of the eight contractor teams that studied more than one activity area produced a report that summarized all their findings.

Original signed by:

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Director, Office of Safety and Traffic Operations Research
and Development

NOTICE

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16. Abstract

This study examines the impact of alternative propulsion systems and fuels on the deployment and operation of the Automated Highway System (AHS). Alternative propulsion systems and fuels are compared to the gasoline-fueled spark-ignition engine in the areas of: specific power, drivability, pleasability, emissions, infrastructure support, production readiness, cost, and energy efficiency. Issues and risks related to the deployment of a large fleet of alternative propulsion vehicles on the AHS are examined. Alternative AHS configurations are identified and analyzed for their compatibility with alternative propulsion systems and fuels. Long-term design issues and enabling technologies required to incorporate alternative propulsion systems and fuels into AHS are identified.

17. Key Words

alternative propulsion, alternative fuels, Automated Highway System, infrastructure, emissions, performance, cost

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EXECUTIVE SUMMARY

Activity M–Alternative Propulsion Systems Impact analyzes the impact of propulsion systems and fuels other than the gasoline-fueled spark-ignition engine on the deployment and operation of AHS and identifies key design issues and enabling technologies for these alternative propulsion systems. At the direction of FHWA the analysis, as here reported, excludes roadway provided electric power since that technology is being addressed in depth by another contractor.

This analysis proceeds in 6 parts, or tasks:

Identify Alternative Propulsion Systems

The spark ignition engine (SI) is reviewed and serves as a baseline to which alternative propulsion system are compared. These alternatives are:

- Compression Ignition (diesel).
- Gas Turbine.
- Rankine Cycle (steam engine).
- Stirling Cycle.
- Battery Electric.
- Fuel Cell.
- Hybrid Systems–e.g., battery electric coupled with a small SI engine.

These alternative systems are compared for:

- Specific Power.
- Drivability.
- Pleasability.
- Emissions.
- Infrastructure Support.
- Production Readiness.
- Cost.
- Energy Efficiency.

A summary of results is found in table 1 from which it is concluded that the SI engine is unlikely to be replaced by any of the alternatives unless by legislative mandate. This is due to the long history of development and refinement, overwhelming infrastructure support, and production readiness of the SI engine.

Assess Alternative Fuels

A comparison is made among:

- Fossil fuels.
- Fossil fuel derivatives (e.g., methanol, hydrogen).
- Non-agricultural renewable resources (hydropower).
- Biofuels.
- Nuclear power.

These are compared in the areas of:

- Infrastructure support (See table 2.).
- Emissions (See figures 3 and 4 and tables 3 through 5.).
- Cost (See table 6.).

Some conclusions from the comparison are:

- In infrastructure support nothing comes close to reformulated gasoline (RFG), the evolving status quo fuel.
- Excluding California, only compressed natural gas (CNG) and liquefied petroleum gas (LPG) offer full fuel cycle advantages over RFG. All alternative fuel offer an advantage in California.
- Gasoline is the cheapest fuel when considering total cost of energy, vehicle modifications, and delivery.

A review is also made of alternative batteries. The review is summarized in table 7 and figure 5. The review showed that none of the low risk batteries were competitive with gasoline engines in either specific power or specific energy.

Identify Performance Issues, Benefits, And Risks

Compatibility of alternative fuels with the alternative propulsion systems is examined and summarized in table 8.

Some predictions of trends in alternative power/fuel systems based on the research of tasks 1 and 2 are:

- Most automobiles will continue to use SI engines.
- Compression ignition engines will continue as the engine of choice for heavy trucks.
- 85 percent methanol (M85) and compressed natural gas (CNG) will each comprise about 10 percent of fuel usage by 2010.
- Electrics will have limited popularity due to limited range, long recharge, and high cost.
- Demand for electrics will be driven by Government influences.
- Rise in fuel economy standards, upward trend in fuel taxes will tend to halt present trend to higher performance vehicles.

Additional trends, including the projected usage of alternative fuels can be found in the task 3 written material.

Performance issues, benefits, and risks associated with the above trends are:

- Dynamic performance–pressure from fuel economy/price and the addition of electric vehicles will tend to decrease performance.
- Safety–no safety issues, benefits, or risks are expected from the introduction of alternative fuels or propulsion.
- Range–all of the alternative propulsion/fuels have a negative impact on range.
- Environment–when examined on a full fuel cycle the environmental impact of the alternative fuels present mixed results, even for electric vehicles. This can be seen in tables 3 through 5.
- Cost Efficiency–when cost of fuel, distribution, and on-vehicle storage is considered all alternative fuels suffer a disadvantage compared to gasoline.
- Controllability–no issues or benefits arose from considering alternative propulsion/fuel.
- Unique Operational Attributes–unique fuels are required and unique check-in requirements will exist for battery electric vehicles.

Identify Alternative AHS Configurations

Alternative AHS configurations were examined which make possible or enhance the use of alternative fuel/propulsion vehicles. The issue raised is degraded dynamic performance. Conclusions reached regarding handling of the differences in performance were:

- Limiting access to the AHS to certain times of day is not suitable.
- Separate lanes are not economically justifiable.
- Separate platoons are not viable unless the platoons can be formed while traveling on the AHS.
- One-vehicle platoons are the most likely method for accommodating vehicles with unique dynamic characteristics.
- Separate check-in lanes offer advantages for vehicles with unique characteristics, but separate check-in facilities are justifiable only for AHS service vehicles or heavy duty commercial vehicles.

Identify Deployment and Operation Issues and Risks

These are the issues and risks associated with deploying a significant fleet of alternative fuel/propulsion vehicles. These issues and risks arise from possible need for routine and emergency refueling on the AHS, vehicle range factors, and design and performance standards. The conclusions are:

- Routine refueling as part of the AHS infrastructure will not be needed as alternative propulsion vehicles must exist as a viable economic and consumer concept independent of AHS.

- Emergency refueling will likely be needed regardless of the fuel or propulsion type of the vehicles on the AHS.
- Enhanced range estimation at check-in and on an ongoing basis is needed, with the possibility that the vehicle may have to exit for refueling earlier than planned. The alternative is to apply a very conservative estimate of remaining fuel at check-in time. This is certainly unacceptable for battery-electric vehicles with their already limited range.
- It is the desire of the vehicle manufacturing industry to build power systems which meet uniform standards as much as possible. Aspects of vehicle performance which do not come under specific regulation may need to be commonized to meet some minimum level. The responsibility for setting these requirements must be assigned by Federal Authorities.

List AHS Technology And Design Issues

The long term design issues and enabling technologies which are required to incorporate alternative propulsion systems and alternative fuel vehicles into the AHS are identified as:

- Control coordination approaches that allow entry of vehicles with lower level dynamic performance into the AHS.
- Battery designs that have significantly increased specific power and energy.
- New vehicle designs for alternative propulsion and fuel that provide better solutions for the location of fuel storage and for smaller, lighter vehicles and more efficient operation.
- Enhanced measurement of energy supply and range prediction algorithms for alternative fuel vehicles.
- Determination of unique safety requirements associated with the use of alternative fuel vehicles.

INTRODUCTION

Objective

The objective of the Alternative Propulsion Systems Impact activity is to assess the impact on the deployment and operation of AHS of propulsion systems and fuels other than the gasoline-fueled spark-ignition engine and identify key design issues and enabling technologies for the alternative propulsion systems. At the direction of FHWA the analysis, as here reported, excludes roadway provided electric power since that technology is being addressed in depth by another contractor.

Technical Approach

The technical approach breaks the analysis into the following six tasks.

Identify Alternative Propulsion Systems

This task starts with a review of the characteristics of the internal combustion engine in order to provide a basis for comparing other propulsion systems. A broad range of alternative propulsion systems is then identified and characterized. Their characteristics for specific power, drivability, pleasability, emissions, infrastructure, production readiness, cost, and energy efficiency are then systematically compared with the baseline internal combustion engine.

Assess Alternative Fuels

In this task alternative fuels are identified and assessed for their implications in the broad areas of infrastructure, emissions, and costs. Electricity, which is one of the alternative fuels considered, must be stored in batteries located in the vehicle. Thus, as part of this task, a number of different batteries are identified and assessed for their suitability and availability.

Identify Performance Issues, Benefits, and Risks

In this task the compatibility of the several alternative propulsion systems and alternative fuels is first considered. Then, based on present trends and the preceding analysis, predictions are made as to the direction and changes which automotive powertrain and fuel systems will experience out through the year 2010. The issues, benefits, and risks associated with these changes are then discussed in the areas of dynamic performance, safety, range, environmental impact, cost efficiency, controllability, and other attributes.

Identify Alternative AHS Configurations

Alternative AHS configurations which make possible or enhance the use of vehicles with alternative propulsion systems and alternative fuels are identified, discussed, and assessed in this task.

Identify Deployment and Operation Issues and Risks

This task identifies and discusses the deployment and operation issues and risks associated with the presence of a significant fleet of AHS vehicles having an alternative propulsion system or using an alternative fuel.

List AHS Technology and Design Issues

Key long term design issues and enabling technologies that are required by the incorporation of vehicles having an alternative propulsion system or using an alternative fuel are listed in this task.

REPRESENTATIVE SYSTEM CONFIGURATIONS

The representative system configurations (RSC’s) were generated very early in this Precursor Systems Analyses of AHS program. These RSC’s are used throughout the various areas of analysis whenever a diversity of system attributes is required by the analysis at hand. The RSC’s identify specific alternatives for 20 AHS attributes within the context of three general RSC groups. The Roadway Provided Electric Vehicle (RPEV) concept is not specified for any of the RSC’s. Thus it is not addressed as part of this activity. This is in keeping with FHWA direction that this concept be only addressed by another PSA contractor.

Since the RSC’s have such general applicability to these precursor systems analyses, they are documented in the Contract Overview Report.

TECHNICAL DISCUSSION

Task 1. Identify Alternative Propulsion Systems

In this task a broad range of propulsion systems will be discussed. The discussion will begin with the spark ignition internal combustion engine in order to provide a basis for comparing other propulsion systems. The propulsion systems discussed are:

- Spark ignition.
- Compression ignition.
- Gas turbine.
- Rankine cycle.
- Stirling cycle.
- Battery-electric.
- Fuel cell.
- Hybrid.

At the end of the task, the alternatives are systematically compared across a number of characteristics.

Spark Ignition Engine

The homogeneous-charge spark-ignition (SI) piston engine operating on a four-stroke cycle is the dominant light-duty automotive power source. The four-stroke cycle consists of an intake stroke during which the fresh fuel-air mixture is induced into the cylinder, a compression stroke during which that charge is compressed, an expansion stroke during which work is extracted from the cylinder charge, and an exhaust stroke during which the burned charge is expelled from the cylinder. Internal combustion of the fuel-air charge is initiated by a spark late during the compression stroke and essentially completed during the early part of the expansion stroke. Work developed during the expansion stroke is consumed in compressing the cylinder charge, pumping the charge into and out from the cylinder during the intake and exhaust strokes, overcoming engine friction, and powering accessories. The balance of the expansion work is delivered as useful output from the engine for vehicle propulsion.

This engine is quite mature, with opportunities for revolutionary advances probably exhausted. Evolutionary gains can be expected, however, that will gradually improve further its output per unit weight and volume (specific output), its fuel efficiency, and its exhaust emissions. Improvements in specific output will come from enhanced engine breathing (more than two valves per cylinder), tuned intake and exhaust systems, variable valve actuation, variable induction systems, supercharging, incremental reductions in engine friction (pistons, rings, valve train, bearings), use of lighter materials (aluminum, plastics, magnesium), and modest increases in compression ratio. Many of these steps will also benefit fuel efficiency, as measured in kilometers per liter. Modest improvements in engine-out emissions will continue, but the largest gains are expected from the exhaust after treatment system.

Specifically, after treatment will be improved during the startup of a cold engine, during which most of the tailpipe emissions are released in the Federal test procedure.

Many offshoots of the homogeneous-charge four-stroke SI engine exist, but improved versions of the present engine will continue to dominate through the first decade of the next century and provide the benchmark against which other options are measured.

Among the possible variations is the four-stroke SI direct-injection stratified-charge (DISC) engine. In this engine the charge is intentionally stratified by injecting the fuel into the cylinder air during the compression stroke rather than attempting to premix it by adding it to the air upstream of the cylinder. Injection may occur either early during the compression stroke or late, near the end of the compression stroke. The four-stroke DISC engine eases the restriction on compression ratio imposed on the homogeneous-charge version by combustion knock, thus promising improved fuel efficiency. Efficiency is also enhanced by use of a lean mixture at part load, which eliminates or at least minimizes the use of inlet throttling for control of engine load. However, these advantages are eroded by lower specific output, relatively higher mechanical friction, and a more complex and costly fuel-injection system. Without the as yet unsuccessful lean engine catalyst, this engine appears unlikely to satisfy future light-duty NOx emission standards when operated on gasoline or diesel fuel.

The two-stroke DISC engine has received considerable attention of late. In the two-stroke cycle, the intake and exhaust strokes are eliminated in favor of a gas-exchange process that occurs while the piston is near the bottom of its travel between the expansion and compression strokes. Since the apertures through which the burned gas leaves the cylinder and the fresh air enters the cylinder are open concurrently during gas exchange, a positive pressure difference must be established between the intake and exhaust to ensure that the combustion products are scavenged from the cylinder. This pressure difference is produced either by using the underside of the piston and the crankcase as a scavenging pump, in which case the sump cannot be used as an oil reservoir, or by employing an external engine-driven blower, in which case the conventional wet sump is employed. Each approach has its advantages and disadvantages. Modest gains in fuel efficiency have been claimed for both, along with improved specific output. The unresolved concerns about the two-stroke DISC engine that will likely determine its acceptability are durability and emission performance after long use.

The rotary engine credited to Wankel is a kinematic variation of the four-stroke piston engine. In it, a three-cornered rotor orbits within a wasp-waisted cavity enclosed between two parallel plates. With this special geometry, three chambers are formed between the flanks of the rotor and the inner wall of the cavity. These chambers change volume periodically as they travel around the cavity with the orbiting rotor. The changes in chamber volume mimic the changes in cylinder volume that occur in a piston engine as its pistons reciprocate. The rotary engine offers greater specific output and operating smoothness than the piston engine, but entails sub-standard fuel efficiency. Its hydrocarbon emissions have proved to be a challenge. This engine is installed in limited quantities by one manufacturer in a sports car. Other manufacturers no longer show interest in it.

Compression Ignition Engine

The four-stroke compression-ignition (CI) engine, or diesel, incorporates the same piston-stroke events as the four-stroke SI engine. The charge is stratified, however, by injecting the fuel into the cylinder late during the compression stroke. Ignition of the fuel occurs spontaneously as a result of the temperature reached by the cylinder air during compression. This requires, first, that the CI engine employ a higher compression ratio than can be tolerated by the conventional SI engine because of the combustion knock associated with its homogeneous charge. Second, the CI engine uses diesel fuel, a petroleum distillate less volatile than gasoline that self-ignites more readily at high temperature.

The CI engine provides better fuel efficiency (kilometers per liter) than the SI engine because it is freed of the knock limited compression ratio constraint, and because it uses an unthrottled lean mixture at part load. Moreover, diesel fuel contains about 12 percent more energy per liter than gasoline. However, the diesel engine suffers from lower specific output because its higher cylinder pressure demands sturdier construction and because the most fuel-rich mixture tolerated by its combustion process at full load is leaner than the stoichiometric (chemically correct) ratio. Its specific output can be improved by turbocharging because CI combustion is freed from the knock phenomenon that plagues the conventional SI engine.

In the direct-injection (DI) diesel, fuel is sprayed directly into the combustion chamber above the piston. DI diesels may incorporate a piston bowl to enhance turbulence for faster mixing of fuel and air, or they may incorporate a bowl-less piston in a quiescent design that eschews turbulence and achieves the required mixing through use of high injection pressures, or they may use a wall-wetting configuration in which the objective is to vaporize the fuel from a piston surface on which the fuel spray is intentionally impinged. In the indirect-injection (IDI) diesel, the fuel is sprayed into an ante-chamber communicating with the main chamber above the piston through a passageway.

Heavy-duty diesels are all of the DI type, most often with a quiescent chamber and a multi-hole nozzle. Past passenger car diesels have been of the IDI type, with a single-stream nozzle. Efforts are strong, especially in Europe where fuel pricing makes the diesel more attractive, to develop a DI diesel for that application because it achieves higher fuel efficiency than the IDI version.

Although CI engine-out hydrocarbon and carbon monoxide emissions are low, the emissions of NOx and particulate matter (PM) are a problem. Unfortunately, most of the strategies that decrease NOx increase PM, and vice versa. If a lean-mixture NOx-reducing catalyst were developed for road vehicles, it might improve the NOx / PM tradeoff, but so far such a catalyst has not been successful. Tailpipe PM emissions have been decreased on some engines by installing an oxidizing catalytic converter in the exhaust system that removes a fraction of the PM attributed to hydrocarbons adsorbed on the carbonaceous soot constituting the bulk of PM. A recently legislated reduction in the sulfur content of diesel fuel is also helping to meet PM standards. Particulate traps have been under development for some time.

