A REPORT ON THE FEASIBILITY
OF ALTERNATIVE
GROUND TRANSPORTATION SYSTEMS

Final Report

June 1990

by

**The University of Michigan
Office for the Study of Automotive Transportation
Transportation Research Institute**

for

**Chevron Research Company
Richmond, California**

UMTRI Report Number: 90-16

1. Report No. UMTRI 90-16	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A Report on the Feasibility of Alternative Ground Transportation Systems		5. Report Date June 1990
		6. Performing Organization Code
7. Author's) Cole, David; Patterson, Don, et. al.		8. Performing Organization Report No.
9. Performing Organization Name and Address Office for the Study of Automotive Transportation Univ. of Mich. Transportation Research Inst. 2901 Baxter Road, Ann Arbor, MI 48109-2150		10. Work Unit No.
		11. Contract or Grant No.
		13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address Chevron Research Co. Richmond, CA		
		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

    This study investigates the future role of alternative ground transportation systems in the United States. The central research questions concern the development and use of alternative modes of land transportation that can substitute for traditional gasoline/diesel fuel powered motor vehicles in the 2000-2010 period. Two of the four alternative systems examined in this report, Electric/hybrid vehicles and increased mass transit, are regarded as possible substitutes for traditional motor vehicle transportation. The remaining two technologies, improved internal combustion engines (ICE) and intelligent vehicle highway systems (IVHS), are seen, in their most likely variants, as potential improvements to current 1990 motor vehicle technology. This study describes the four alternative technologies; discusses their status in terms of development and ongoing research; discusses technical and social barriers, if any, to their future adoption; and forecasts use of these technologies to move passengers and freight in the future transportation system of the United States in 2000-2010.

17. Key Words Automotive, Alternative Fuels, IVHS, Mass Transit, Electric Vehicle, Internal Combustion Engine.	18. Distribution Statement Restricted Distribution Before April 1, 1991		
19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages 94	22. Price

A REPORT ON THE FEASIBILITY
OF ALTERNATIVE
GROUND TRANSPORTATION SYSTEMS

Final Report

June 1990

By

David E. Cole and Donald J. Patterson, Mechanical Engineering and Applied Mechanics, The University of Michigan

Kan Chen, Electrical Engineering and Richard L. Doyle, Transportation Research Institute, The University of Michigan

Robert D. Ervin, Transportation Research Institute, The University of Michigan

Charles Wright, University of Brazilia and Howard M. Bunch, Transportation Research Institute, The University of Michigan

Edited by

Sean P. McAlinden and
David J. Andrea
Transportation Research Institute
The University of Michigan

Table of Contents

A Report on the Feasibility
of Alternative
Ground Transportation Systems

Executive Summaries

This study investigates the future role of alternative ground transportation systems in the United States. The central research questions concern the development and use of alternative modes of land transportation that can substitute for traditional gasoline/diesel fuel powered motor vehicles in the 2000-2010 period. Two of the four alternative systems examined in this report, **electric/hybrid vehicles** and **increased mass transit**, are regarded as possible substitutes for traditional motor vehicle transportation. The remaining two technologies, **improved internal combustion engines (ICE)** and **intelligent vehicle highway systems (IVHS)**, are seen, in their most likely variants, as potential improvements to current 1990 motor vehicle technology. This study describes the four alternative technologies; discusses their status in terms of development and ongoing research; discusses technical and social barriers, if any, to their future adoption; and forecasts use of these technologies to move passengers and freight in the future transportation system of the United States in 2000-2010.

Each of the transportation alternatives is the subject of a separate evaluation performed by an independent research team made up of staff from both the University of Michigan's Transportation Research Institute and School of Engineering. The research teams were directed to conform to a common outline in preparing their reports. Differences in approach and style remain, however, and naturally arose because of differences in the natures and status of the technologies. Separate summaries for each report are presented below to ensure that final conclusions of each research team are fully respected regarding their assessment of the technology's future in the American transportation system of 2000-2010.

Internal Combustion Engines through 2010

David E. Cole and Donald J. Patterson

Intense effort has been underway for many years to find a replacement to the conventional internal combustion engine (ICE). However, this has proven to be a difficult challenge because the traditional engine has been improved significantly and therefore is a fast moving target. Essentially all attributes of the present engine including fuel economy, performance, exhaust emissions, reliability, and durability have been enhanced. Cost certainly has risen, but this must be compared to consumer enhancement and social (environmental) improvements to determine change in consumer value. Furthermore, the prospect of even tougher emission standards has raised some additional barriers that are particularly formidable to many of the alternative engines. Until emission regulations are stabilized for an extended period, it is doubtful that any major variation of the present ICE or an ICE-alternative will be adopted in high volume. This summary will first review the feasibility of prospective alternatives to the conventional spark-ignited gasoline engine, then review major improvements or modifications to current engine technology, and finally discuss the likely performance of improved engines in terms of complying with new emission regulations being proposed in the State of California.

Alternative Powerplants

Two-cycle, spark ignited engine with direct cylinder fuel injection. This engine has perhaps the best potential for introduction during the next twenty years. It has been used for many years for a variety of applications in a carbureted version, but the very high level of hydrocarbon (HC) emissions have precluded use in automotive vehicles. It has significant advantages in low weight, potentially low cost, small size, and perhaps 15-20% better fuel economy. Major uncertainties are its ability to meet future emission standards and emission durability. New developments in this area warrant continuing attention.

Light duty diesel engine. The diesel engine is a well developed technology on a world wide basis. However, it has been tried and rejected by the North American market. While it has a significant advantage in fuel economy, this has not offset its reputation for smoke, noise, odor, and high cost. Future emissions standards, particularly HC, oxides of nitrogen (NO_x), and particulate emissions, appear to be a serious barrier. Unless fuel costs change significantly, light duty engine penetration is not expected to increase.