They must be regenerated periodically by burning off the accumulated particulates, which has led to durability difficulties. This characteristic, combined with the added cost involved, has encouraged engine producers to search for other means of meeting particulate standards.

The CI engine completely dominates the heavy-duty field and is used to a decreasing extent in medium duty and light-duty vehicles. Sales of diesels in U.S. passenger cars reached a peak of six percent in 1981 and have since decreased to less than one percent. No automotive engine provides better fuel efficiency than the diesel, but its difficulty with light-duty emission standards, the comparatively low cost of gasoline, the higher first cost of the diesel engine, and previously exhibited disaffection of the public with diesel cars have dampened the enthusiasm of car manufacturers for this power plant.

The two-stroke diesel has been marketed successfully for trucks and buses by one domestic manufacturer for many decades. It is of uniflow design, with blower scavenging, intake ports in the cylinder wall and exhaust poppet valves in the cylinder head. Like its four-stroke counterpart, it is available either naturally aspirated or turbocharged, with or without after cooling.

The low-heat-rejection (LHR) diesel, broadly but improperly termed the “adiabatic” diesel, began to receive notable attention over a decade ago. The expectations in some quarters was that with its elimination of the traditional liquid cooling system, the waste heat normally rejected to the coolant would be recovered on the crankshaft for increased efficiency. The laws of thermodynamics preclude complete recovery of this energy, however. Instead, heat rejection to the lubricating oil rose substantially, and much of the rest of the heat conserved appeared in the exhaust gas. To capitalize on this exhaust heat, the LHR diesel normally incorporates turbocompounding, whereby a conventional turbocharger increases the density of the air entering the cylinder to compensate for the otherwise reduced air mass inducted by the hotter running cylinder, and a second turbine downstream of the turbocharger and geared to the crankshaft extracts additional energy from the hotter exhaust stream. In principle, such turbocompounding is advantageous at high engine loads but can be detrimental at the light loads associated with passenger cars. Meanwhile, the high temperatures encountered with uncooled cylinders makes NOx compliance problematic and demands either ceramic construction or judicious use of ceramic coatings. Neither of these ceramic options has yet attained attractive levels of reliability and cost. Additionally, a satisfactory means of lubricating an uncooled cylinder has yet to be developed. Commercialization of the ceramic LHR engine in the next 15 years is not assured.

Gas Turbine

The gas turbine is an internal-combustion engine like the SI and CI engines, but in the gas turbine the combustion is continuous rather than intermittent. Engine inlet air is compressed in a rotary machine, in the automotive application usually a centrifugal compressor. Following combustion, the hot gas is expanded through one or more turbines, of either the axial or the radial-inflow type. In the traditional combustor, located between the compressor and the turbine(s), a spray of fuel is burned in air at an overall lean mixture ratio.

The compressor, burner, and turbine constitute a simple-cycle engine, but there is no hope thermodynamically of achieving acceptable automotive fuel efficiency without adding a heat exchanger. By transferring heat from the turbine exhaust stream to the compressor discharge air, the heat exchanger preheats the air entering the burner, thus decreasing the fuel flow required to reach a specified turbine inlet (= burner outlet) temperature.

Two types of heat exchanger have been used. In the regenerator a porous matrix, usually in the form of a large disk, rotates slowly in such a way that each sector of the disk stores heat as it rotates through the turbine exit gas, then rejects that heat as it rotates through the compressor exit air to preheat that air before its passage to the combustor. In contrast, in the recuperator the heat is transferred from the turbine exhaust to the compressor discharge air across an extended stationary surface that separates the two streams. The regenerator generally offers greater heat exchanger effectiveness in a given space but has greater parasitic leakage and requires a drive mechanism.

Essentially all successfully demonstrated automotive gas turbines have been of the two-shaft type. In this arrangement the compressor and first turbine are mounted on a common shaft and function solely to deliver hot compressed gas to a second “power” turbine that is connected to the vehicle wheels. This arrangement allows the compressor to continue running during engine idling, while the power turbine is stationary with the vehicle drive wheels. This two-shaft arrangement provides maximum torque when the power turbine is thus stalled, a desirable characteristic that the piston engine can achieve only when coupled to a torque converter transmission.

In the single-shaft gas turbine, the engine must be decoupled from the drive wheels at idle, and the engine lacks the desirable torque characteristic of the two-shaft version. To drive an automotive vehicle, it needs a transmission with a continuously variable speed ratio. A suitable transmission for the single-shaft gas turbine remains to be developed.

The gas turbine operates at a very high rotational speed that tends to increase as engine power rating is lowered. Slow response to sudden changes in power demand has been a problem. The turbomachinery is compact, but the heat exchanger is bulky and can present a packaging problem. The high air consumption of this engine calls for large inlet and exhaust ducting. The conventional gas turbine avoids the liquid cooling system of the piston engine, but this welcome deletion rules out the normal approach for heating the passenger compartment. The gas turbine enjoys remarkable insensitivity to fuel type. Aside from its comparatively high cost, the characteristic of the gas turbine engine that has blocked its acceptance in the automotive field is its poor fuel economy, especially at light load.

Other factors remaining fixed, the gas turbine cycle is influenced strongly by peak cycle temperature. To increase fuel efficiency, ceramic construction capable of accepting higher temperatures than current super alloys is undergoing aggressive research. Higher peak temperature also means a lower engine airflow requirement, which leads to a more compact and lighter engine. It also means smaller turbomachinery. As the compressor and turbine shrink, their respective component efficiencies suffer, and those efficiencies also affect fuel economy. To date, the problems of ceramic reliability and cost have forestalled evaluation of a ceramic gas turbine in an automotive vehicle that demonstrates fuel efficiency objectives. Barring an unexpected breakthrough, it is uncertain that the gas turbine can attain commercial automotive service in the next 15 years. As progress is made in that direction, the need exists for a fresh approach to the combustion system that can satisfy new NOx standards.

Rankine Cycle Engine

The traditional steam engine operates on the Rankine cycle. Water is pressurized by a pump and passes into a steam generator, where an external-combustion source is used to boil the water and then superheat the steam. The steam passes through an expander that extracts power for vehicle propulsion. Expanders of both the reciprocating piston and turbine types have been employed. The spent steam then passes through a condenser, which is a heat exchanger in which ambient air is used to transform the steam back into water for reentry into the pump.

Steam cars were once commonplace but were displaced by the rapidly improving gasoline DI engine. In the late 1960s the automotive steam engine was revisited in the belief that its continuous external combustion would result in lower emissions. That experience taught a number of lessons. First, continuous combustion did not automatically guarantee low emissions. Second, the extra warm-up time inherent in a cold external-combustion engine before significant power can be developed was both unpopular with the driver and a source of unwanted fuel consumption. Third, engine fuel efficiency was unacceptably poor. Fourth, the low efficiency required a larger condenser than could be reasonably accommodated in a passenger car, with the result that steam had to be released from the condenser at high engine loads and made up from an on-board water tank that required periodic refilling. Fifth, engines that require on-board storage of water are unsuited for use in cold climates because of the potential for freezing. Given its large size and weight, and its poor fuel economy, the automotive steam engine is no longer considered a contender.

Stirling Cycle Engine

The Stirling engine is also an external-combustion closed-cycle machine. The preferred working fluid is hydrogen, although helium can be used at a sacrifice in efficiency. In the ideal Stirling cycle, the hydrogen is compressed isothermally. It is then heated as it passes through a regenerator. Next the gas expands isothermally. The heat required to keep the temperature from falling during expansion is provided by a continuous external-combustion source. The gas again passes through the regenerator, flowing in the opposite direction and depositing heat for pickup again by the working fluid following compression on the next cycle.

The ideal Stirling cycle boasts a thermodynamic efficiency as high as can be achieved by any cycle operated between the same temperature extremes. The actual engine has shown admirable efficiency during steady state operation on a dynamometer, but fuel economy in a car operated according to the Federal test procedure has proven disappointing. The deficiency was traced to engine warm-up fuel and to high fuel consumption when idling. This characteristic, along with engine size, weight, and cost, and an unresolved problem with hydrogen leakage, has eliminated the Stirling engine from serious consideration as an automotive prime mover.

Battery Electric System

Although common at the start of this century, by 1920 the electric car had been essentially displaced by the gasoline engine. Interest in the electric vehicle (EV) has been rekindled several times in recent decades because of concerns about air quality, the oil embargo, and rising oil import, but each time interest has waned. The new focus on EV's is motivated by the California law requiring zero emission vehicles (ZEV's) beginning in 1998. The battery electric powertrain is the only realistic candidate for satisfying the ZEV standard. California wants 2 percent of 1998 new vehicles from major manufacturers to be ZEV's in 1998, that fraction rising to 10 percent in 2003. Also, 12 northeastern States that do not meet the present ozone standards are considering adopting the California regulations. If this happens, about one in every three new cars could be subject to the California standards.

Advances have been made over the years, especially in electronics. With modern inverters now available to transform DC into AC, it is possible to replace the DC motor with a smaller, lighter, higher speed AC motor that avoids the brush wear problem of the DC machine. But the EV bottleneck remains the battery. Discussion which relates to specific batteries will be delayed until task 2.

The battery electric powertrain has several advantages over the current gasoline spark ignition engine. It has the equivalent of zero idle fuel consumption (unless, of course, accessories like air conditioning are operating while the vehicle is stationary). It is capable of recovering kinetic energy from the vehicle during deceleration and braking by operating the propulsion motor as an electric generator to recharge the batteries. These advantages should be particularly beneficial when driving “stop and go” in congested city traffic.

Battery electric systems also have their disadvantages. A traction battery is comprised of hundreds of cells connected together. Individual cells can be expected to deteriorate at different rates. When one cell fails to carry its share of the load, the others must work harder. This hastens their deterioration. Battery deterioration is more severe in actual vehicle service than in laboratory evaluations because of vibration, shock, and temperature variations. The domestic manufacturers are just beginning to fleet test their EV's to gain such experience.

Long recharge times are one of the traditional negative aspects of batteries. Various approaches to decrease this time are being studied but this fundamentally implies higher power levels and the commensurate increase in the cost of the charging station equipment and usually a decrease in efficiency as well. The aggravation of long recharge times is worsened by the short driving range on a battery charge. Room temperature batteries generally suffer from poorer performance in cold weather. Vehicle acceleration and hill climbing ability deteriorate as the battery charge is consumed. Passenger comfort may be sacrificed in extreme climates. For example, the Ford Ecostar requires about 8 kW at a steady 80 km/hr.[1] In northern climates, it can take an additional 5 kW to heat the passenger compartment electrically. After initially disallowing fossil fueled heaters in ZEV's, California now permits them if they have zero evaporative emissions and if they are disabled at ambient temperatures above 4.5° C. Air conditioning the Ecostar in Phoenix when the temperature is 40° C consumes about 3.5 kW. Obviously, electrical heating or cooling of the vehicle's passenger compartment reduces range significantly.

Fuel Cell

The fuel cell converts energy stored in a fuel directly into electricity. The fuel is hydrogen. It chemically reacts with oxygen in the air to produce electricity and water. No combustion is involved in the fuel cell itself, so its contribution of regulated emissions is very low. Because it is not a heat engine, its efficiency is freed from the Carnot limitation imposed on heat engines and is about double that of such an engine.

Development and demonstration of fuel cell propulsion can be accomplished using hydrogen fuel stored on-board, but this is not an acceptable approach for large scale vehicle application of the fuel cell as a propulsive means. Hydrogen simply is not available in the required quantities, nor at an acceptable price. A significant change in that situation is not foreseen over the next 15 years. Consequently, in advanced development of the vehicular fuel cell supported by the Department of Energy (DOE), the required hydrogen is generated on-board in a reformer. The reformer produces hydrogen through partial oxidation of another fuel, typically methanol or natural gas. Because the reformer has trouble following the rapid transients typifying automotive operation, the reformer/fuel cell system is connected in parallel with a storage battery. The concept is to use the battery as a load leveler. The fuel cell is operated at a more or less constant power level, with the battery supplying supplemental energy to the vehicle during periods of high demand and being recharged by the fuel cell when the energy it delivers exceeds that required for propulsion. Two types of fuel cell are being explored for vehicle propulsion, the phosphoric acid fuel cell (PAFC) and the proton-exchange membrane (PEM) fuel cell.

The PAFC operates at about 190° C. Starting from room temperature requires a fuel burner for preheating and currently takes about an hour. Such a warm-up requirement would restrict its use to specialized applications like a transit bus.

The PEM fuel cell,[2] with its methanol reformer, is diagrammed in figure 1. It is less developed than the PAFC but is currently preferred because it can start from room temperature in minutes, for its lower operating temperature of about 80° C avoids the need for preheating. Presently it is a very expensive power plant, partially due to the quantity of precious-metal catalyst in the fuel cell.

The fuel and oxidant streams must be humidified to avoid dehydration of the membrane above 50° C. This requires a tank of mineral-free water to be carried, raising concern about operation in sub-freezing temperatures. To minimize the capacity of the water tank, a condenser recovers water from the fuel cell exhaust. A motor-assisted turbo-compressor maintains the fuel cell at three to five atmospheres pressure to aid in membrane humidification. The low operating temperature of the PEM makes the catalyst sensitive to poisoning by carbon monoxide. To lower the CO content of the reformer exhaust to a couple of ppm or less, a preferential oxidizer is inserted between the reformer and the fuel cell. This presently preferred fuel cell/reformer/battery system is in the R&D stage under DOE sponsorship, with vehicle application yet to be demonstrated. Given its current status, the probability of reaching large-scale commercialization in the next 15 years seems low.

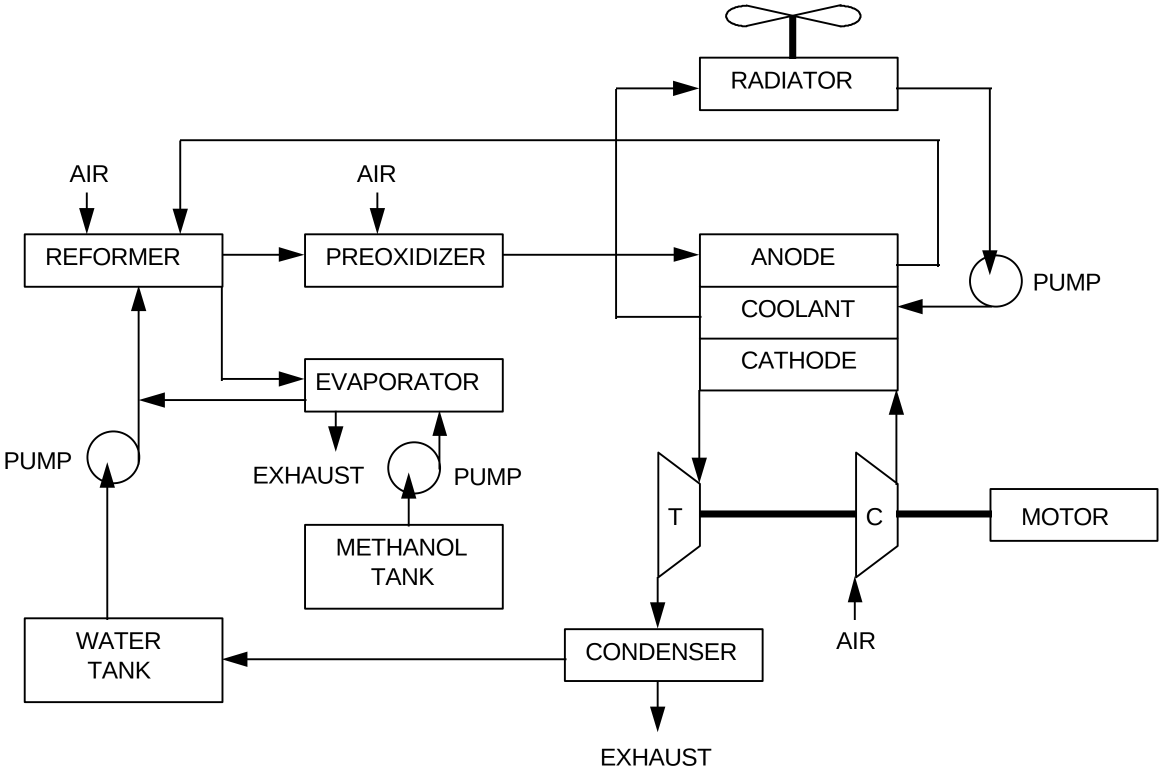


Figure 1. PEM Fuel Cell Diagram

Hybrid Systems

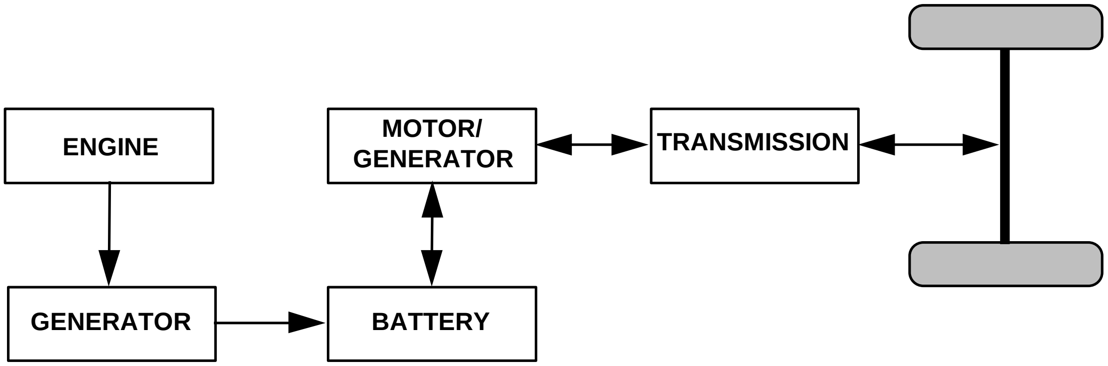
Hybrid propulsion systems refers to systems which combine two or more power storage and production devices into a system which has characteristics superior to those of the individual components. Three examples of hybrid propulsion system configurations are illustrated in figure 2. A battery electric combined with a small IC engine driving a generator corresponds to the case (a), Series Elements. The case of a small IC engine used to augment the battery electric drive for peak acceleration and long grades is shown in (b), Parallel Elements. Finally, the use of a mechanical flywheel or an ultracapacitor as a quick charging and releasing electrical storage devices to augment the battery pack is shown in (c), Fast Storage.

In the series hybrid, all of the propulsive power passes through an electric motor, which draws its energy from the battery. Operating the motor as a generator during deceleration and braking transfers some of the vehicle kinetic energy back into the battery. The engine is started to run the generator whenever the state of battery charge falls below a specified level and is shut down when a specified higher state of charge is reached. If a gasoline engine is used, the battery can preheat the exhaust catalyst before the engine is restarted in order to control emissions. The battery can be used to provide emission free driving within the central city, with the engine being used as a range extender outside the city center. With the series arrangement, performance is limited by the electric powertrain and range by the capacity of the engine fuel tank.

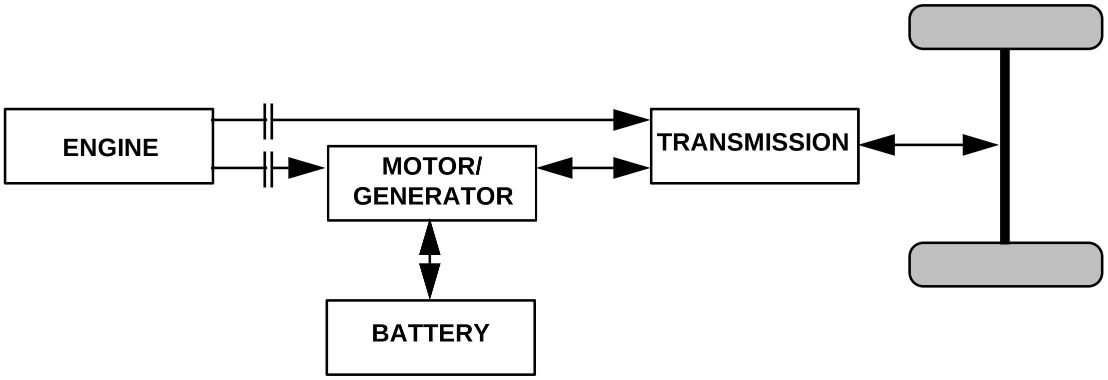
In the parallel hybrid, both the motor and the engine can deliver power to the vehicle. Again, the motor can be used as a generator for regenerative braking. It can also be run as a generator by the engine to recharge the battery. Performance depends on the sum of power from the engine and the electric system, with range again depending on the capacity of the engine fuel tank. Either of these arrangements of elements allows use of a battery with a smaller energy capacity than in a non-hybrid electric vehicle because the range deficiency is compensated for by the engine. In the series hybrid, though, the smaller battery limits performance.

The fast storage configuration offers performance advantages both as shown without an engine and in combination with an engine (particularly the series arrangement of case (a)). The fast storage element is able to quickly absorb short duration but high power levels of the regenerated energy of braking, and when properly precharged, can provide short bursts of energy for improved acceleration or for short duration hill climbing.

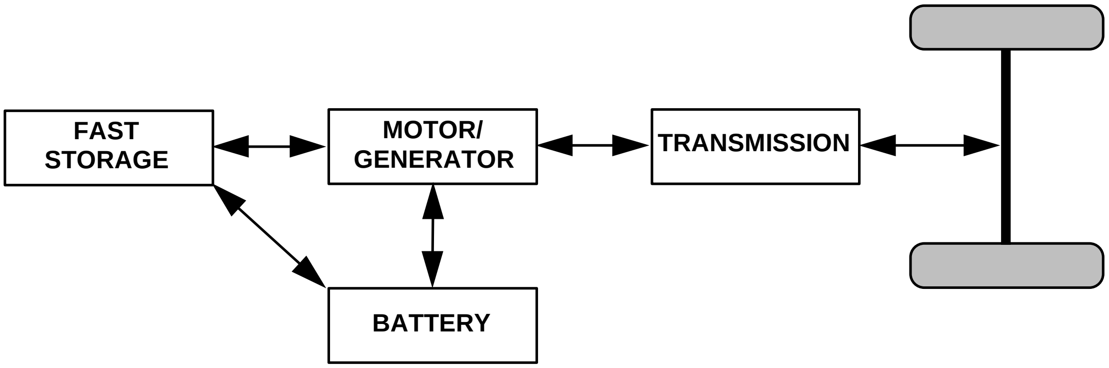
Because hybrid systems fundamentally involve multiple sources for propulsive power and allow braking power to be stored rather than dissipated as heat, they require a power management controller. Among the more interesting devices which have possible applicability to hybrid systems are the ultracapacitor, flywheel, and turbo-alternator. These devices are discussed in the following subsections.



(a) Series Elements



(b) Parallel Elements



(c) Fast Storage

Figure 2. Hybrid Propulsion System Alternatives

Ultracapacitor

The ultracapacitor is a condenser that can store electricity like a battery but can receive or release it quickly.[3] The quantity of electrical energy it can store is almost negligible compared to that stored in a battery, however. Ultracapacitors which have a specific energy of less than about 10 Wh/kg but a power density as high as 1000 W/kg are anticipated. The ultracapacitor is used as a power-peaking device to make available higher power for acceleration and greater power acceptance with regenerative braking. For EV's in which the battery cannot supply energy fast enough to meet the power demand, an ultracapacitor connected in parallel could provide the short power bursts, being subsequently recharged over a longer time period by the battery or by regenerative braking if the vehicle is frequently decelerating. DOE is monitoring ultracapacitor development, but successful demonstration in an EV has not yet been announced.

Flywheel

Because of the limited range and performance of the battery-electric vehicle, interest has been increasing in the flywheel, a mechanical energy storage system. Flywheels have been used for many years particularly in spark and compression ignition engines for the purpose of smoothing the discrete power pulses. Flywheel energy storage could be used as the sole source of stored energy, or more likely in a hybrid in combination with a battery pack. A flywheel/electric battery hybrid would have no tailpipe emissions and so should qualify as a zero-emission vehicle.

The best flywheels today rival the best available batteries in energy storage per mass (specific energy–Wh/kg). This is still far short of the present gasoline engine system. The flywheel is not constrained by the electrochemical limitations of the battery in delivering power quickly on demand. Thus its delivered or received power per mass (specific power–W/kg) is much higher than that of a battery. The flywheel promises shorter recharge time and longer cycle life than the battery, plus insensitivity to ambient temperature.

The energy stored in a flywheel is directly proportional to its mass, but to the square of the tangential velocity of its radius of gyration. Given this second power dependency, the incentive is for a lightweight flywheel with a high tangential velocity. To conserve space, it is desirable to achieve the high tangential velocity with a small diameter flywheel turning at a very high speed. In advanced flywheels this is being achieved by filament winding, on a mandrel, a high strength fiber and epoxying it in place.

This technology is still evolving and the prevention of delamination of the filament flywheel during service is one of the major challenges. Because of the high rotational speeds, the flywheel must be housed in an evacuated container to minimize parasitic windage losses. If conventional oil lubricated bearings were used, they would have to be located outside the container, necessitating a shaft seal that invites loss of vacuum. Consequently, magnetic bearings are being applied within the container. Provisions must be made in these bearings to contend with gyroscopic forces and road shock loads, realistic in a vehicle but not experienced in the typical development laboratory. Lightweight containers capable of sustaining the necessary vacuum and strong enough to contain burst flywheels are another developmental challenge.

Because the flywheel decelerates as energy is provided to accelerate the vehicle, and with regenerative braking accelerates as energy is recovered when the vehicle decelerates, a mechanical connection between the flywheel and the vehicle drive wheels would require a continuously variable transmission. To overcome this hurdle, transmission of power between the flywheel and the vehicle if preferably accomplished electrically. Clearly, a decelerating flywheel presents a variable frequency source of electricity. Advanced electronic controls are thus necessary to accommodate this characteristic as well as the needs of the magnetic bearings. The electric transmission does however facilitate regenerative braking and provides the ability to charge the flywheel with energy from an electrical source.

The simple flywheel is seen to be not quite so simple when applied as a energy storage device for vehicles. The technology requires extensive development and may ultimately prove attractive.

Turbo-Alternator

The turbo-alternator, also called a turbogenerator, is a gas turbine as previously discussed which is directly linked to an electric power generator. These units have received considerable development work as auxiliary power units for military tanks. The turbine is of a simple one shaft design but does use a recuperator to increase efficiency. The turbo-alternator as part of a hybrid system acts as an onboard electricity generator to supply power to batteries, which in turn power electric drive motors. The turbo-alternator may thus be run at close to a constant speed. This allows the speed to be optimized for fuel economy and emissions. This overcomes the disadvantages in terms of fuel economy and acceleration lag which the gas turbine has as a primary automotive engine. The turbo-alternator in preliminary testing meets the requirements of an ultra-low emissions vehicle. Also, if the battery pack is sufficiently charged, the turbo-alternator could be turned off while driving within a city or other high-pollution areas with the vehicle running wholly on stored battery energy. Thus this form of hybrid could qualify as a zero emissions vehicle for limited periods of time.

Comparison Of Alternative Propulsion Systems

The eight alternative propulsion systems discussed above will be assigned a qualitative score from A (standing for excellent) to E (standing for failure) with respect to a number of desirable characteristics. The characteristics are:

Specific Power

Specific power refers to the amount of available power output per unit of installed propulsion system mass. Thus, this measure if it were quantified would have units of watts per kilogram. Also considered under this category is the power per unit of volume. It is desirable that both of these specific power values be large for power sources intended to propel vehicles since this leads to generally efficient machines with a minimum of the vehicle's mass and volume devoted to the propulsion system. This measure of mass and space efficiency applies to the combination of the engine (or electric motor) and its nominal source of energy. Many of the propulsion systems may be powered by alternative fuels as will be discussed in detail in the following task, but in this present context, the nominal fuel or energy storage medium is indicated. Thus the spark ignition engine is fueled by gasoline, the compression ignition engine is fueled by distillate, the gas turbine and the Rankine and Stirling cycle engines are fueled by either gasoline or distillate, and the fuel cell is fueled by hydrogen generated by an on-board reformer. The battery-electric uses of course battery stored electrical energy.

A low ranking against this characteristic impacts AHS to the extent that entry ramp length and the time and space allocated to acceleration maneuvers on the AHS may have to be greater. Thus the high performance aspect of RSC 2 is at risk. Note that specific energy, which relates to the ease of providing driving range, is not considered as a propulsion system characteristic but will be considered for alternative fuels.

Drivability

This category refers to the propulsion system's ability to propel the vehicle in a smooth, predictable, and easily controlled manner for starting, stopping, and cruising under all conditions of temperature and altitude for which vehicles are normally used. A propulsion system with a significant lag in power output or inability to maintain similar characteristics under all temperature conditions would be rated lower in this category. Also included in this category is any cold start problems such as unsuitability for freezing conditions or long warm up characteristics.

Drivability is primarily a characteristic needed to please the vehicle buyer. The closed loop control inherent in AHS may have to be designed to be compatible with degraded plant characteristics if drivability is low. The cold start and long warm up aspect of drivability should not affect AHS because vehicles would be running for some time before entering the AHS.

Pleasability

Pleasability refers to the absence of noise and vibration, and the general contribution to passenger comfort such as providing a source of heat for heating the vehicle interior when needed.

Pleasability is also primarily a characteristic needed to please the vehicle buyer. An inherent low level of noise and vibration would enhance the trip experience at high speeds. Low noise would contribute to AHS not being disruptive to the urban environment. Failure to provide a source of heat for heating the vehicle interior when needed would contribute to reduced and less predictable vehicle range and thus would need to be considered as part of the vehicle check-in process.

Emissions

Emissions refers to the desirable minimization of emissions locally at the vehicle. Full fuel cycle emissions will be discussed elsewhere. The emissions consist of: reactive organic gases (ROG) which are generally essentially equal to non-methane organic gases (NMOG) or non-methane hydrocarbons (NMHC) that are used as an alternative by some, carbon monoxide (CO), nitrogen oxides (NOx), sulfur oxides (SOx), and particulates of size less than ten microns (PM10). Note that nitrogen oxides include nitric oxide (NO), nitrogen dioxide (NO_2), and nitrous oxide (N_2O). For regulatory purposes, NOx concentration is assigned the molecular weight of NO_2.

Acceptable vehicle emissions characteristics are subject to legislation. Thus all vehicles would need to meet applicable standards. However exemplary levels would tend to make AHS installation less disruptive to the urban environment.

Infrastructure

Infrastructure refers to the degree to which service facilities are presently available or can be easily converted to provide needed maintenance on the propulsion systems.

Infrastructure is of course needed irrespective of any AHS installation. However, should the AHS implementation be keyed to a vehicle propulsion system which needs new infrastructure, then the creation of that infrastructure would need to be planned for and created at the time of the AHS installation.

Production Readiness

Production readiness is the degree to which the total manufacturing processes are in place and the degree to which the present design approaches exist that necessary for large scale production.

This characteristic has an impact on AHS only to the extent that it tends to predict and modulate future trends. No AHS could realistically be considered which was keyed to a vehicle propulsion system which was not production ready at the time of the planned AHS implementation

Cost

Cost is simply the dollar cost of the installed propulsion system. Government taxes and/or subsidies can drastically change the cost as perceived by the end consumer.

Since vehicle based AHS equipment will increase the cost of a vehicle, it is unlikely that the consumer would choose a higher cost propulsion system unless it offered some other desirable characteristic not offered by other propulsion systems.

Energy Efficiency

Energy efficiency refers to the degree to which the propulsion system converts the fuel energy to mechanical motion of the vehicle. To be quantitatively measured, a specific driving cycle would need to be defined.

Energy efficiency translates into extended range for a given load of fuel or battery energy charge. This would enhance long rural trips on the AHS and also allow urban trips with a lower fuel/charge level at the check-in.

The scores for the alternative propulsion systems are presented in table 1. Two of the alternative propulsion systems require additional specific definition in order that the comparisons can be made for a clearly defined configuration. In this comparison, fuel cell will refer to a fuel cell/reformer/battery pack combination as previously described. The on-board reformer produces hydrogen from another fuel, the fuel cell generates electricity from the hydrogen, and a battery pack is used as a load leveler. The hybrid propulsion systems can take several different forms. The most likely by the 2010 time frame is an internal combustion engine combined with a battery-electric. Flywheels seem unlikely in this time frame. The form of internal combustion engine could be either spark ignition, compression ignition, or a gas turbine such as the turbo-generator.

Table 1. Comparison Of Alternative Propulsion Systems

	Specific Power	Drivability	Pleasability	Emissions	Infrastructure	Production Readiness	Cost	Energy Efficiency
Spark Ignition	B	B	B	B	A	A	A	B
Compression Ignition	C	C	C	C	B	B	B	A
Gas Turbine	A	D	B	C	D	D	D	C
Rankine Cycle	D	E	B	C	D	D	D	D
Stirling Cycle	D	D	B	C	D	D	D	C
Battery - Electric	E	D	D	A	E	C	D	B
Fuel Cell	E	D	D	A	E	E	E	A
Hybrid	D	D	C	A	C	C	E	A

Key: A = Excellent, through, E = Failure

The specifics of the comparisons will now be discussed. The spark ignition engine is the baseline against which the alternative systems will be compared. Largely due to its long period of continuous development, this engine is given a B in specific power, drivability, pleasability, and efficiency. It is possible to imagine a motive source which is better in all these categories but hard to make large improvements. Some may question the category of emissions as a B. However, the spark ignition engine has improved dramatically, and is still being improved to meet more stringent standards. Most of the present vehicle pollution is produced by old vehicles manufactured under more modest emissions requirements. This engine clearly deserves an A in infrastructure and production readiness. Cost can always be (and is being) improved, however at this time all alternative propulsion systems can at best only strive to match the spark ignition engine in cost given its long period of manufacturing experience. The energy efficiency of the spark ignition engine is good and continues to make incremental improvements. However, since it is thermodynamically limited by its inherent cycle, it is rated a B because others can be more efficient.