Gas turbine engine. This engine has been under investigation for many years as a possible replacement for both gasoline and diesel engines. Its prospects are lower today than twenty years ago, in spite of some critical advances in design and materials technology. This engine is quite

clean, but may not be sufficiently clean to meet future emission standards: it presents some very difficult exhaust clean up problems, particularly with NO_x and also transient cycle HC. Additionally, it is difficult to make it both small and powerful enough to meet the requirements of today's smaller vehicles. There is nothing on the horizon to suggest increased potential for automotive-related gas turbine engines.

Stratified charge. A variety of different stratified charge spark ignition engines have been proposed, including both pre-chamber and various open chamber designs in which direct cylinder injection is required. Key potential advantages include use of existing engine hardware, high fuel economy, and fuel flexibility. Major problems have been high cost and serious difficulties with emission control in most configurations. There is no reason to believe that the problems associated with direct injection stratified charge engines are any nearer to solution than they were twenty years ago. The relatively poor fuel economy of pre-chamber engines has virtually eliminated interest in that design for automotive applications.

Advanced Internal Combustion Engines

The present day reciprocating spark-ignition internal combustion engine continues to undergo substantial improvement. Major changes of the past few years have included increases in manufacturing precision, leading to lower friction; extensive use of electronic control, permitting optimization of key operating parameters; and the introduction of new materials and design methods. More engines may incorporate some axial charge stratification achieved by port fuel injection. The catalytic reactor is the single most important factor in the excellent emission performance of these engines. Intense effort is underway to improve the engine further.

Most of the engines in current production in North America will be completely redesigned during the next decade. All engines of the future will be high precision, but it is less certain to what extent they will be "high tech" (four valves per chamber, double overhead cams, etc.). The relative advantages and disadvantages of the higher technology—high specific power versus low technology low specific power engines and fewer number of cylinders per engine—are not clear at the present time. The exact mix will depend extensively on customer considerations and future regulations. There is the potential of perhaps a 15-20% improvement in efficiency over existing designs.

Future Standards and Performance

Future emission standards - federal. The Clean Air Act is still being formulated in Washington and may involve two tiers (Tier 1 and Tier 2) of future emission standards. Tier 1 standards can probably be met with only modest changes in current engines. Tier 2, on the other

hand, if implemented can probably be met with significantly modified ICE technology but at an additional cost of perhaps $500 per vehicle. Another possible challenge is the increased durability requirements, perhaps to as high as 75,000-100,000 miles. This may require the manufacturers to schedule mid-life update or service of the emission control system, rather than trying to build such long term durability into the initial product.

Proposed future California standards. The proposed future California standards create a much more serious problem for the ICE than those being considered at the federal level. The California standards have been broken down into three stages: transitional low emission vehicle (TLEV), low emission vehicle (LEV), and ultra-low emission vehicle (ULEV). Modified present technology should satisfy transitional low emission vehicle standards but it is very uncertain whether either the low emission vehicle or ultra-low emission vehicle requirements can be met with even highly modified ICE and emission control systems. If forced to speculate, we believe the LEV capability can be achieved with highly modified internal combustion engine technology with a liquid hydrocarbon fuel.

The Significance of Intelligent Vehicle-Highway Systems (IVHS) for the Future of Motor Vehicle Travel in the U.S.

Robert D. Ervin

Intelligent Vehicle Highway Systems (IVHS) represent a concept whereby information and control technology will make motor vehicle transportation more efficient and safe. In a generic form it will utilize electronic communication between the vehicle and the roadway, eventually culminating in completely automated vehicle control. Such features can be expected to achieve commercial viability on an incremental basis based on consumer perceived cost/benefit. It should be noted that the realization of highway travel via IVHS technologies calls for both a new highway infrastructure and the mass purchase of compatible, in-vehicle technology. It is presumed that the enabling infrastructure will be funded via governmental agencies and in-vehicle packaging through private financing. It is apparent that IVHS will be adopted only with private/public collaboration. To facilitate such collaboration an *ad hoc* group called"Mobility 2000" has been formed to lay the foundation for an IVHS program within the United States.

An increasing overload of the U.S. highway system is expected well into the next century. As traffic volume approaches a saturation point, average travel speed drops and the total accrued travel time rises exponentially. Given the inevitability of"congestion crises" in many metropolitan centers worldwide, it seems clear that IVHS solutions will be increasingly advocated.

IVHS Options

- The "Advanced Traffic Management Systems" (ATMS) will offer a complete surveillance of the freeway and major arterial systems. It is projected that ATMS will see deployment in at least 12 large U.S. cities by the year 2000.

- "Advanced Driver Information Systems" (ADIS) which will provide the vehicle operator with individualized routing instructions, hazard warning, travel services information, etc. It is projected that ADIS will reach 50% of vehicle penetration by the year 2010. It is estimated that beyond providing relief for traffic congestion, ADIS packages will reduce the national accident rate by 20%.

- Delphi forecasts in both the U.S. and Europe estimate that highway automation systems will not achieve significant deployment until the year 2040. However, the California Department of Transportation has indicated an intention for vigorous development of automation technology.

Barriers

Technical
- Systems Architecture: The cost for IVHS equipment will increase the cost to the individual vehicle owner. Both the OEMs and the consumer are resistant to the increasing cost of private passenger and utility vehicles. It, therefore, appears likely that an IVHS infrastructure would be financed largely through public/governmental

funds. It is also clear that resolution of the basic issues of system architecture, with associated interface standards, will pose a significant barrier to the implementation of IVHS technologies.

• Traffic Surveillance Technology: Deployment of real-time traffic advisory information for motorists is essential for IVHS. At the present time a number of technologies (both hardware and software) present formidable barriers. Among these are: (1) radio frequency bandwith allocation for data transmission, (2) map and "normal traffic" databases, (3) dynamic modeling of traffic networks, and (4) collision avoidance systems. The lack of resolution within these areas will pose inhibiting factors.