The compression ignition engine as compared to a spark ignition engine is heavier, harder to start at very cold temperatures, and is noisier. Thus the Cs in the first three categories. Most emissions are similar to spark ignition emissions but NOx and particulates remain a problem. In particular, the Mercedes and VW diesel cars for sale in the United States have a temporary waiver of 0.625 g/km NOx as compared to the 0.25 g/km standard faced by the spark ignition engine. The service infrastructure is not as extensive and production readiness is not domestically in place. The engine is generally produced at a cost premium as compared to the spark ignition engine. The efficiency from a thermodynamic cycle efficiency point of view is better than the spark ignition engine. This engine also enjoys the perceived efficiency advantage of burning a fuel with higher energy content per volume.

The gas turbine, even when it uses a regenerator, is lighter and smaller for the same power output as compared to the spark ignition engine. Thus its specific power is given an A. Because it has poor throttle response and provides very little engine braking, it is given a D in drivability. It has superior noise and vibration characteristics but has inadequate heat rejection to provide cold weather passenger compartment heating. Thus its pleasability is taken as equal to the spark ignition engine. Its emissions are given a C because the ability to match a present spark ignition engine with a three-way catalytic converter after long use has yet to be demonstrated. Trained service personnel do not exist but the skills would be similar to those for spark ignition, thus a D. Automotive sized gas turbines are not close to mass production readiness but nothing fundamental prevents this being achieved, thus a D. Cost is rated a D but extensive productionization may improve this. Efficiency is a function of peak temperature which is related to costly ceramics.

The Rankine and the Stirling cycle engines are similar in many categories and will be contrasted with the spark ignition engine together with some differentiation. Both are bulky and heavy which results in a specific power rating of D. Both have a long cold-start warm-up time which is inherent in an external combustion engine. In addition the Rankine is unsuited for sub-freezing ambient temperatures because of freezing of the water which constitutes the working fluid. No suitable anti-freeze is available which meets the demands of the steam cycle. Because of these characteristics the Rankine is rated a E and the Stirling is rated a D for drivability. With respect to noise, vibration, and passenger comfort both can approach the spark ignition engine. Both are similar to a gas turbine in that their emissions have not yet been demonstrated as being the equal of a spark ignition engine with a three-way catalyst. The Rankine and Stirling cycle engines are similar to the gas turbine for the categories of infrastructure, production readiness, and cost. Their demonstrated efficiencies are poorer than a spark ignition engine with the Rankine being the poorer of the two. Thus they are rated a D and C respectively.

The battery-electric system is bulky and heavy as compared to the spark ignition engine, even when the full charge range is significantly less. Thus it is rated E for specific power. The drivability is degraded because of the difficulty in getting enough power into the vehicle for brisk performance and also because the energy of room temperature batteries deteriorates in cold weather. Thus it does not have repeatable performance under all normal conditions. This warrants a D. Noise and vibration are very good but to use stored electrical energy to heat the passenger compartment under cold conditions results in the D rating for pleasability. Emissions are excellent at the vehicle. Full fuel cycle emissions are discussed elsewhere. The infrastructure of trained personnel does not now exist and the skills to service electric motors and especially batteries are sufficiently different to warrant an E. Since battery-electric vehicles are being produced in small quantities today, the production readiness is quite good but not as good as for a spark or compression ignition engine. The cost of batteries and the power conversion and recovery equipment is still high, thus a D. The energy efficiency is about the same as a spark ignition engine, thus a B.

The fuel cell is bulky and heavy as compared to the spark ignition engine, thus a E rating in specific power. The acceleration performance is limited by the battery pack so is about the same as the battery-electric, giving a D in drivability. Since limited electrical energy or hydrogen needs to be used to heat the passenger compartment, the pleasability is also a D despite good noise and vibration potential. The local emissions would be better than a spark ignition engine, thus an A. The service infrastructure is completely nonexistent and the system exists only as a laboratory unit at this time, thus Es in infrastructure and production readiness. The cost will likely be higher than any unit discussed so far, thus an E. The fuel cell is not limited by the thermodynamic cycle efficiency so the efficiency is excellent, an A.

The specific power of the hybrid should be somewhat better than the battery-electric in a parallel hybrid, as illustrated in figure 2 (b), because of the superiority of the engine, hence a rating of D. However if a series hybrid, as illustrated in figure 2 (a), is used the power is limited by the power available through the electric side of the hybrid, hence no better than a battery-electric rating of E is warranted. If an ultracapacitor is used then this would be significantly improved at the expense of increased complexity and cost. Drivability is rated a D as for the battery-electric because of the poor battery performance in cold weather. Since some, but limited, rejected heat would be available for heating the passenger compartment in cold weather, pleasability is rated a C. Local emissions would not be as good as a battery-electric but would be superior to the spark ignition engine, thus indicating an A for emissions. Infrastructure is rated a C since, unlike the battery-electric, charging stations are not needed, however trained service personnel are only partially existent. The production readiness is about equivalent to the battery-electric, thus a C. The use of multiple power sources and the required power management raises the cost of a hybrid resulting in a rating of E. The efficiency should be superior to a spark ignition engine primarily because the engine used in the hybrid is either off or running at or very close to its most efficient condition, thus an A.

In summary, it is seen that the spark ignition engine combines generally good characteristics, a long history of development and refinement, and an almost overwhelming infrastructure and production readiness advantage to present a propulsion system which is very unlikely to be significantly replaced without the inputs of exogenous market inputs such as legislative mandates within the time frame of this study.

Task 2. Assess Alternative Fuels

Basic Energy Sources

In this section a number of basic energy sources which have applicability for automotive use will be identified and discussed.

Fossil Fuels

Fossil fuels are derived from prehistoric underground deposits, either solids, liquids, or gases, and are nonrenewable. Their combustion adds new carbon dioxide (the principal greenhouse gas) to the atmosphere.

Petroleum, the primary liquid fuel, is the major source of energy for automotive propulsion today. It provides gasoline and petroleum distillates. These distillates are heavier and less volatile than gasoline. They include diesel fuel, kerosene, and furnace oil.

The leading gaseous fossil fuels are natural gas and liquefied petroleum gas (LPG). As delivered for commercial use, natural gas is typically about 90 percent methane. Natural gas which is compressed in order to achieve a volume efficient source of portable energy in often called compressed natural gas (CNG). LPG is a byproduct of natural gas extraction and petroleum refining. It is about 95 percent propane.

The primary solid fuel is coal. Coal can be burned directly in electrical generating plants. It can also serve as a feedstock from which other fuels are made, ranging from methane to automotive liquids like gasoline. Such conversion is not done presently to a significant degree in the U.S. because of economic and environmental considerations. Liquid fuels can also be made from oil shale and tar sands, but these options are presently unattractive for the same reasons.

Fossil Fuel Derivatives

Methanol, which will be listed below as a biofuel, can also be made from natural gas. For economic reasons nearly all of it is. Hydrogen, also discussed separately below, is usually derived today from fossil fuel, either natural gas or petroleum.

Non-Agricultural Renewable Energy Sources

The leading non-agricultural source of renewable energy is water (hydropower). The hydraulic head required for hydropower may exist naturally in mountainous terrain. It may be created or augmented by damming rivers and streams. Economically attractive and environmentally acceptable sources of hydropower in the U.S. have already, for the most part, been exploited to generate electricity. Another form of hydropower energy which is being harnessed to a limited degree is the hydraulic head created by tides. Automotive use of hydropower requires battery-electric vehicles.

Geothermal energy production taps underground heat to generate electricity in a steam power plant. Realistic sources of geothermal energy in the U.S. are even more limited than are hydropower sites.

Wind power can be used by windmills to generate electricity. To be economically attractive, windmill “farms” must be located where a reasonably high and consistent wind exists. Such sites are limited in the U.S. Existing windmill farms have elicited objections on aesthetic grounds.

Solar energy can be used to generate electricity, either by focusing the rays of the sun to provide heat for a heat engine driving a generator or by generating the electricity directly in a photovoltaic cell. Both face economic barriers, although ongoing progress in the development of solar cells may eventually increase their attractiveness.

Operating a battery-electric car on solar electricity involves a time mismatch, for solar electricity is available only during daylight hours, but battery charging is expected to occur to a large extent at night. Generation of solar electricity in the large quantities required for propulsion of a significant automotive fleet is reasonable only in geographic areas like the Southwest, where the annual insolation is highest. Even there, the land required for significant generation is enormous and invites aesthetics based protest.

Solar cell efficiency is already high enough that on-board solar cells can operate such low power accessories as an air circulating blower in a parked car. Average insolation is so low, though, that the probability of installing enough solar cells on board an automobile to meet its own power needs is essentially zero. The special purpose solar cars that have been demonstrated competitively around the world should not be confused with practical automobiles for the public.

Biofuels

Biofuels are those made from a harvestable crop and are therefore renewable.

Forest wood was once the most widely used fuel. Population growth and environmentalism now preclude the use of natural forests as a significant energy source, although waste wood from commercial forestry and the lumber industry is used in a few locations to generate electricity.

Methanol (methyl alcohol) can be made from wood. Ethanol (ethyl alcohol) is presently made from crops, corn in the U.S. and sugar cane in Brazil. Corn based ethanol is presently the most expensive alternative fuel in the U.S. that is being considered as a gasoline replacement.

The National Renewable Energy Laboratory (NREL) is developing a process to make ethanol from cellulose in waste wood, new trees from tree farms, certain grass like crops, and municipal waste. The process in approaching the pilot plant stage, but is not yet economically competitive. NREL projects that if the project proves successful, enough ethanol might be produced to replace a significant fraction of highway fuel. Achieving that objective by 2010 is very questionable, however, considering the current status of the research.

Diesel fuel can be made from vegetable oil. In the U.S., soybeans are the leading candidate as the source of the oil. Unless chemically reacted first with methanol to form an ester, vegetable oil has caused unacceptable engine deposits. This methyl-ester biodiesel fuel made from soybean is known as methyl soyate or “SoyDiesel”. It is being blended with petroleum based diesel fuel and used experimentally in bus fleets, but it is not presently cost competitive. Other possible feedstocks for diesel fuel are waste animal fat, used frying oil, peanuts, cottonseed, sunflower seeds, and canola.

Nuclear Energy

Nuclear energy can be used to generate electricity for battery-electric vehicles. This source produces no air pollution, although disposal of radioactive waste remains a concern. Because of public disfavor regarding nuclear power and its high cost relative to generation of electricity using fossil fuel, significant expansion of nuclear electricity in the next 15 years is unlikely.

Hydrogen

Hydrogen is the favorite fuel of environmentalists because burning hydrogen produces no hydrocarbons, no carbon monoxide, no carbon dioxide, no carbonaceous particulates, and none of the regulated toxics. However hydrogen must be produced and as mentioned above, today it is made mostly from fossil fuel. This method of producing hydrogen is not pollution free.

Hydrogen can be made by electrolyzing water, but not at low cost. This process is clean if nuclear or non-agricultural renewable energy is used to generate the electricity. At least during the next fifteen years or more, the amount of hydrogen made using these methods will be negligible alongside the energy needed by the automotive fleet. Despite its cleanliness, such issues as cost, storage, and lack of an infrastructure indicate that hydrogen will not see significant automotive application in the next fifteen years.

Alternative Automotive Fuels

Over about the past 25 years, Government has increasingly influenced the automotive marketplace. Regulations and other initiatives have significantly influenced automotive development in the areas of safety, fuel economy, and emissions. Regulations will continue to have even a stronger influence on propulsion and fuel system development. Alternative fuels are one of the possible approaches towards achieving the desired levels of emissions.

Candidate Alternative Fuels

Fuel alternatives to conventional gasoline are foreseen as a possible path to improved air quality in non-attainment areas. By 1995, nine areas with extreme or severe ozone problems are required to change over to reformulated gasoline (RFG), and about 100 other cities with lesser ozone problems may elect to join them. At least 30 percent of the current gasoline market is expected by EPA to be converted to RFG by 1995. Gasoline consists of over a hundred distinct components. Each of these components when burned in an engine produces reactive organic gases (ROG) which have differing tendencies to produce ozone and smog. Each of the components has been assigned a reactivity factor which can be used to multiply its gm/km emissions to represent a tendency to contribute to air pollution. RFG is gasoline which is reformulated with the purpose of reducing the air pollution consequences of ROG emissions.

Improved local air quality is also anticipated from the use of alternatives to gasoline. These include M85 (85 percent methanol plus 15 percent gasoline), E85 (85 percent ethanol plus 15 percent gasoline), LPG (liquefied petroleum gas, mostly propane), CNG (compressed natural gas, mostly methane), hydrogen, and electricity. In the Energy Policy Act of 1992, Congress made clear its desire to replace 10 percent of petroleum-derived fuel energy by 2000 and 30 percent by 2010. One reason is to reduce oil imports. Today, close to half of U.S. petroleum consumed is imported, and thus adversely affects the national trade imbalance. It is also anticipated that a switch away from petroleum derived fuels would result in a reduction in greenhouse gas emissions.

Emissions Background

There are many measures and initiatives which can affect automotive emissions. A recent study at General Motors estimated the reduction in volatile organic compounds (VOC, for cars essentially equivalent to HC) in a city like Chicago in 2010, relative to a 1991 baseline.[4] The Environmental Protection Agency's latest atmospheric model, MOBILE 5a, was used. Older vehicles were replaced by new ones each year. The total vehicle kilometers traveled was assumed to grow at a compounded rate of 1.8 per cent per year.

The projected reduction in VOC emitted by light duty vehicles in 2010 is presented in figure 3. If 1993 regulations continued unchanged, VOC from the light-duty fleet would fall about 22.5 percent from the 1991 baseline as new vehicles replace older ones built to more lenient standards. Tier 1 tailpipe regulations phase in from 1994 to 1996. That is expected to drop fleet VOC another 3.5 percent. Use of reformulated gasoline provides an additional 24 percent reduction in VOC. Improvements to the evaporative control system account for another 7.5 percent reduction. An additional 4 percent is attributed to the capture of gasoline vapor normally displaced into the atmosphere whenever the fuel tank is filled. Planned improvements to the vehicle inspection and maintenance procedure, which involve changing from a simple idle test to a brief test under load on a chassis dynamometer, is credited with an additional 12 percent. Finally, if California Low Emission Vehicle standards were implemented, another 3 percent drop would occur. Of the total VOC reduction of over 75 percent, the largest single contributor is the change to reformulated gasoline, followed by exchanging old cars in the fleet for newer cleaner ones. In contrast, the small contributions from the Tier 1 and California LEV standards suggest that further reductions in tailpipe emission standards are relatively ineffective.

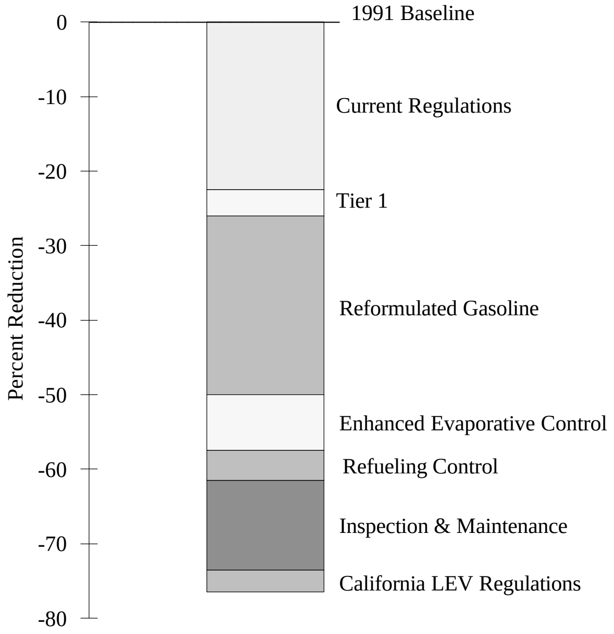


Figure 3. Reduction In Volatile Organic Compounds Emitted In 2010

A study performed by the Environmental Protection Agency (EPA) projected the national NOx emissions from several sources.[5] Their historical and projected NOx emissions are presented in figure 4. Note that the anticipated national NOx emissions from highway vehicles in 2010 is expected to fall to less than half of the 1980 level and that the projected contribution from electric utilities in 2010 remains high. These projections raise concerns about the environmental impact of widespread use of electric vehicles.

Because tailpipe standards must be met regardless of their relative effect on total fleet emissions, car manufacturers are working hard to achieve future standards. The most stringent set for engine-powered cars are the California ULEV (ultra-low emission vehicle). Compared to the Federal tailpipe standards that have been in place for over a decade, the ULEV standards call for reductions of approximately 90 percent in NMOG (non-methane organic gases, replacing HC), 50 percent in carbon monoxide (CO), and 80 percent in NOx. Effort is being devoted to the engine in the areas of mixture preparation, ignition, cylinder design, and engine controls. But because most of the HC and CO emissions are exhausted during the first minute or two after the cold start, before the catalyst has reached its lightoff temperature, much attention is focused on faster catalyst lightoff. Catalyst heating, both electrically and by a fuel-fired burner, is being researched, along with a HC trap. The durability and cost of such devices are important issues. There is some optimism that ULEV standards can be met, at least in the smaller cars. If this optimism proves unfounded, the remaining possibilities are alternative fuels, hybrids, and electric vehicles.

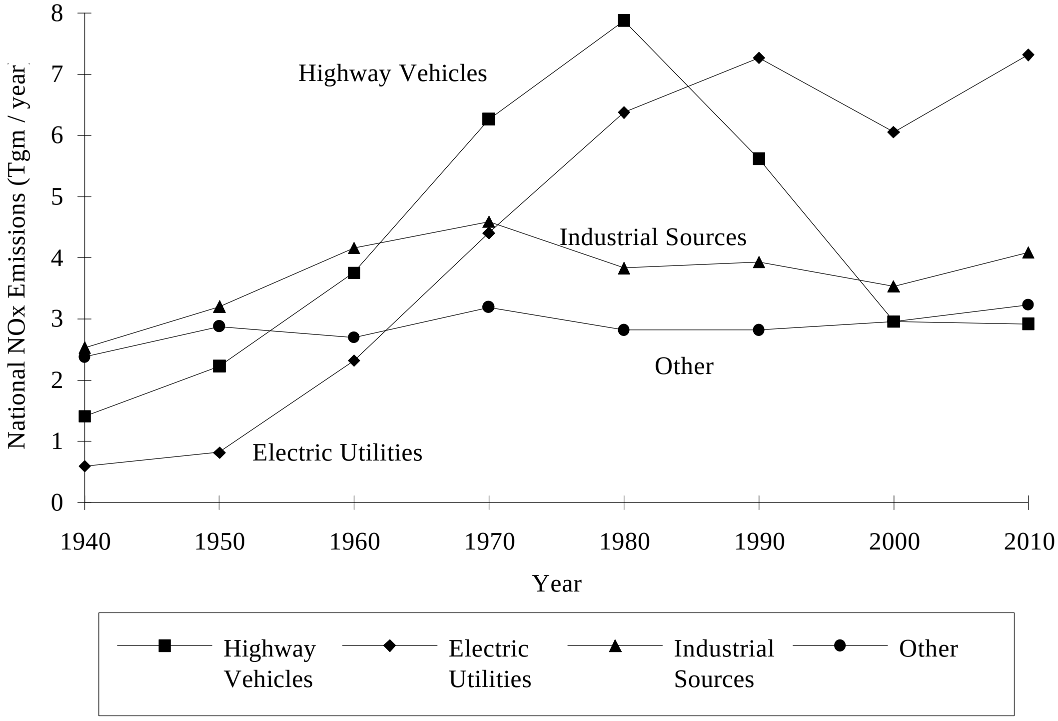


Figure 4. Historical And Projected U.S. NOx Emissions

Alternative Fuels–Infrastructure

Infrastructure is an important issue in judging alternative automotive fuels. A successful fuel must have an adequate supply, a means of distributing it to delivery stations, delivery stations which deliver fuel to vehicles, and a means of storing the fuel on board the vehicles. The alternative fuels just discussed are ranked for these four aspects of infrastructure in table 2. In the discussion which follows for each of the alternative fuels, the context assumes that each is being considered as the alternative for 10 percent of the highway vehicle energy consumed in 2010.

Reformulated Gasoline

It seems clear that in 2010, most passenger cars will be using gasoline, specifically, reformulated gasoline (RFG), if for no other reason because of the many cars in service that cannot use any other fuel without extensive modification. On a scale ranging from A for excellent to E for failing, RFG deserves only a C for supply because it uses so much imported petroleum. It earns B's for distribution, delivery, and storage, however. The only fluid which is superior in these categories is tap water.

Table 2. Grading The Infrastructure For Alternative Fuels

Fuel	Supply	Distribution	Delivery	On-Board Storage
RFG	C	B	B	B
M85	D	C	B-	C-
E85	D	C	B-	C
LPG	C	B	B	C
CNG	B	B	C	D
Hydrogen	E	E	E	E
Electricity	C	A	D	D-

Key: A = Excellent, through, E = Failure

Methanol

Most methanol is made from natural gas, with an associated energy loss of about 30 percent. The energy content of all the methanol produced annually in the U.S. is less than one percent of the energy in the gasoline consumed annually by highway vehicles. It has been anticipated that replacing even 10 percent of highway gasoline with M85 would result in importing cheaper methanol from overseas rather than expanding domestic production facilities.[6] Importation seems to violate one of the objectives of the Energy Policy Act. Because of the lack of a present source capability and because of the likelihood of importation, a supply grade of D is assigned. Once imported methanol is received at marine terminals, it would likely be trucked to delivery stations rather than transported through existing pipelines alternating with gasoline because of concerns about water contamination and phase separation. Such distribution by tanker truck may tend to exclude some States from M85 supply but would nevertheless cover enough of the nation to supply M85 for about 75 percent of the potential vehicle-kilometers traveled. For this reason a distribution grade of C is assigned. Although M85 can be delivered through existing service stations, those service stations would require modification to ensure compatibility with the solvent properties of methanol, thus a grade of B- for delivery. Because M85 stores only about half of the energy per liter as compared to gasoline, more storage volume at marine terminals and service stations, and more tanker trucks, would be required than for RFG. This low energy density also penalizes vehicle range for a fixed size fuel tank, thus a C- for on-board storage is indicated.

Ethanol

Most U.S. ethanol is made from domestic corn. Enough is available to serve as an octane improver for unleaded gasoline, but if 30 percent of the fleet were operated on E85, the supply would again be inadequate. Total U.S. ethanol production is less than 1 percent of highway gasoline use on an energy basis. The National Renewable Energy Laboratory is working on a promising process to make ethanol from cellulose.[7] Although a more plentiful supply is projected for this process, it is uncertain that even if its development proves successful, it could be expanded into a significant automotive energy source by 2010. Thus a grade of D is indicated for supply. Distribution, delivery, and storage obstacles for E85 are generally similar to those for M85 except that E85 contains about 25 percent more energy per liter. The same grades are thus assigned as for M85 except that on-board storage is upgraded slightly to a C.

Liquefied Petroleum Gas

LPG is a byproduct of petroleum refining and natural gas extraction, so its supply is limited by the use of those fuels. It has many established non-automotive uses in the U.S. The energy use of LPG in transportation is presently less than 1 percent of that of highway gasoline. It is graded as a C for supply. In the small quantities in which it is used for transportation, distribution and delivery networks are in place. These networks would need to be expanded but this should not present a severe obstacle. Distribution and delivery are graded as B's. Range on a tank of LPG is less than on gasoline stored in the same volume, thus a C for on-board storage. LPG is a good automotive fuel, but its inherently limited supply severely restricts its broad usage.

Compressed Natural Gas

Domestic natural gas is in comparatively plentiful supply. Its industrial, commercial, and residential use, plus that consumed in generating electricity, is about 50 percent greater on an energy basis than that of the gasoline used in highway transport. Thus its supply is graded as B. Because of its widespread use, a distribution network is in place, earning a B. CNG lacks adequate refueling sites, thus earning a C for delivery. Initial purchasers of CNG vehicles are mostly operators of centrally fueled fleets with their own fueling facilities. Most fleet vehicles are resold after three to five years to individuals or small businesses. These secondary owners will reject natural gas unless they have access to fueling facilities accessible by the general public. One means of mitigating this is for the vehicle to be a bifuel vehicle, that is, capable of running on either natural gas or gasoline. A bifuel M85 or E85 vehicle can use the same fuel tank for either its alternative fuel or for gasoline. A gaseous bifuel vehicle burning CNG and gasoline however must have separate fuel storage capability. CNG vehicles store gas in high pressure cylinders at about 200 atmospheres of pressure. Even at these pressures, the volumetric energy density is so poor that vehicle range is severely curtailed by the space required for storage. A grade of D is thus indicated for on-board storage.

Hydrogen

Hydrogen is a favorite of environmentalists. Its combustion products contain no unburned HC or CO. It must be produced however by the expenditure of some other fuel. Current U.S.

production of hydrogen is less than one percent of the gasoline used in highway transportation, on an energy basis. Thus a grade of E is assigned. Moreover, hydrogen has no distribution and delivery system, and its on-board storage problem is much worse than for CNG. In all these areas it receives a grade of E. Because it fails in all infrastructure categories, it is not a contender between now and 2010.

Electricity

A recent study concluded that an electric vehicle fleet of 35 million would require electricity representing about five percent of the projected 2000 total peak-day electricity demand.[8] This size fleet is about 25 percent of the 1990 passenger vehicle fleet so may be somewhat short of the desired 30 percent diversion of energy consumption. The five percent increase in peak electricity, although modest, represents a very large investment in additional infrastructure. These considerations would be mitigated if late night and early morning charging of electric vehicles could be required and automated. However, considering the "on demand" nature of electrical energy and the present instances of "brown outs", the supply of electricity should be graded no higher than a C. The distribution system may need some increase in capacity but this should be minor, thus indicating an A. The delivery system is a completely different matter. Houses not equipped with the required outlet and other equipment would have to have them installed at a cost estimated at from $100 to $675.[9] Installation of charging stations at rental housing, public parking lots, and at centers of employment also represent a problem. Quick charge stations decrease the time needed to charge but increase the amperage above that which may normally be accessible and may result in lower efficiencies. Thus the delivery system is graded as a D. Finally, the on-board storage of electrical energy, although dependent on evolving battery technology, is considered to fall between that for hydrogen and CNG, resulting in a D-.

This study of the infrastructure of alternative fuels indicates that there is no alternative which begins to equal RFG, the evolving status quo fuel. LPG, CNG, electricity, ethanol, and methanol follow fairly closely together in that order, while hydrogen trails badly.

Alternative Fuels–Emissions

The emissions potential of alternative fuels is also important. U.S. regulators have focused on local air quality in metropolitan areas. This has led California to call the electric vehicle a zero-emissions vehicle (ZEV) when in fact the California electric vehicle contributes significant emissions to the environment where the electricity is generated, which is mostly outside the State of California. The "full fuel cycle" emissions account for this by adding to the vehicle emissions the emissions generated in extracting, refining, generating, transporting, and etc. the propulsive energy used by the vehicle.

The Gas Research Institute has commissioned a study of the full fuel cycle emissions for various fuels.[10] The study presents the results in terms of grams per kilometer for the pollutants: reactive organic gases (ROG, which excludes methane and may sometimes be referred to as non-methane hydrocarbons), carbon monoxide (CO), nitrogen oxides (NOx), sulfur oxides (SOx), PM10 (particulate matter smaller than 10 microns), and carbon dioxide (major greenhouse gas). In order to aid in the comparison of the alternative fuels, the fuels have here been ranked according to their production of the above emissions. The same ranking has been assigned to quantitative results which are within about 30 percent of each other. The results for the U.S. case (excluding the State of California) for the year 2000 are presented in table 3. Results were also calculated for California where different assumptions were made. One of the most important changes in assumptions affects the generation of electricity. Electricity in California is generated by burning a significantly different mix of fuels than the other 49 States. In general, electricity is generated by a cleaner process in California than the rest of the nation. The rankings for the alternative fuels for the California scenario are presented in table 4. Finally for comparison, the rankings of the vehicle combustion and evaporative emissions only for the various fuels is presented in table 5. The vehicle only results do not vary between the 49 State scenario and the California only scenario.

Table 3. Full Fuel Cycle Emissions Summary–U.S. Case

Fuel	Emission Ranking						Ranking Sum
	ROG	CO	NOx	SOx	PM10	CO_2	
Gasoline	4	3	2	2	2	2	15
RFG	4	3	2	2	2	2	15
M85	4	3	3	1	1	3	15
E85	4	3	3	4	3	1	18
LPG	3	3	2	1	1	1	11
CNG	2	2	1	3	1	1	10
Electricity	1	1	3	5	4	2	16

Notes: Full Fuel Cycle, U.S. Case (49 State), Year 2000

Table 4. Full Fuel Cycle Emissions Summary–California Case

Fuel	Emission Ranking						Ranking Sum
	ROG	CO	NOx	SOx	PM10	CO_2	
Gasoline	4	3	3	4	3	3	20
RFG	4	3	3	4	3	3	20
M85	3	3	3	2	2	3	16
E85	3	3	3	2	2	2	15
LPG	2	3	3	2	2	2	14
CNG	2	2	1	1	1	2	9
Electricity	1	1	2	3	3	1	11

Notes: Full Fuel Cycle, California Only, Year 2000

Table 5. Vehicle Combustion And Evaporative Emissions Summary

Fuel	Emission Ranking				Ranking Sum
	ROG	CO	NOx	CO_2	
Gasoline	4	3	3	3	13
RFG	4	3	3	3	13
M85	4	3	3	3	13
E85	4	3	3	2	12
LPG	3	3	3	3	12
CNG	2	2	2	3	9
Electricity	1	1	1	1	4

Notes: Both California and U.S. (49 State) Cases, Year 2000

Overall conclusions from these results indicate that only CNG and LPG offer broad full fuel cycle emissions advantages as compared to RFG in the 49 States analysis and all alternative fuels offer advantages in California. Also of interest is that on a full fuel cycle basis, electricity offers no advantage in the 49 State analysis while it does offer an advantage in California. Also, CNG offers the greatest broad advantage across all full fuel cycle analyses. For the vehicle emissions only case, electricity which has no tailpipe emissions obviously offers the greatest advantage, followed by CNG which offers significant advantages as compared to the other alternative fuels which are very close to each other.

Alternative Fuels–Cost

An important influence on customer selection of a fuel is its cost. Fuel cost is difficult to assess meaningfully because it varies with time, geographical location, and imposed taxes. It is easier to rank the alternatives on the basis of delivered energy cost before taxes. This in indicated in the left portion of table 6. Electricity delivered to the wall outlet for an electric vehicle is cheapest. LPG, CNG and conventional gasoline (and RFG) fall within a band of about ±10 percent and are cheaper than RFG, M85, and E85 which are of increasing cost in that order.

However, examining energy costs alone is not sufficient. ARCO recently estimated pretax energy costs including the expense of modifications to the vehicle and to the delivery system.[11] The results of their analysis are presented in the right half of table 6. Electricity for the electric vehicle is projected to cost 4.5 times as much as conventional gasoline, moving from the least costly to the most costly on the list. This is due primarily to the high cost of the battery. CNG also becomes significantly more expensive, primarily because of the high cost of the on-board storage tanks. The tank cost increment depends on the life assigned to it. ARCO used 7 years, but high pressure tanks passing the new standard are certified for a useful like of 15 years without the need for removal and pressure testing every 3 years, as required of tanks built to the previous standard.

Table 6. Ranking Of Automotive Energy Sources For Pretax Cost

Ranking Based On Energy Only		Energy, Vehicle, and Delivery Modifications	
Energy	Cost Range	Energy	Relative Cost
Electricity	Low	Gasoline	1.0
LPG ⎫	↑	RFG	1.2
CNG ⎬	│	LPG	1.2
Gasoline ⎭	│	M85	1.6
RFG	│	CNG	2.6
M85	↓	Ethanol	2.7
E85	High	Battery–Electric	4.5

The importance of taxes in fuel economics can not be overlooked. At the time of the ARCO study, adding the average tax on gasoline would have increased its relative cost from 1.0 to 1.5. This suggests that Government can influence fuel preference by manipulating taxes and incentives. That is a major reason why penetration of the diesel car is so high in some European countries where diesel fuel costs significantly less per liter than gasoline even though it contains more energy per liter. Diesel fuel enjoys no similar advantage in the U.S. and the interest in diesel cars is low.

Alternative Batteries

Up to this point in the assessment of alternative fuel systems, electricity used to charge on board batteries has been compared as one of the alternative fuel systems. In addition to the questions of electrical infrastructure, emissions, and general cost analysis, another dimension is introduced by the fact that there are a number of battery types currently being developed and considered for automotive application. In 1987-88 the Department of Energy (DOE) convened a panel of experts to rank various batteries then undergoing research and development.[12] Scores were assigned for performance, cost, resource conservation, and safety / environment. The batteries were further grouped according to their risk level for technical success. The results are summarized in table 7 against a maximum possible score of 60. Each of the low risk batteries has been used in an electric vehicle by one of the three domestic manufacturers.