Nontechnical

In addition to the technical barriers to IVHS there are also a number of nontechnical factors that will either delay IVHS deployment or will pose conflicts after IVHS deployment. These factors are as follows:

• Private investment discouraged by the shaky dependence on governmental financed infrastructure.

• Social/jurisdictional conflicts.

• Conflicts regarding urban versus rural use of federal highway funds.

• Tort liability.

• Privacy of movement.

Forecast

A University of Michigan Delphi survey on IVHS has forecast that by the year 2000 there will be major installations of "Advanced Traffic Management Systems" in a dozen U.S. cities, as well as large-scale deployments of in-vehicle location and communication technologies by commercial highway users. A high level of development of "Advanced Driver Information Systems" is also expected in the next ten years.

Factors that will determine the rate of development of IVHS include:

• Institution of a National IVHS program by the U.S Congress.

• Initiatives and investments by foreign electronics and telecommunication companies and automotive manufacturers.

• Successful IVHS field demonstrations.

Electric and Electric Hybrid Vehicles

Kan Chen and Richard L. Doyle

Despite a long history of development, current technological and economic bases for electric vehicles (EV) and gasoline-electric hybrid vehicles (EHV) are not sufficient to pose a near-term competitive threat to the conventional internal combustion engine (ICE). However, a convergence of social and political factors could allow for a significant penetration of EVs and EHVs in selected markets and in specific locales. A historical review suggests that the future potential of EVs and EHVs is closely tied to the availability and price of gasoline, as well as other factors perceived as being in the national interest, particularly with regard to environmental concerns and petroleum as a political commodity.

Current Technology

Although advanced battery technologies (e.g., sodium-sulfur, zinc-bromine, lithium alloy-iron sulfide, and nickle-cadmium) have realized considerable progress, the lead-acid battery remains the predominate system. Despite the disadvantage of weight versus energy ratio, lead-acid batteries will power the GM "Impact" and the Fiat "Elettra" EVs. However, a recent announcement by Isuzu of a proprietary "revolutionary" type of "electric power storage" system, together with emerging battery system technologies described in the very recently released (April, 1990) 13th Annual Report to Congress for Fiscal Year 1989 by the U.S. Department of Energy (DOE), Office of Transportation Systems (OTS), could significantly alter the perspective for future advanced battery systems. These battery technologies should be subjected to close scrutiny and ongoing monitoring.

U.S. EV/EVH Status

General Motors announced on April 18, 1990, that it will produce and market an EV for personal transportation usage. The "Impact" will utilize two AC induction motors, each driving one of the front wheels. The "Impact" prototype, using a 870 pound lead-acid battery pack, is capable of accelerating from 0 to 60 mph in 8 seconds and can attain a top speed of 75 mph.

Other projects currently undergoing R&D include an Electric Power Research Institute (EPRI) sponsored cargo-carrying, conventional lead-acid battery powered GMC "Vandura" (G-Van). Chrysler is developing an EV "Caravan" powered by a nickel-iron storage battery. The U.S. DOE/OTS, has several projects under R&D including a Dual-Shaft Electric Propulsion system using Eaton Corp. and Eagle-Picher Industries components in a Chrysler mini-van with power provided by a nickel-iron battery.

The U.S. DOE/OTS has a Single-Shaft Electric Propulsion (ETX-II) system under R&D, as well as a Fuel Cell/Battery Powered Bus program. Detroit Edison Company is continuing over-the-road evaluation of the GM "Griffon" electric van in an effort to provide a basis for comparison with the GM G-Vans. In addition, the OTS administers a number of private enterprise cost-shared, proof-of-concept/state-of-science advanced battery system R&D programs.

International EV/EHV Status

A number of countries spurred by high gasoline prices and increasing environmental concerns have been aggressively pursuing EV and EHV programs. Notable among these countries are the United Kingdom, West Germany, France, Italy, and Japan. Other European countries with ongoing EV/EHV programs are Belgium, Denmark, The Netherlands, Switzerland, Austria, Sweden, and Finland.

Driving Forces

The primary forces for EVs and EHVs are concerns regarding ICE emissions and their effects on public health and the environment. This concern is particularly acute in certain diverse geographic areas such as California, Mexico City, and Singapore. At the present time it appears that the legislative mandates of state and federal governments and gasoline prices, rather than commercial considerations, will continue to be the major drivers of electric vehicle R&D.

Barriers

Even if a dramatic increase in the driving forces were to prompt an increase in the market demand for EVs and EHVs, a widespread increase in the use of these vehicle would not be possible until the necessary infrastructure is built up. Barriers in conventional electrochemical kinetics preclude any major breakthroughs in present state-of-the-science battery systems without conceptually innovative technological breakthroughs. Aside from an industrial technological infrastructure, there is the necessity for a widespread availability of battery recharging facilities, maintenance facilities; a trained human resource pool for sales, operations, manufacturing, and maintenance; as well as aftermarket development. If there are governmental legislative mandates, there must also be adequate mechanisms for policing.

In addition there exists in almost every part of this country the need to meet consumer demands for comfort and versatility, particularly in the areas of heating and cooling of the passenger compartment. This is not an inconsequential impediment for EVs. While ICE heat loss through the radiator and exhaust pipes can be utilized for heating the passenger compartment and additional accessory drives provide power for air conditioning compressors, power steering

pumps, etc., electric engines have no heat loss, *per se*, and accessory drive units would, by necessity, impact primary energy capacity. Therefore, it would be necessary to use some of the primary energy of the battery system to heat or cool the passenger compartment, resulting in a decrease of vehicle range. Additionally, there is the energy drain incumbent with night driving.