Lead-Acid Battery

A maintenance-free lead-acid (Pb/acid) battery powers the General Motors Impact electric car. The Pb/acid battery has a cost advantage over most other types but offers the shortest vehicle range between charges. GM hopes to get the cost of a 20,000-kilometer battery for the Impact down to $1700. The resulting battery cost of $0.042/km compares with a gasoline cost of $0.033/km for a car achieving 10 km/liter at $0.33/liter. Of course, the cost of electricity must be added for the electric vehicle, but that is small compared to the gasoline cost for the conventional car.

Table 7. DOE Suitability / Risk Assessment (1988)

Low Risk Batteries	**Suitability Score**
Pb / acid (sealed)	35
Na / S *	34
Ni / Fe	27
Medium Risk Batteries	
Pb / acid (flow - through)	32
Li / FeS*	32
Fe / air	30
Na / $NiCl_2$*	29
Na / $FeCl_2$*	29
Zn / Br_2	27
High Risk Batteries	
Pb / acid (bipolar)	35
Zn / air	35
Li / FeS_2*	34

* High - Temperature Battery

Sodium-Sulfur Battery

The Ford Ecostar is a small European van using a sodium-sulfur (Na/S) battery. These batteries must be kept at about 320° C, whether or not in use, to maintain the elements in a molten state. When in use, the battery is self heated by the inefficiency of discharge and must therefore be cooled, so a sophisticated thermal management system is required. The Na/S battery offers about triple the range of the Pb/acid battery for the same battery weight. That is important because batteries are very heavy devices for storing energy. Ford hopes to drop the battery cost to $15,000, which for a 5-year life (not yet demonstrated) at 20,000 km/year amounts to $0.15/km.

Nickel-Iron Battery

The Chrysler TEVan is a larger van using a nickel-iron (Ni/Fe) battery. It operates at room temperature and is intermediate in both range and cost between Pb/acid and Na/S. Unlike the Pb/acid battery, the Ni/Fe battery requires maintenance in the form of programmed filling with water. It emits hydrogen gas during charging and discharging, the venting of which has caused safety concerns.

Comparison Of Low Risk Batteries

It is difficult to compare battery electric systems with the gasoline engine against which it must compete because of the many parameters needed to characterize battery technology. One representation often used is a graph of specific power (W/kg) versus specific energy (Wh/kg). Specific power is indicative of performance potential while specific energy is indicative of range on a battery charge. The three low risk batteries discussed above as well as nickel-cadmium (which has received attention mostly outside of the U.S. and will also be subsequently discussed) are plotted for their representative performance in figure 5.

The energy stored in a gasoline tank depends only on the liters of gasoline it contains, but the energy recoverable from a battery depends on the rate at which it is withdrawn. A frequently used battery test involves a three hour discharge. The points plotted along the three hour discharge line in figure 5 show typical specific powers and energies available from the four different types of batteries.[1] The batteries are also capable of providing short bursts of power for vehicle acceleration that exceed the average power available during the three hour discharge test. These values of specific power are the points plotted for each battery significantly above the three hour discharge line. These levels of power are sustainable at the illustrated power levels for only about a half minute. These power levels thus cannot be sustained at the energy levels associated with them on the horizontal axis. The open square plotted in the upper right hand area of the figure indicates the general area of the plot where gasoline plus engine performance is located. Different engines and fuel tank sizes would plot differently so only a general location on the graph should be inferred from this point. In determining this general location, the gasoline engine powertrain and its tank of fuel was considered and was debited with a conversion efficiency from the fuel tank to the vehicle wheels. Clearly by either method of comparison, the low risk batteries are not competitive with gasoline and engine.

Other Batteries

Of the fairly large number of different batteries presently being developed for possible future automotive application, two that were not considered at the time when the assessment of table 7 was made deserve additional discussion.

Nickel-Cadmium Battery

A battery not appearing in table 7 that deserves mention is the nickel-cadmium (Ni/Cd). Used primarily in Japanese demonstration EV’s, it has been shunned by most U.S. companies out of concern over the toxicity of cadmium, as well as the high cost of the nickel electrode. Cadmium is more toxic than lead. About 90 percent of Pb/acid batteries are recycled in the U.S., but a similar infrastructure is not in place for recycling cadmium. The Ni/Cd battery can be recharged quicker than most other types, but that requires more electric power than available at most charging sites. The Ni/Cd battery has not responded well to partial discharging and is not yet maintenance free in car propulsion versions.

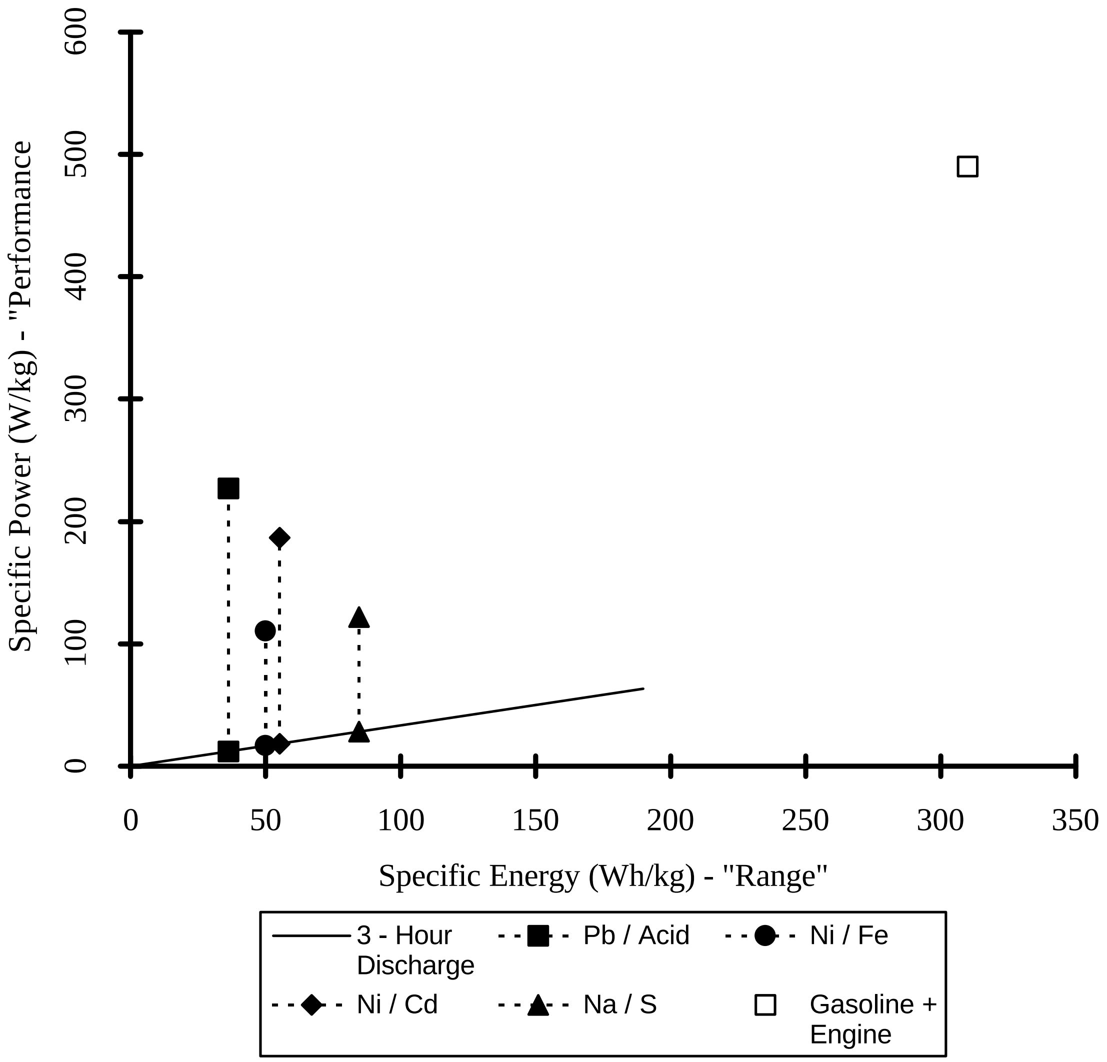


Figure 5. Comparison Of Four Batteries To Gasoline Engine

Nickel-Metal Hydride Battery

In 1991, the U.S. Advanced Battery Consortium (USABC) was formed to search for a better battery. Participants include the domestic auto manufacturers, representatives of the electric utility industry, and the Department of Energy. USABC has developed a set of mid-term (1995-1996) and long-term goals. The mid-term goals include a specific energy of 80 Wh/kg and a specific power of 150 W/kg (for 30 sec at 80 percent depth of discharge). Initial funding has gone for the development of a nickel-metal hydride (Ni/MH) battery. The nickel-metal hydride (Ni/MH) battery, also absent from table 7, is a promising new option that is the first to receive USABC support. Its source, Ovonic Battery Company, claims that in the laboratory it meets nearly all of the USABC mid-term goals, cost being one of the exceptions.[13]

Neither of these batteries nor any in table 7 can be said to be able to meet the mid-term goals set by USABC in actual vehicle operating conditions. Even when a battery that meets the mid-term goals is fully developed, it would still be disadvantaged in many respects relative to the current gasoline automobile. Limited range, long recharge time (measured in hours), high battery cost and short life, inferior acceleration performance, large size and weight, and performance deterioration in cold weather or as the battery reaches a low state of charge are among the problems faced. In addition, there is inadequate heat available for passenger comfort in cold climates, and air conditioning in hot climates significantly decreases range. Thus even though it is technically possible to demonstrate an electric car that satisfies the California 1998 ZEV mandate, the question remains as to its acceptance by the vehicle buying public.

Task 3. Identify Performance Issues, Benefits, and Risks

Alternative Power / Fuel Systems

The compatibility of the power systems discussed in task 1 with the various alternative fuels discussed in task 2 is summarized in table 8.

Table 8. Power Systems and Preferred Energy Sources

	Gasoline	Distillate	Methanol	Ethanol	Biodiesel	LPG	Natural Gas	Hydrogen	Coal	Biofuel	Nuclear	Solar	Hydro	Geothermal	Wind
Spark Ignition	P	U	F	F	U	F	F	F							
Comp. Ignition		P	F	F	F	U	U		U						
Gas Turbine	P	P	F	F	U	F	F	F	U						
Rankine Cycle	P	P	F	F	U	F	F	F	U	U					
Stirling Cycle	P	P	F	F	U	F	F	F	U	U					
Battery - Electric	U	P	F	F	U	U	P	U	P	F	P	F	P	F	F
Fuel Cell			F	F		F	F	P							

Key: P–Preferred, F–Feasible, U–Unlikely but possible

For the spark ignition engine the preferred fuel is gasoline. As years pass, more and more of it will be reformulated gasoline (RFG) in order to improve air quality. With minor modification, the conventional spark ignition engine will operate on the alcohols, LPG, or natural gas. The alcohols will be used in the form of M85 and E85 which are blends of 85 percent of the alcohol with 15 percent gasoline. The gasoline addition to the alcohols ensures the ability to start on cool days. Because of octane requirements of the conventional spark ignition engine, distillate and biodiesel can be used only in direct injection stratified charge versions of the spark ignition engine, should such a powerplant make it to the marketplace. Because of the ready ignitability of hydrogen, a spark ignition engine using it would require more extensive modification than for the other gaseous fuels.

For the compression ignition (diesel) engine, the fuel of choice is the distillate classified as diesel fuel. As with gasoline, it will be reformulated to improve air quality. Biodiesel, methanol, and ethanol can all be used in diesel engines. Biodiesel requires no engine modification, but in four stroke diesels, burning the alcohols is not so simple. Typically, a pilot injection of diesel fuel is needed to ensure compression ignition. In the two stroke diesel, compression ignition of the alcohol is achieved without a diesel fuel pilot by bypassing the scavenging blower to raise the compression temperature by means of a high residual gas content. A glow plug is then necessary for engine starting. When the automotive diesel is converted to gaseous fuel, the preferred technique in four stroke engines is to abandon pilot injection in favor of a spark plug, thus removing these engines from the compression ignition category. The two stroke diesel has been operated on natural gas admitted to the cylinder just after the intake ports have closed and then compression igniting the mixture with a pilot injection of diesel fuel, but this approach is seemingly being abandoned. Finely powdered coal has been burned experimentally in large, low speed diesels along with diesel fuel, but particulate emissions, and wear, along with lack of an infrastructure, make coal an unlikely choice for automotive use.

The external combustion engines, Rankine and Stirling, are more fuel tolerant than any other option except the battery-electric. The improbability of these engines becoming the exclusive power source in automotive service does not warrant their further consideration.

The probability of the gas turbine appearing as the exclusive power source in automotive service is only slightly higher than for the Ranking and Stirling engines. Its preferred fuel would be gasoline or a petroleum distillate, but it can also operate well on alcohols or the gaseous fuels. It could run on biodiesel, but that fuel would likely be reserved for the compression ignition engine. The gas turbine has been demonstrated on powdered coal, but particulate emissions, blade erosion, and lack of an infrastructure make it an unlikely choice.

The battery-electric system is the most omnivorous of the power systems considered. Which of the energy sources used to generate the electricity is irrelevant to the operation of the vehicle. However, as the full fuel cycle emissions analysis presented in task 2 shows, the mix of fuels and details of the generating process are very important in arriving at a balanced appraisal of emissions relative to other fuel systems.

Hydrogen is the fuel for the fuel cell. However, given the poor availability of hydrogen and its lack of infrastructure, this fuel would likely be made on board the vehicle from an alcohol or a gaseous fossil fuel. With the expected low availability of an automotive fuel cell before 2010, however, this selection is not of practical importance.

Alternative Power / Fuel Systems Trends Predictions

In the U.S. there were about 195 million registered vehicles accruing about 17.6 thousand kilometers each for a total of about 3,456 billion vehicle kilometers traveled in 1991.[14] For the years 1984 through 1993 an average of 14.3 million new cars, minivans, sport utilities, and other light trucks were sold in the U.S. each year.[15] Estimates for average yearly sales between now and 2000 range from less than 15 to over 17 million. Approximately 37 percent of the U.S. vehicles are 10 years old or older.[16] At an average yearly sales rate of 15 million it takes 13 years to completely replace the existing fleet. Thus many of the vehicles for the year 2010 have already been built. Probably more than one third of the 2010 fleet are presently in the engine, transmission, electronics, and vehicle platform design process today. The infrastructure which designs, manufactures, sells, services, scraps, and fuels this fleet is in place today and has a long useful lifetime. The characteristics of this fleet are constantly changing, however the above facts enforce a very strong continuity over time. That is not to say that the character of the fleet does not change. One very interesting change is the change in percent sales representing the light truck (including sport utilities and minivans). In 1984 this category of vehicle represented 27 percent of total sales and in 1993 it represented 39 percent of total sales.[15] The domestic automotive industry is still in a catch up mode to change its production capacity to fully supply the demand for this category of vehicle. Any realistic prediction of the characteristics of the vehicle fleet in 2010 must consider the long time constant enforced by these circumstances.

Considering the results of tasks 1 and 2 and the just discussed long term continuity of the U.S. fleet, the following represents the predictions of the direction and changes which the automotive powertrain and fuel systems will experience out through the year 2010:

- Most automobiles will use a reciprocating spark ignition engine burning gasoline, with a growing fraction of the fuel being reformulated as time progresses.
- M85 and CNG will be the fuel for some light duty vehicles, especially in metropolitan areas with air quality problems.
- CNG is more likely in trucks and vans, where fuel storage space is more available than in passenger cars.
- About 10 percent of the fleet burning M85 and 10 percent burning CNG represents a realistic possibility by the year 2010.
- E85 will probably not achieve widespread use in this time frame, despite its popularity in agricultural States.
- The compression ignition diesel engine will remain the preferred choice for heavy duty trucks, and to a lesser degree in medium duty trucks. However, some heavy duty trucks will use natural gas, probably liquefied.
- Many urban and school buses will operate on CNG with M85 and E85 providing a weaker possibility.
- The push for electric vehicles will continue, but weak performance, limited range, long recharge time, and high battery cost will limit their popularity.
- Consumer demand for electric vehicles will be only as great as Government is able to influence through incentives and the manipulation of taxes.
- The case for hybrid vehicles would be greatly strengthened should California amend its definition of the zero emission vehicle to allow the inclusion of hybrids using low emission engines.

- Existing engine designs with improvements have a strong possibility of meeting California standards for ultra-low emission vehicles, thus negating a possible area for hybrid application.

- A likely slow rise in fuel economy standards along with a slow trend of increasing taxes on fuels will tend to end and possibly turn around the present trend for vehicles to have higher levels of acceleration and speed.