Forecast

It is clear that social and political forces affecting the R&D and potential commercial viability of EVs and EHVs are developing on a daily basis. The Bush Administration's "Clean Fuels Program" could have a dramatic impact on electric vehicle programs. A conceivable scenario would have EVs and EHVs increasing in specific market segments (e.g., commercial fleets) and in specific geographic locales (e.g., California). However, it is unlikely that EVs and EHVs will be widely implemented within the next five to ten years due to an apparent lack of revolutionary developments in key advanced battery technologies that would dramatically improve range and performance.

Nevertheless, it is extremely important that careful scrutiny of emerging battery technology be continued. In addition to federal agencies and laboratories (e.g., U.S. DOE, U.S. Navy, Sandia, and Argonne National Laboratories) and U.S. companies (e.g., GM's Delco Electronics, Ford Motor Company, Johnson Controls, Eagle-Picher, and others), a number of foreign governments and companies (e.g., Fiat, Isuzu, and others) are also proceeding in this area.

Mass Transit Innovations—2000 to 2010

Charles Wright and Howard M. Bunch

The term "mass transit" is herein employed to include bus, guided and rail transit as well as rapid rail transit. The most important innovations of interest are likely to be organizational in nature, i.e., learning to use existing modes better, especially bus transit as an individual mode and in connection with other modes.

With respect to increasing ridership, bus transit, precisely the lower end of the technology and cost scale, offers the greatest potential, but only on relatively dense traffic corridors when given priority use of road space through exclusive or semi-exclusive lanes and busways and, in some cases, lanes shared with other high occupancy vehicles. Buses can also be joined together in articulated units with the tractive vehicle and one or two trailer units, which can be operated on a fixed guideway, as in Essen (FRG) and Adelaide. Under any such set of conditions, they can carry rail-level volumes and still offer the advantages of greater flexibility, speedier implementation and fewer transfers.

Bus transit also can be effectively used in conjunction with rail transit and, with auxiliary parking facilities, the private car, and are probably the only mode where private owners could operate at a profit in a less-regulated or unregulated environment. The technological innovations are expected to be rather modest, with some decrease in vehicle weight, and slightly more energy efficiency for diesel and electric buses, and options for cleaner-burning motor-fuel combinations where diesel faces stringent emissions requirements (probably cancelling out those gains and increasing fuel costs per passenger kilometer). In other countries, semi-exclusive bus lanes have been installed for as little as $1.5 million/km, or $3.5 million/km with a contingent of electric buses.

Increases in rail ridership will be concentrated in locales where existing systems are being completed or extended. The gains in energy efficiency and other improvements are likely to be more pronounced where older systems are upgraded than from the relatively modest technological innovations in transmission and use of electricity. The only major innovation which has a greater— but unproven—potential is linear induction motors with steel-wheel-on-steel-rail technology. This offers the potential of decreasing the costs of civil works associated with new urban rail lines, by permitting sharper curves, steeper grades and smaller tunnels.

Magnetic levitation, if relevant at all, will be so only on longer routes with very long distances (say at least 10 km) between stops, such as inter-city travel and airport-to-downtown routes. It is completely unsuited to typical urban routes which require stops at say, every 600 m..

The chief barriers to rail systems are their costs. Those with substantial underground segments have cost $85 - 115 million/km in Brazil and up to $160 million/km in Japan.

Monorails and proprietary guided transit systems, such as the Detroit People Mover, are very expensive ways of moving very few people. The monorails and some other the other guided systems are limited to loops or airport-downtown type routes since their switching operations are complicated and they are thus difficult to expand in a network. The smaller vehicle systems (2-3 passengers per vehicle) have never been installed in an urban traffic setting, having been limited to expos and amusement parks.

The only major innovation in the monorail class of vehicles is the Sür Coester Airtrain, which is moved by air at low pressures with industrial fans and uses lightweight, motorless cars with steel-wheel-on-steel-rail technology. This system has the potential of transporting monorail level volumes (say 8,000 passengers/hour per direction) with an investment cost of perhaps $8 million/km (all system costs included, although elaborate stations could increase this) and lower operating costs than any other automated guided system. The small vehicle systems would probably cost this much without civil works, and recent Japanese monorails have run $60 million/km.

The outlook for urban transit ridership is rather bleak, due to the very low population densities of U.S. cities, the almost universal pattern of auto ownership among workers, and the increases in the number of available cars per capita within households. Even with all the improvements listed and a number of new/expanded rail transit systems coming on stream, mass transit is unlikely to maintain its current small share of roughly 6% of commuting trips and less than 4% of all trips. Surprisingly, the overall level of transit ridership might not increase all that much even under shock scenarios such as emissions regulations favoring electric vehicles (trains and trolleybuses), real price increases of 4-10 times in fuel costs and expanded gridlock. The short and medium term reaction would be to eliminate a considerable number of non-work related trips (77% of the private car total) and to form an increased number of car and vanpools. A tripling of transit commuting by 2010 would mean an increase to only 18 million round trips daily, compared with 83 million round trip commutes for cars at present, and about 360 million total daily car trips.

Under most realistic scenarios, attempts to increase transit use would not significantly reduce fuel use. Although public modes are typically somewhat more fuel efficient than cars for average U.S. occupancy ratios, increased use might extend buses into very low density routes and, running nearly empty, might even require more fuel per passenger/km than automobiles (a phenomenon that occurs today during some off-peak hours and on some lightly travelled routes).

A truly optimistic scenario for mass transit would require a shock scenario in the short and medium terms and relocation in the long term of residences and other activities in a more dense, clustering pattern. Gasoline at $4/gallon would probably not be enough to cause this, although there might be an appreciable effect if that level approached $10/gallon. As stated, however, the effect would be much stronger in reducing car use than in increasing the absolute levels of transit use.

The most interesting developments for monitoring are the use of high occupancy lanes and the trends for promoting the use of carpools and vanpools. A distant second is the Sur Coester Aeromovel.

Current Status of Alternative Land Transportation Systems

Chapter One: Overview

This study investigates the future role of alternative land transportation systems in the United States. The central research questions concern the development and use of alternative modes of land transportation that can substitute for traditional gasoline/diesel fuel powered motor vehicles in the 2000-2010 period. Two of the four alternative systems examined in this report, **electric/hybrid vehicles** and **increased mass transit**, are regarded as possible substitutes for traditional motor vehicle transportation. The remaining two technologies, **improved internal combustion engines (ICE)** and **intelligent vehicle highway systems (IVHS)**, are seen, in their most likely variants, as potential improvements to current 1990 motor vehicle technology. This study describes the four alternative technologies; discusses their status in terms of development and ongoing research; discusses technical and social barriers, if any, to their future adoption; and forecasts use of these technologies to move passengers and freight in the future transportation system of the United States in 2000-2010.

Americans have been, by tradition, free to choose their mode of transportation. Since the turn of the century, and particularly since 1950, Americans have increasingly relied on privately owned, petroleum powered, motor vehicles to move themselves and freight to both local and intercity destinations. The latter half of the 1970s were marked by a slowdown in the rate of increase in vehicle miles traveled in the United States. Yet, with the stabilization of fuel prices in the early 1980s and the availability of fuel efficient vehicles, vehicle miles traveled increased, with an average annual rate of increase of 3.4% for the 1980-1988 period. Total vehicle miles traveled reached a level of 1,991 billion in 1988.

Passenger cars are now responsible for over 70% of the total land vehicle miles traveled in the United States. On the average in 1987, each passenger car annually consumed 515 gallons of fuel, and carried 2.3 passengers per mile traveled. In 1987, a record 137 million passenger cars were registered in the United States and private automobiles were responsible for about 80% of total intercity passenger miles traveled. This last percentage represents a decline from the car share of 87% in 1970, as air travel increased its share of overall passenger miles traveled from 10% to 18%. Private automobiles still accounted for over 86% of intra-city passenger miles traveled in 1987.

Motor vehicle trucks accounted for almost 29% of total land vehicle miles traveled in 1987. Motor truck share of total intercity freight ton miles fell from 24% in 1978 to less than 22% by 1981. By 1987, however, the share of intercity freight ton miles accounted for by trucks had risen to almost 25%. Motor truck share of *intra*-city freight ton miles is far higher than this level. About 41 million trucks were registered in the United States in 1987 when the average truck consumed about 1,359 gallons of motor fuel.

As a group, motor vehicles were responsible for over 49% of all petroleum energy consumed in the United States in 1988, up from about 43% in 1980. This increase is important since the U.S. Department of Energy reports that total petroleum energy consumption in the United States fell between 1980 and 1988, but consumption by motor vehicles rose about 15%. In other words, motor vehicle fuel sales may have constituted the only large growth market for petroleum energy in the United States in the 1980s. This occurred despite the fact that the average amount of fuel annually consumed by passenger cars fell from 716 gallons in 1975 to 515 gallons in 1987.

The steady growth of motor vehicle transportation in the 1980s represents an important achievement by the motor vehicle manufacturing and petroleum industries. Challenges in the 1970s that included energy price shocks, two serious economic downturns, and stringent environmental regulations, such as the Clean Air Act and CAFE, were overcome in the 1980s, a period of increasing demand for transportation from a highly mobile and enlarged U.S. population and labor force. New challenges have appeared in recent years, however, that again threaten the traditional role of gasoline powered motor vehicles in the U.S. transportation system.

Two major challenges confront the future of traditional motor vehicle transportation in the United States. First, there is now renewed concern by the public and their local and national policy makers regarding remaining levels of emissions from mobile sources in the United States. Despite significant reductions to date in lead, hydrocarbons, carbon monoxide, and nitrous oxides, policy makers in Washington and in several regions and large states are demanding almost complete elimination of the standard list of air pollutants, including major reductions in particulates, evaporative emissions, and carbon dioxide. Many experts have concluded that the new emissions and CAFE levels being discussed can only be achieved through the development and use of "ultra-low" emissions vehicles and transportation systems. Flexible and alternative fuel vehicles are often presented as logical solution to proposed air quality requirements.

2

The second major challenge is linked to the apparent undercapacity situation of the nation's highway transportation road network. In the 1980s, mileage of paved roadways increased by only 4.3% while vehicle miles traveled increased by 30.3%. Many critics have charged that levels of federal and local highway expenditures have been inadequate in the 1980s, even for maintaining the road network already in place. Traffic congestion in most major metropolitan areas, including many medium sized cities have reached levels far beyond that of simple irritation for most users, perhaps to the point of placing the efficiency of the transit system at serious risk.

Alternative fuel vehicles are not a solution to the problems of traffic congestion and insufficient highway infrastructure. The usually unpopular alternative of mass transit has received increased attention from local and regional transportation planners in recent years. Since it is now apparent that the nation's current road network will call for an enormous public investment for both replacement and capacity purposes—if it is to have any chance to meet future needs—other publicly funded alternatives such as mass transit or IVHS may receive more favorable critical attention on cost/benefit grounds.

Because of the special nature of the challenges ahead, several alternative transportation technologies are receiving increased attention and consideration, some for the first time. Several technologies would clearly call for enormous investments from both the public and private sectors. Other technologies are not serious alternatives until major technical barriers are surmounted. Since several proposed systems are mutually exclusive—at least to the point where adoption of one system restricts the scope of others—investment in infrastructure or research in any of the systems carries with it considerable risk. A cautious, comparative study of the technical, commercial, and policy feasibility of each alternative system is the task of this current study.

This study does not review the well publicized alternative of flexible and alternative fuel vehicles. Instead, it evaluates four other alternatives to traditional motor vehicle transportation. Each alternative is subject to a separate evaluation carried out by an independent research team. The first phase of the study determines the status of each technology. The alternatives are described separately, and major R & D efforts here in the U.S. and abroad are identified, with the organizations carrying out these activities. Possible applications of the technology are also discussed which naturally leads to the second phase of the study . This second step of the study describes and discusses both major technical barriers and political and social driving forces associated with the most likely variants of each technology for the period 2000-2010. The authors of each of the technology essays finish their evaluations in a third step that

contains conclusions, a forecast, and suggestions for effective monitoring of future developments in their technology.