Performance Issues, Benefits, and Risks Associated With Predicted Fleet Characteristics

In this section the implications of the above noted likely trends in alternative power / fuel systems are analyzed. The analysis will consider vehicle dynamic performance, safety, range, environmental impact, cost efficiency, controllability and any other unique operational attribute.

Dynamic Performance

Long term pressures for improved fuel economy and fuel price increases (including taxes) will tend to decrease the typical dynamic performance, that is acceleration capability and maximum speed, of future vehicles. Detailed advances in engine design and lighter and generally more efficient vehicles will tend to offset this, with the result being that vehicles with internal combustion engines will have performance very close to present standards. Since light trucks, as a group, have dynamic performance somewhat lower than passenger vehicles, their increasing numbers also tend to limit the fleet’s performance. Thus it is concluded that the likelihood of a large number of vehicles with very significantly improved dynamic performance is very low.

Battery-electric vehicles will, as a class, have lower dynamic performance because of the already noted low specific power of batteries and the complexity and cost of augmenting batteries with other energy sources. Consumer demand will however likely favor those battery-electric vehicles with dynamic performance which most closely matches the performance of non battery-electric vehicles in the fleet. This raises an issue as to whether battery-electric vehicles will require special consideration for AHS maneuvers. The probable situation will be that the battery-electric vehicle will fit into the continuum of vehicle characteristics which AHS will be designed to accommodate, albeit on the low side for dynamic performance.

Safety

CNG and batteries both present design challenges to ensure their safety in an automotive environment. The containers for CNG must be capable of withstanding pressures on the order of 200 atmospheres while battery containers must prevent leakage and spills of the battery chemicals. These are areas for which design standards presently exist and which will likely evolve with time as more experience is gained with these alternatives in automotive application. There is no reason to expect that these alternatives will exhibit a level of safety which is better or worse than that achieved by the mainstream propulsion and fuel systems in 2010. Thus no issue, benefit, or risk is identified with respect to safety.

Range

All of the alternatives identified have a negative impact on the range of a vehicle for a comparable volume and mass of fuel. M85 has a minor impact, CNG has a moderate impact and battery-electric has a severe impact. Because M85 would likely be transported by fuel carriers, the lower energy content on a volume basis also implies that the fleet of carriers must be larger than the displaced fleet of gasoline carriers. In the case of M85 and CNG a range comparable to a vehicle fueled by RFG could be achieved but at a minor or moderate impact in volume devoted to fuel respectively. In the case of battery-electric, the impact would be severe in terms of both mass and volume to achieve a comparable range. If a battery-electric were designed to have the same range, a significant portion of other aspects of vehicle utility would be sacrificed. For M85 and CNG the effect remains constant but the impact is of a nature that alternative vehicle designs could largely mitigate. However this would suppose a vehicle uniquely designed for these alternative fuels. This does not appear likely since one of the desirable features of these alternative fuels is that the vehicle in general needs only minor changes to accommodate these fuels. The battery-electric is another case. The impact is so severe in terms of both batteries and other aspects of the propulsion system that a vehicle designed to be uniquely battery-electric is the preferred approach. Batteries are however an evolving technology and there is reasonable hope and expectation that the impact on range, vehicle mass, and volume will be mitigated with time. One of the ultimate risks of battery-electric vehicles is whether the vehicle range and volume/mass efficiency of design will satisfy customer expectations.

Environmental Impact

The emissions impact of the identified alternative power/fuel systems as compared to the standard engine fueled by gasoline or RFG may be identified from tables 3, 4, and 5. When considered on a vehicle only basis, the use of M85 would have essentially no emissions impact, the use of CNG would decrease all emissions significantly except for CO_2, and the use of battery-electric would eliminate all emissions from the vehicle. On a full fuel cycle basis the emissions impact is more complicated and offers less clear benefits. For the U.S. case (49 States) the impact is as follows: the use of M85 would increase the emissions of NOx and CO_2 while decreasing the emissions of SOx and PM10, the use of CNG would decrease all emissions (particularly ROG) with the exception of SOx which would increase, and the use of battery-electric would result in a major decrease in ROG and CO but would also result in a major increase in SOx and PM10 and a moderate increase in NOx. For the California case the impact is as follows: the use of M85 would result in a moderate decrease in ROG and PM10 and a major decrease in SOx, the use of CNG would moderately decrease CO and CO_2 and result in a major decrease in the other emissions, i.e. ROG, NOx, SOx, and PM10, the use of battery-electric would moderately decrease NOx and SOx and give a major decrease in all the other emissions with the exception of PM10 which would be similar to the base case.

In conclusion, on a vehicle basis, CNG and battery-electric offer emissions benefits with battery-electric the clear winner. On a full fuel cycle basis, in California, all the three alternatives offer emissions benefits with CNG and battery-electric about equal and better than M85. The full fuel cycle comparison for the remaining 49 States analysis shows that CNG offers clear benefits for all but SOx but both M85 and battery-electric on a broad basis are comparable to the base case but do offer benefits with respect to selected emissions categories. This identifies a risk associated with battery-electric vehicles. The risk is how much should the conversion to battery-electric be encouraged to improve urban air quality when analysis shows that its impact outside the urban area, where the vehicles are used, is to possibly worsen air quality, that is, battery-electric tends to shift the geographical location of air pollution and not eliminate it on an absolute basis.

Cost Efficiency

An evaluation of the efficiency of the alternative power/fuel systems will be done on the basis of cost as presented in table 6. On the basis of the cost of consumed energy only, the battery-electric is the clear winner considering the cost of delivered electrical energy. CNG is closely grouped with gasoline but somewhat lower in cost than RFG. The energy cost of M85 is higher than RFG and thus also higher than CNG. When the cost of vehicle and delivery modifications is added into the cost of the consumed energy, the comparison changes. In this comparison the total cost of M85 fueled systems is about one third higher than RFG, the cost of CNG fueled systems is about twice as costly (this should be decreased by the more recent standards adopted for CNG pressure tanks), and the cost of the battery-electric alternative is about 3.75 times the cost of RFG. The cost of each of these alternatives is altered by Government as taxes and/or incentives are applied to the various energy sources. The higher cost of CNG and battery-electric indicates that there should be concern over the acceptance of these systems should the consumer see the true cost of the alternatives.

Controllability

Both M85 and CNG are burned in engines which have very limited modifications as compared to the base case. These power systems have the same driver feel and controllability characteristics as the base case. The battery-electric power systems have quite different controllability characteristics. However, since the battery-electric vehicle is in direct competition with the base vehicle, the vehicle power systems will be engineered to have feel and controllability characteristics as presented to the driver or to a potential AHS controller which are similar, or even superior, to the base case power system. This adds to the electrical power management system cost but will be standard on any commercially viable battery-electric vehicle. Some examples of similar characteristics are: the tendency to provide a low level of decelerating force when the throttle is released at speed even when the brake is not applied, and a seamless blending of braking by electrical regeneration and traditional friction braking as the brakes are applied progressively. An example of a superior characteristic concerns the tendency for present base case vehicles to slowly move forward when stopped with the engine running if the brakes are not applied. This characteristic can be engineered into battery-electric systems if desired but an alternative is to design the system so that the vehicle will not move, even on a hill, until the throttle is pressed. AHS controllers for battery-electric vehicles will thus need to be designed to be compatible with the unique characteristics of battery-electric vehicles. However, no issue or benefit associated with controllability is identified for any of the alternative systems.

Unique Operational Attributes

Two unique operational attributes are identified for the alternative power/fuel systems. The first is the obvious, each requires a fuel which is unique to that system. This attribute is mitigated if the several alternative systems are available in bifuel form. The M85 fueled system is the most likely to be capable of bifuel operation since ordinary gasoline or RFG could be stored in the M85 fuel tank. CNG can be make in bifuel form but this requires more modification and definitely a separate fuel tank. Battery-electric when combined with an internal combustion engine (a hybrid power plant) in effect then also becomes bifuel. Thus there is a likely possibility that each of the alternative power/fuel systems will appear as a unique fuel system even though some of their numbers may be bifuel.

The other unique operational attribute is associated only with the battery-electric system. All of the required motor, power management, and etc. controllers are very different from the engine and transmission controllers on other powertrains. The sensors, actuators, diagnostics, and all aspects of the powertrains are different. Thus the battery-electric system will have a unique check-in requirement as it addresses this aspect of vehicle operation and preparedness for operating on an AHS.

Task 4. Identify Alternative AHS Configurations

In this task alternative AHS configurations which make possible or enhance the use of AHS vehicles with alternative propulsion systems and/or which use alternative fuels will be identified and analyzed. This task will identify probable alternative AHS configurations consisting of special uses depending on the time of day, special lanes, different mixes of vehicles, particular platooning, and provision for separate check-in and check-out lanes or bays.

As identified in task 3, the primary issue associated with alternative propulsion system vehicles which may require such an alternative AHS configuration is the issue of degraded dynamic performance. It was concluded that alternative propulsion system vehicles would likely fit into the continuum of dynamic characteristics of the general fleet of vehicles, but generally on the low side. In the event that the differences in dynamic performance are greater than anticipated, alternative AHS configurations may present an approach to mitigate this issue. Also identified in task 3 were two unique operational attributes associated with alternative power/fuel systems. The first was the obvious need for a fuel unique to that system. The second was the unique check-in requirements associated with a battery-electric system. Both of these unique operational attributes will be associated with deployment and operation issues and risks addressed in the following task 5. The unique check-in requirements for battery-electric systems will also be addressed in the present task.

Thus the alternative AHS configurations discussed in this task will be evaluated for their tendency to provide for the operation of vehicles with widely varying dynamic characteristics as well as unique check-in diagnostics and verification needs.

Use At Separate Times Of Day

During certain times of the day the AHS, or a major section of the total system, may accept only vehicles which need special consideration because of their low level of dynamic performance. Since similar vehicles have the same nominal performance they should be capable of being platooned closer together due to matching response characteristics. Thus this approach would be expected to provide for efficient operation of the low performance vehicles but at the expense of excluding other vehicles meeting higher performance requirements. This approach would not be appropriate for accommodating a limited subset of the fleet unless that subset could make use of the AHS system during the very late hours of the night when general demand would be very low. Thus this approach may be a viable approach for accommodating very heavy duty commercial vehicles which have low performance capabilities on the AHS. They would be able to use the system to cross urban areas and move between freight terminals located within the urban area.

However during periods of very low demand, AHS vehicles would not be required to be closely spaced. Also, the velocity of vehicles on the AHS could more easily be varied to allow extra time and space for low performance vehicles to enter the AHS. Thus a fleet of vehicles with widely varying dynamic characteristics could be accommodated on the AHS during very low demand without the need to exclude any vehicle. Thus even though a policy of AHS use at separate times may be a possible approach for accommodating low performance vehicles, it is not seen as a suitable solution. Passenger vehicles with alternative propulsion systems need access at the same time that other passenger vehicles require access. Heavy duty commercial vehicles may well be required to use the urban AHS only during late night hours but other vehicles would also be allowed access. A flexible headway policy would allow a mix of vehicles to be safely supported by imposing the required long spaces between appropriate vehicles. This would not be a severe impact for normal vehicles since the overall system capacity demand would be low during the late night.

Separate Lanes

In order to provide the controlled environment which AHS needs to operate safely, AHS will require lanes which are separate from non-AHS traffic. In addition to this level of separation, a possible AHS configuration is to provide separate automated lanes for use by AHS vehicles with low performance capabilities. Even though this may be attractive from a control standpoint, it is not likely due to the cost and time necessary to construct the separate lanes. Utilization of newly constructed lanes must advance rapidly in order to economically justify their construction and any disruption of neighborhoods. High utilization precludes reserving a lane just for platoons of a certain vehicle type.

Platoons With Specific Mixtures of Vehicles

Another possible AHS configuration is to have platoons consisting of vehicles which all have some common characteristic or even some mutually complementary set of characteristics. The entry check-in access control would be used to form platoons with only specific vehicles. For example, if all vehicles in such a platoon had a significantly lower acceleration capability, this may be an efficient way to enter a number of such vehicles onto the system with a minimum of disruption of mainstream AHS traffic. The mainstream traffic would need to be slowed to open up a longer than normal gap but once accomplished, several vehicles would enter rather than just one. Another example could be vehicles with a lower level of braking capability. The open space ahead of such a platoon may be kept longer to maintain the same level of platoon safety. On the other extreme, if a platoon consisted of only vehicles having outstanding performance for speed and acceleration, they may be able to take advantage of occasional passing lanes to maintain higher average speeds.

Less likely, but still possible, would be platoons of complementary characteristics. One example would allow vehicles with less than a full complement of stand-alone AHS equipment to use the AHS. The vehicle may be capable of operating on the AHS as long as it is in a platoon for which another vehicle acts as the platoon leader, navigator, or possibly the platoon to wayside communicator. Another possibility which is also considered very unlikely, could use a platoon of complementary characteristics to allow a number of battery-electric vehicles to recharge their batteries when connected by umbilical cords to a vehicle with a generator.

Some of these examples require that the platoon be formed at the AHS entry facility. This of course suffers from the delay of waiting for additional vehicles, a delay in physically forming a platoon, and the space at the entry needed to accommodate this process. Because of these factors, any such use of special platoons is considered as very unlikely. It is expected that only platoons of mutual advantage which can be flexibly formed on the AHS as vehicles come into general proximity will be acceptable to the non-commercial AHS user.

Platoons Of One Vehicle

A platoon of one vehicle is considered to be the likely configuration used to accommodate vehicles with a significantly different dynamic characteristic. Note that RSC 3 by its use of individual vehicle space/time slots is equivalent to a platoon with one vehicle as far as the implications for the present discussion. This single vehicle would have greater space than normal between it and the preceding platoon and/or would be allowed extra space to accelerate to AHS speed and merge with traffic. Since such preferential treatment would impact the free flow of other vehicles on the AHS, unless the system were running at very much less than full capacity, such a vehicle should expect to be charged more for the use of AHS than vehicles which have mainstream dynamic performance capabilities. This approach requires that the system be capable of interrogating the vehicle for its special needs and then commanding surrounding vehicles to adjust their operating condition to accommodate the special vehicle.

Separate Check-In / Check-Out Lanes Or Bays

An alternative AHS configuration consisting of separate check-in and check-out lanes or bays for vehicles with special characteristics is an alternative with many desirable attributes. Since a check-in or check-out facility would likely have multiple lanes or bays, to provide one additional lane or bay for vehicles with special needs would not constitute a major capital expenditure, especially as compared to the cost of separate AHS highway lanes.

This alternative would not accommodate a varying dynamic characteristic but would accommodate unique operational (particularly check-in related) needs. Since most of the powertrain equipment of the battery-electric vehicle is different from internal combustion powered vehicles, they would have a unique set of check-in requirements for test and verification of the remaining battery charge state. This may best be accomplished by using a unique check-in lane or bay. Also, should the time needed for check-in be significantly different, a unique check-in location may be called for. Alternative fuel vehicles may require specialized test equipment to validate vehicle operation and fuel remaining, thus indicating another possible use of an alternative check-in lane or bay. By having each check-in lane specialized for one type of propulsion system or alternative fuel the overall capacity of the check-in facility could be optimized.

If one out of three or four bays were “battery-electric only” this could be used as an incentive to consider acquiring a battery-electric vehicle for commuting, just as multiple passenger only lanes bypass timed freeway entry portals. However, such a bay must be designed so that it does not create additional delay, confusion, or contribute to a traffic jam at check-in.

The need for unique check-in lanes or bays will be mitigated to the extent that vehicle manufactures can cost effectively equip AHS vehicles with all the sensors required to perform the full powertrain checks. If the vehicle itself is capable of accurately monitoring all functions required for AHS entry, then only the readouts need be transmitted to the check-in station upon arrival. This is particularly true in the case of battery-electric vehicles due to the fact that almost all of their drivetrain components are unique to battery-electric. Each manufacture should develop their best power remaining estimation technique, specific to the type of battery pack, power source, and historical computer logged driving patterns of the operator, to estimate travel range remaining. Local conditions of temperature, time of day, slope of roadway, and destination would be involved in the calculation at the check-in facility to determine if sufficient energy is stored to make the desired trip.

Separate Check-In / Check-Out Facility

It is possible to envision an AHS configuration with separate check-in and/or check-out facilities for vehicles with unique characteristics. This is expected to be too costly for servicing the needs of ordinary vehicles which just happen to have some unique characteristic. It may however be the best approach for AHS service vehicles and heavy duty commercial vehicles. Such facilities would be spaced much further apart than facilities for ordinary passenger vehicles.

Task Conclusions

- Allowing access to the AHS at only certain times of the day is not suitable for alternative propulsion vehicles because they need access at all times of the day. However heavy commercial vehicles may need to be restricted to late night use only. Other vehicles could still safely mix with the commercial vehicles because low demand would allow the greater spacing needed for safe operation.

- Separate lanes are concluded to not be economically justifiable.