*References

U.S. Department of Transportation, Federal Highway Administration. Highway Statistics, 1988. U.S. Government Printing Office, Washington, D.C., FHWA-PL-89-003.

U.S. Department of Transportation, Research and Special Programs Administration. National Transportation Statistics, Annual Report. U.S. Government Printing Office, Washington, D.C., August, 1989.

Motor Vehicle Manufacturers Association. Facts and Figures '89. MVMA, Detroit, Michigan, 1989.

Chapter Two: Internal Combustion Engines through 2010

David E. Cole and Donald J. Patterson
Mechanical Engineering and Applied Mechanics
The University of Michigan

Section One: Current Status

Overview

The conventional spark-ignited engine has become well established as the engine of preference for light duty vehicles in North America. Throughout this century, many alternatives to the reciprocating gasoline engine have been proposed including the diesel, rotary combustion, and gas turbine engines. Electric vehicles and steam or Rankine, Stirling power plants, and several hybrid combinations have also been proposed. However, the Otto cycle or gasoline engine has proven to be a formidable competitor and has presented a fast moving target to all challengers.

Today, no viable alternative seems to be on the horizon, other than possibly the two-stroke gasoline engine, which closely resembles, at least in terms of the work-producing thermodynamic cycle, the four-stroke design. Engine technology advances during the last ten years have been substantial on a world-wide basis. In North America there has been a general trend to engine downsizing, with a significant number of improvements ranging from greatly increased manufacturing precision to the application of advanced design methodology and the incorporation of features leading to significant improvements in thermal efficiency, exhaust emissions, performance, and complete customer satisfaction. Electronics have played a particularly prominent role in the improvement of North American engines during the past ten years and have facilitated optimization of emissions, fuel economy, and driveability to an extent not possible before this technology entered the scene. Electronic control coupled with modern exhaust catalytic converters has led to a reduction of hydrocarbon and carbon monoxide emissions of over 96% and more than 75% for nitrogen oxides.

Improvements in the conventional engine are difficult to quantify precisely, and the present status of engine efficiency is very difficult to define for the average engine produced here in North America or elsewhere. While the maximum thermal efficiency of an engine might seem to be a proper measure to use as a basis for comparison, this is not appropriate, since an engine, as installed in a vehicle, operates over a broad operating cycle: the brake

efficiency ranges from 0% at idle to an intermediate level of about 25% in typical urban driving, and perhaps as much as 36% if the engine is optimized for fuel economy at full load. So in an arbitrary manner, we will assign a good engine installed in a typical vehicle an efficiency rating of 100. It is our judgement that continued incremental improvement with known technology should yield an increase of approximately ten points—10%—in overall brake efficiency. Furthermore, the application of advanced technology that in most cases is not yet proven, such as variable valve timing and lift, might lead to as much as another 8 to 10 point increase. Thus, through the year 2010, we could foresee approximately a 20% improvement in the basic four-stroke cycle gasoline engine over the present day level, assuming constant emission performance and power requirements. The engine control system, including drive-by-wire, may give some efficiency improvement by operating engines at the most efficient points.

The University of Michigan forecast of future automotive trends, Delphi V, provides some insight regarding the North American industry expectations for engines in the next ten year period. Significant changes are forecast. In North America, 70% of four cylinder, 65% of six cylinder and 60% of eight-cylinder engines are expected to be fundamentally redesigned in the next decade. Average engine size and cylinder configurations are expected to hold relatively steady, assuming major changes in CAFE do not occur in the next decade. There will be a growing trend in the use of aluminum in heads, with more modest use in engine blocks. In addition, some components will begin to use non-traditional materials including plastic for inlet manifolds (weight/cost reduction), metal matrix composite pistons and connecting rods (weight/friction reduction), and possibly even ceramic materials in exhaust port liners (enhance exhaust treatment) or valves. Components, such as distributorless ignition (minimize timing changes with high mileage) and electronic fuel injection will become essentially standard. High-technology engine features, like single and double overhead camshafts, and three- and four-valve combustion chambers will surely expand, but not to the level forecast just two years ago. These developments make the most sense for high-speed engines.

There seems to be a considerable moderation of expectations for advanced engine technology which in part is based on the high cost of these technologies and the potentially marginal consumer value. The cost issue is particularly interesting. A modern double overhead cam, high-technology 4-cylinder engine produced by one manufacturer, exceeds the cost of a lower tech V-6 engine of about 1-litre greater displacement produced by the same manufacturer. Furthermore, the smaller, high specific power, advanced technology engines,