- Platoons consisting of all one type of vehicle with special operational needs are concluded to be unlikely unless the platoons can be flexibly formed while the vehicles are on the AHS, thus incurring the absolute minimum delay to form a special platoon.

- Platoons consisting of one vehicle are the most likely method whereby vehicles with unique dynamic characteristics may be accommodated.

- Separate check-in lanes or bays offer advantages for vehicles such as battery-electric which will have their own unique powertrain check-in tests. However this will be mitigated if vehicles can be economically equipped with all the required sensors.

- Separate check-in or check-out facilities are concluded to be only justifiable for AHS service vehicles and heavy duty commercial vehicles.

Task 5. Identify Deployment and Operation Issues and Risks

This task will identify and analyze the deployment and operational issues and risks associated with the presence of a significant fleet of AHS vehicles having an alternative propulsion system or using an alternative fuel. The areas discussed arise due to possible need to provide for the routine and emergency refueling of AHS vehicles, vehicle range factors and their importance to alternative propulsion vehicles, and the need to consider vehicle design and performance standards.

Routine Refueling Capability

Some visions of AHS have identified it as an ideal environment to foster the wider deployment of some particular form of alternative propulsion vehicle. The tempting idea is that by combining, for example, battery-electric vehicles with AHS that there may be synergism resulting in new and potentially unexpected benefits. Towards that end, the AHS is viewed as a means of providing the infrastructure necessary to support the operation of the alternative propulsion vehicle. Providing for the refueling, or battery charging, while on the AHS or providing special capability at AHS entry/exit facilities has at times been proposed.

The present analysis of alternative propulsion systems has highlighted the diversity of alternative systems and the strong market forces which impact the evolution of all vehicles. It is concluded that the routine refueling of alternative propulsion vehicles is not needed as part of the AHS infrastructure. This is based on the economic assumption that any form of alternative propulsion system as well as the AHS must both be viable economic and consumer concepts independent of each other. A viable alternative propulsion system will generate the incentive for present refueling facilities to adapt or modify their capability so that they also serve the needs of the alternative propulsion vehicle. AHS will undoubtedly require major Federal funding to arrive at the initial design as well as the construction of the required infrastructure. For many years during the initial deployment of AHS the number of vehicles sold which are AHS compatible will be small as compared to all vehicles sold. Also, the number of alternative propulsion vehicles sold will be a small subset of all vehicles sold. The intersection of these two subsets will thus be an even smaller fraction of vehicles sold. To burden the AHS program with the additional expense of providing refueling capability for such a small subset of vehicles could seriously jeopardize the entire program.

Emergency Refueling Capability

One of the most important functions of the AHS check-in process will be to confirm that each vehicle entering the AHS has more than sufficient fuel or battery charge for the trip to its planned AHS exit. This will be accomplished by accurate estimates of the fuel remaining or battery charge. In the event that there is not sufficient energy, the driver would be given the choice of not entering the AHS or of entering but accepting an intermediate destination which would allow the vehicle to be refueled. Thus in the case of alternative fuel vehicles, the AHS would need to have data on the availability of alternative fuels at its various exits. This type of data may also be needed for all fuels at selected exits at which fuel is not readily available.

This data would also need to be time dependent since many fuel stations close during late night hours.

Ideally vehicles are evaluated so carefully during the check-in phase that none will run out of fuel during their trip on the AHS. However, no matter how carefully this function is planned and implemented there will undoubtedly be an occasional error and vehicles will run out of fuel or energy while on the AHS. This is one of the malfunction events discussed in the Activity E–Malfunction Management and Analysis report. The preferred response is to require the vehicle to exit from the AHS while some fuel still remains. However, should this not be possible, the vehicle would pull over to a break down lane. Even though these occurrences would be extremely rare, AHS operational plans must consider the need to extricate such vehicles from the AHS.

Emergency vehicles designed for this purpose would be capable of towing the stranded vehicle off the AHS or providing a refueling for the vehicle and then allow the vehicle to exit the AHS under its own power. For those stranded vehicles which only need a refueling, this option is considered to be preferable to physically towing the vehicle from the AHS. The relative difficulty of refueling or recharging a battery for alternative propulsion vehicles has been evaluated. The results are summarized in table 9. Two general categories of vehicles are considered. Dedicated fuel vehicles are capable of using only one type of fuel. The other category consists of vehicles commonly referred to as flexible fuel, bifuel, or hybrid vehicles. These vehicles have engines and fuel management systems designed to generally accept gasoline as well as the indicated alternative fuel. In the case of battery-electric, a hybrid vehicle with two interconnected sources of power as previously described in task 1 is indicated.

Notice that all flexible/bifuel/hybrid vehicles, which are capable of accepting a secondary fuel, are rated excellent in that the refueling is very easily accomplished (once the emergency vehicle reaches the stranded vehicle). Generally only two types of fuel must be carried by the emergency vehicle for this category, either gasoline or diesel fuel. Dedicated fuel vehicles which use a liquid fuel are also easy to refuel, however the emergency vehicle must carry a supply of each of the involved fuels. Dedicated fuel vehicles which use a gaseous fuel are more difficult to refuel. These require a mechanical connection to transfer the gaseous fuel. Liquefied petroleum gas and compressed natural gas are rated a B for ease of refueling whereas liquefied natural gas which is cryogenic is rated a D or a C. The C is for the case of refueling a vehicle which normally accepts the liquid form and the D is for the case which needs additional attention due to the phase change to compressed gas. Battery electric vehicles which rely solely on batteries for their energy supply present a significant challenge to servicing. As indicated in table 9, four options for handling this situation are identified. Exchanging the dead battery pack with a charged battery pack and recharging the dead pack while the vehicle is in the AHS break down lane are determined to be the least desirable approaches because of either the heavy and bulky nature of the batteries or the time involved to recharge. Towing the stranded vehicle off the AHS is rated somewhat more acceptable. Finally, a portable motor generator set which could be either towed by the stranded vehicle or mounted on the roof or trunk is seen as the most desirable alternative, but it is still graded only a C. A small motor generator set would be used to recharge the vehicle's battery and thus allow it to drive off the AHS after a period of time. A larger motor generator set could in effect temporarily convert the stranded vehicle into a hybrid vehicle and the vehicle could immediately proceed to the nearest exit. To make this a viable alternative the battery-electric vehicle must have a junction which would accept a power line from the generator set.

Table 9. Run-Out-Of-Fuel-Problem

Fuel Type	Dedicated Fuel Vehicles		Flexible/Bifuel/Hybrid Vehicles	
	Required Refuel	Score	Required Refuel	Score
Liquid:				
Gasoline/RFG	Gasoline	A		
M85	M85	A	Gasoline	A
E85	E85	A	Gasoline	A
Diesel	Diesel	A		
Biodiesel	Diesel	A	Diesel	A
Gas:				
LPG	LPG	B	Liquid Fuel	A
CNG	CNG	B	Liquid Fuel	A
	LNG	D		
LNG	LNG	C	Liquid Fuel	A
Electric:				
Battery	Change Batteries	E	Liquid Fuel	A
	Charging Station	E		
	Tow to Station	D		
	Portable Motor/Gen Set	C		

Key: A = Excellent, through, E = Unacceptable

Vehicle Range Factors

The vehicle range achievable for a given amount of stored energy depends on many factors. Some of the factors which affect vehicle range regardless of their propulsion system are: speed, acceleration and deceleration profiles, wind conditions, changes in roadway elevation, vehicle load, vehicle aerodynamics, closeness to preceding vehicle, and propulsion system efficiency. These factors, with the exception of wind, would rarely change for a given vehicle making a trip between a given entry/exit location. Thus after some calibration and considering the specifics of a given trip, the energy required for a trip could be predicted within a few percent uncertainty. The impact of these factors would also be quite constant from one AHS system to another.

Other factors, primarily related to temperature and humidity, have a major impact on the range of some alternative propulsion vehicles while only very modest impact on others. The greatest impact is on battery-electric and fuel cell vehicles and to a lesser extent on hybrid vehicles. These vehicles have no rejected heat (only a very limited amount in the case of hybrid) to use for heating the passenger compartment. Air conditioning when used also imposes a greater impact on vehicle range for these vehicles than for typical internal combustion engine vehicles. This is because the air conditioning compressor must be powered electrically and becomes a direct consumer of the stored energy. If heating or air conditioning is used extensively, the range of these vehicles can be reduced by up to about 70 percent. These factors change hourly and are more severe at some geographical locations than at others.

An AHS which operates with these severely impacted alternative propulsion systems could follow one of two possible operational policies. The simplest policy would be to apply very conservative estimates for remaining range at the time of vehicle check-in processing for these impacted vehicles. This may be acceptable for hybrid vehicles which are not expected to have inherent difficulty in providing adequate range capability. This policy would certainly be unacceptable for battery-electric vehicles unless battery technology makes major advances. This would severely impact the utility of the battery-electric vehicles which exhibit range deficiencies. The second possible policy would be one of enhanced range estimation at check-in and on an ongoing basis as the vehicle traveled on the AHS. The driver would have to accept the possibility that an initially approved exit may have to occasionally be replaced with a closer exit should the initial range estimate prove too optimistic.

Transportation Industry Vehicle Standards

Vehicle manufacturers generally do not want to build vehicles to differing standards. Even though the actual manufacturing is an important issue, even more important issues relate to design, test, and component support. As more and more of the differences relate to software functionality, once software is developed and validated there is little cost saving associated with installing it selectively. The only savings may be in the form of lesser requirements for computer memory and computation speed. The hardware cost difference thus becomes quite small. The primary focus is on uniformity.

This is seen in the industry response to the California Air Resources Board requirements for on board diagnostics (OBD II). Compatible powertrain controllers will be installed nationwide even though only mandated initially in California. This was not the case initially for engine emission standards. The more severe California standards were often met with additional pieces of engine hardware. However as engines have continued to be refined, more and more now pass all applicable standards and can be sold as a 50 States emission engine. The same tendency and goals would apply to any alternative propulsion system differences. The industry will try to respond with power systems which meet uniform standards and characteristics as much as possible. It would be very desirable if any additional needs for power system diagnostics and fuel or energy estimation were achievable with general production sensors with the possibility of specialized processing of sensor outputs to provide the additional accuracy or information required for AHS operation.

Because of the major impact that vehicle acceleration, deceleration, and braking capabilities can have on the operation of AHS, it may well be that minimum performance standards will need to be set for each class of AHS vehicle. Vehicles which do not meet normal passenger vehicle standards may need to be classified as heavy trucks, for example, as far as how they are accommodated by AHS. This may imply restriction on their use of AHS and may require higher use fees. These standards would need to be applied to the entire automotive industry and the responsibility for the setting of these requirements determined as part of the total AHS planning effort.

Task 6. List AHS Technology and Design Issues

The following long term design issues and enabling technologies are identified which are required by the incorporation in AHS of vehicles having an alternative propulsion system or using an alternative fuel:

- Control coordination approaches are needed which allow the creation of enlarged openings in AHS traffic to allow the acceleration to line speed and entry of vehicles of limited acceleration capability. These should identify existing gaps and expand them by making the minimum necessary changes in speeds of vehicles already on the AHS. As discussed in other tasks, the alternative propulsion vehicle is expected to have dynamic performance approaching that of normal passenger vehicles. Thus, this capability is required for alternative propulsion vehicles only if this expectation is not realized. However, heavy truck and transit vehicles, if accommodated by AHS, would need this AHS operational capability to enter onto the AHS.

- Battery designs are needed which have significantly increased specific power and energy. This is a general need which would increase the utility of all battery-electric vehicles. This however has additional importance for AHS in that it will improve their dynamic performance level and ease the concerns of battery-electric vehicles running out of energy on the AHS.

- New vehicles need to be designed for alternative propulsion systems and/or fuels. Unique designs can provide better solutions to the location of batteries, fuel cells, compressed natural gas cylinders, and etc. than can adaptations of existing designs. These new designs can thus be smaller, lighter, and generally more efficient. This improves their performance and utility for AHS usage as well as for non-AHS usage.

- Enhanced energy supply measurement and range prediction algorithms are required to enhance AHS operation of alternative fuel vehicles. This will allow the use of decreased energy reserve margins, thus maximizing the allowed AHS range. Such a capability is particularly desirable for alternative fuels such as battery, hydrogen, and CNG which tend to be the most range limited.

- Any use of alternative fuels in an automotive environment will require extensive testing and gradual determination of any unique safety requirements associated with their use. These may include items such as leak detection systems for gaseous fuels, special flame retardant or detection for fuels with explosive characteristics, and noxious byproduct detection and control for certain types of batteries. All of these and other safety design aspects would be part of the normal automotive development process to bring alternative fuel vehicles to market. These efforts would not be directly associated with any additional concern for the use on an AHS but would ultimately contribute to the overall safety of travel on the AHS.

CONCLUSIONS

In summary, it is seen that the spark ignition engine combines generally good characteristics, a long history of development and refinement, and an almost overwhelming infrastructure and production readiness advantage to present a propulsion system which is very unlikely to be significantly replaced without the exogenous market inputs such as legislative mandates within the time frame of this study.

None of the batteries discussed in task 2 can be said to be able to meet the mid-term goals set by USABC in actual vehicle operating conditions. Even when a battery that meets the mid-term goals is fully developed, it would still be disadvantaged in many respects relative to the current gasoline automobile. Limited range, long recharge time (measured in hours), high battery cost and short life, inferior acceleration performance, large size and weight, and performance deterioration in cold weather or as the battery reaches a low state of charge are among the problems faced. In addition, there is inadequate heat available for passenger comfort in cold climates, and air conditioning in hot climates significantly decreases range. However, analysis determines that they should fit into the continuum of performance capabilities for which AHS would be designed. The rational is based on the following observations:

- Fuel economy regulations and fuel taxes will exert pressures on standard propulsion vehicles to not extend their present performance.
- AHS must be compatible with light duty trucks and sport utility vehicles exhibiting performance lower than standard vehicles because they are a large part of the fleet.
- Consumer pressures will force alternative propulsion system vehicles to improve performance until they fall at least into the lower portion of the continuum which includes the above categories of vehicles.

Two unique operational attributes are identified for the alternative power/fuel systems. The first is the obvious, each requires a fuel which is unique to that system. This attribute is mitigated if the several alternative systems are available in bifuel form. The M85 fueled system is the most likely to be capable of bifuel operation since ordinary gasoline or RFG could be stored in the M85 fuel tank. CNG can be make in bifuel form but this required more modification and definitely a separate fuel tank. Battery-electric when combined with an internal combustion engine (a hybrid power plant) in effect then also becomes bifuel. Thus there is a likely possibility that each of the alternative power/fuel systems will appear as a unique fuel system even though some of their numbers may be bifuel.

The other unique operational attribute is associated only with the battery-electric system. All of the required motor, power management, and etc. controllers are very different from the engine and transmission controllers on other powertrains. The sensors, actuators, diagnostics, and all aspects of the powertrains are different. Thus the battery-electric system will have a unique check-in requirement as it addresses this aspect of vehicle operation and preparedness for operating on an AHS. The range of a battery-electric vehicle is very significantly impacted by the use of heating or air conditioning during the trip. Thus the range will vary with the ambient temperature at the time of the trip as well as the individual user's heating or air conditioning setting preference. These factors may need to be considered in real time at vehicle check-in in setting the acceptable destination choice of a battery-electric vehicle. Uncertain environmental factors can also affect energy consumption during the trip period such as depth of snow fall and unexpected traffic delays due to natural disasters and traffic collisions.

As to the question-will AHS need to provide routine refueling capability for alternative propulsion system vehicles? We can conclude that routine refueling for alternative propulsion system vehicles is not needed as a part of the AHS infrastructure. The rationale is based on the assumption that alternative propulsion system vehicles and AHS must both be viable economic and consumer concepts independent of each other. A viable alternative propulsion system will generate the incentive for present refueling facilities to adapt or modify their capability so that they also serve the needs of the alternative propulsion system vehicle. Only should AHS evolve to a point where it resembles a toll road facility, which offers the only viable service in a travel corridor, would AHS need to provide refueling capability for all vehicles.

However emergency refueling capability for alternative propulsion system vehicles should be provided on a limited basis. Analysis concludes that in order to facilitate the extraction of vehicles which run out of fuel while on the AHS, the AHS must consider the refueling needs of all vehicles for the run-out-of-fuel problem. Failure of certain vehicle fuel/power source systems or the check-in process could result in vehicles running out of fuel while still on the AHS. The AHS malfunction response capability must include provision for refueling (and/or possibly towing) such vehicles from the AHS break down lane. A refueling capability on an emergency basis for all forms of vehicles is one response for consideration.

As to the question will industry wide standards be needed to ensure AHS vehicle performance? Reflection shows that some aspects of vehicle performance which do not presently come under specific regulation may need to be commonized or required to meet some minimum level. The responsibility for setting these requirements must be determined as part of the AHS planning effort.

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