must be operated at a higher RPM at a given power level than lower technology designs. This may lead to higher overall friction losses offsetting expected advantages of the smaller engine. However, there are advantages in combustion chamber shape, reduced mass, and lower rubbing contact area with higher tech configurations.
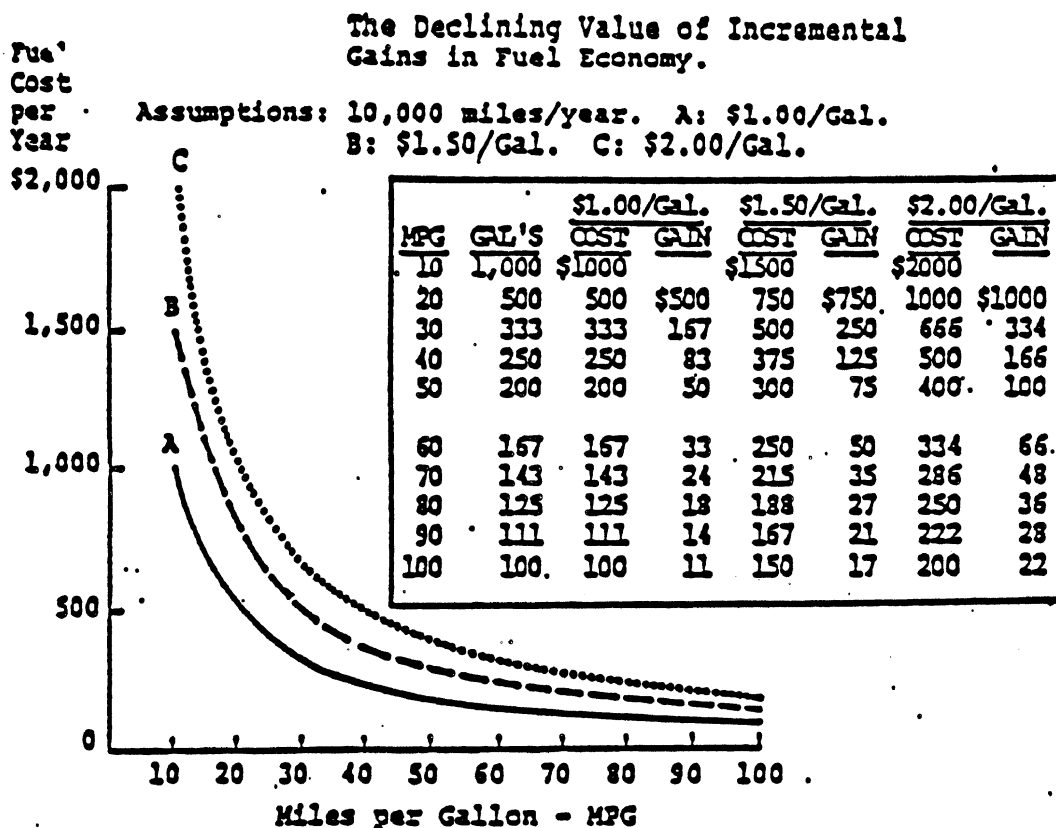
Recent EPA fuel economy data on powertrain performance is quite revealing about the low technology/high technology comparison. On a ton-mile/gallon basis, the average North American passenger car exceeds the fuel economy of the average Japanese product sold in the United States. Since the typical Japanese engine uses high specific power, high-tech designs, versus a more conventional design in North America; these results may be quite significant and to many, quite surprising.

One of the most significant uncertainties affecting powerplant design in the years ahead is exhaust emission requirements. Significant reductions in emission standards have been proposed by Congress and could have a profound effect on engine and vehicle design, including the future role of alternative power plants. Until some stability in federal and/or state regulations occur, it will be very difficult to forecast the future powerplant trends with any degree of accuracy.

One of the greater challenges for policy formulation and engine design and market forces, is the value of fuel economy as perceived by the customer. Annual fuel cost is shown as a function of vehicle miles per gallon (mpg) ratings for three different energy price scenarios in the following figure. Ten thousand miles of annual driving is assumed. Clearly, as fuel economy improves, the cost savings decreases at the margin. In a range from ten to twenty mpg, there is considerable customer value in fuel economy improvement. At higher mpg levels this value decreases significantly. For example, with fuel at $1.00 per gallon and 10,000 miles of annual driving the fuel cost saving in moving from 30 to 40 mpg is only $83.00. Surely, under these conditions the market incentive for improved fuel economy is small, particularly if it results in significant reduction in other vehicle attributes. It would be most unfortunate if future regulatory policies were to cause a significant conflict between the automotive and energy industries and the market.

In the following sections of this report we address the current four-stroke spark-ignited engine, identify possible technological upgrades and provide estimates of fuel economy improvement with these advances. We will also review several possible alternative engines, including the two-stroke gasoline engine, diesel and gas turbine, and variations of the conventional engine, such as the direct injection stratified charge design, in the 2010 time frame

of this study. Clearly, there are no magical carburetors or mystery engines that could dramatically improve emissions, fuel economy, and/or performance over conventional designs.

The Declining Value of Incremental Gains in Fuel Economy.

Fuel Cost per Year

Assumptions: 10,000 miles/year. A: $1.00/Gal. B: $1.50/Gal. C: $2.00/Gal.

MPG	GAL'S	$1.00/Gal. COST	$1.00/Gal. GAIN	$1.50/Gal. COST	$1.50/Gal. GAIN	$2.00/Gal. COST	$2.00/Gal. GAIN
10	1,000	$1000		$1500		$2000	
20	500	500	$500	750	$750	1000	$1000
30	333	333	167	500	250	666	334
40	250	250	83	375	125	500	166
50	200	200	50	300	75	400	100
60	167	167	33	250	50	334	66
70	143	143	24	215	35	286	48
80	125	125	18	188	27	250	36
90	111	111	14	167	21	222	28
100	100	100	11	150	17	200	22

Miles per Gallon - MPG

Conventional Four-Stroke Spark-Ignition Engine

The basic-four stroke Otto cycle engine is the baseline for comparing all light duty alternative powerplants. As noted earlier, this engine type has presented a formidable challenge to all competitors and even today is undergoing steady but significant improvements in fuel economy, performance, emissions, manufacturability, and other key considerations. Important trends are identified in the prior section.

During the past 10 years, a considerable effort has been focused on improving manufacturing precision and bringing the entire engine under electronic control. Improvements have been substantial. No longer are cylinder bores measured during assembly and fitted with pistons selected from five or six different sizes to insure a good fit. Today, almost all engine cylinder bores are made round and of a uniform size. Reciprocating mass (pistons and connecting rods) is being reduced, yielding many benefits including friction and vibration reduction. A brief review of individual engine subsystems and their potential for fuel economy

and emissions improvement follows. All suggested improvement percentages are in comparison with "excellent" present day technology.

Engine Structure

The trend to aluminum heads and some increased use of aluminum in blocks is accelerating. New techniques, such as the lost foam casting process, promise continued weight reduction and reduced manufacturing cost. However, little effect is likely on fuel economy and emissions other than through reduced vehicle weight. Consideration is being given to multipiece construction of the crank case and rolling element bearings for friction reduction.

Fuel Management

The carburetor has essentially disappeared and has been replaced by electronic fuel injection. Multipoint injection is growing rapidly, although some single point injection systems will probably be used through 2000. Relatively little fuel economy improvement seems likely, on the order of 1-2%, but greater gains may be evident in the emissions/economy trade-off. Individual cylinder performance optimization with fuel rate and ignition timing control, based on feedback (including knock and location of combustion with respect to top dead center of the piston) from each individual cylinder prior to power stroke work output could provide further increases, perhaps an additional 2% gain. While the technology is available to accomplish this, application engineering is at an early stage. Also, Laser Doppler Velocimetry promises to extend our knowledge of cyclic variation, reduction of which would allow the optimization of this engine.

There continues to be interest in dilute or ultra lean combustion but the prospect of tougher emission standards (difficulty of achieving NO_x control with excess O_2 present) seems to be working against this strategy. Slower combustion with lean mixtures is also a problem. Overall economy gains of 5% or so would be possible if we could achieve fast burn, lean combustion, but we do not believe it will be achievable for some time. The axially stratified charge engine may make dilute combustion more possible. Again, advanced combustion diagnostics may help, but much work over the years suggests there are no easy solutions.

A fuel system that would aid cold start vaporization could have a positive affect on both HC and CO emissions, but little affect on fuel economy. The effect would be minimal with the 70° F cold start on the EPA test.

Ignition System

Very little in the ignition system can influence emissions and fuel economy if the fire is started at the proper time and place in the cylinder. Ultra high energy or plasma systems may permit ignition of marginal mixture ratios, but little effect is likely with near stoichiometric mixtures. Multiple ignition sources may speed burn rate and reduce octane requirement, but economy gains are marginal for a new engine. There may be benefits at 50,000 or 100,000 miles of service by keeping timing at new engine settings.

There is a trend to distributorless and coil on plug systems but there are other reasons for these systems than emissions and fuel economy. With individual cylinder ignition optimization some improvements are likely, as noted in the Fuel Management Section above.

Valve Train/Combustion Chamber

With the growing trend to three- and four-valve combustion chambers and overhead cam designs some improvement in combustion chamber shape is possible (lower surface/volume ratios, better ignition location, and reduced octane requirement). This could lead to economy (1-2%) and some emission improvements but the added cost, complexity, and higher operating RPM at a given power output (friction increase) raise some important issues. The Delphi forecast for these technologies in the 1990s has been reduced from levels predicted several years ago. Generally, reduced octane requirement is likely with aluminum heads with the better control of "hot spots," controlled "end gas" positioning with respect to the exhaust valve and possibly sodium cooled exhaust valves.

Variable valve lift and/or timing (active valving) are receiving considerable attention from the industry. A pure electromagnetically actuated valve presents a challenging problem because of the large forces called for and the energy losses in a non-conservative system. However, a variety of innovative concepts under development could give rise to production systems during the later part of the decade. With these arrangements, engines could provide a good combination of power and economy. Furthermore, inlet valve throttling and timing control could lead to a modest reduction in the pumping work portion of the operating cycle and enhance mixture motion at light loads. The full discussion of these issues is beyond the scope of this paper. However, it may be possible to increase the efficiency (5-8%) and reduce emissions significantly. Cost effective means of achieving this degree of valve control is the challenge. A viable valve variation mechanism must be developed.

External Boost

Presently both superchargers and turbochargers are available on production engines. The primary advantage of external boost devices is to effectively make a smaller engine larger on demand, but retain the virtues of the small engine for most of its operation. Very modest fuel economy gains are possible compared to a larger engine, particularly since compression ratio is generally reduced to control detonation with a consequent thermal efficiency penalty. When the added cost and complexity of the component is considered, the major reason for these systems over a slightly larger engine is generally the high cost to design and tool the larger engine. This is clearly the case with Chrysler and their extensive use of turbochargers. We do not believe either turbo or super chargers will be used in high volume on four cycle engines for the next 20 years. The Delphi V forecast is 3% use on superchargers and 5% for turbochargers by 2000.

Advanced Engine Materials

Many advanced material technologies are being considered for spark-ignition engines including ceramics, metal matrix composites, and various polymers. Plastics, for example, are expected to be used in a variety of components including various covers, inlet manifolds, and even engine structural components. Usually, these materials hold little promise for either fuel economy or emission improvements. Ceramics may help reduce friction and wear in various valve train- or piston-related components, and some applications such as coatings in exhaust ports (to aid exhaust gas heat conservation) may help with emission control but have little affect on fuel economy. Serious consideration is being given to metal matrix composites (MMC) and other advanced structural materials for such components as pistons and connecting rods. Significant weight reduction of reciprocating components is likely, which will lower engine vibration and modestly reduce friction. Generally, new material technologies could lead to a 2-4% reduction in fuel consumption.

Alternative Engine Technology

Two-Cycle Gasoline Engine

The two-stroke cycle gasoline engine has recently emerged as one of the most exciting alternative engines in the automotive industry. While the two-cycle is hardly new in concept, having been used for decades in both diesel and gasoline engines, new developments in direct cylinder (after exhaust port closing) electronic fuel injection have opened the door to the potential for automotive applications. Traditional, carburetted two-cycle gasoline engines have been characterized by relatively poor fuel economy and extremely high hydrocarbon emissions. With direct cylinder injection it appears possible to inject fuel after exhaust port closing, create

a combustible mixture, and ignite it in a manner similar to the four-stroke engine. It is extremely difficult to create either homogeneous or controlled stratified mixtures in the short time available. This is a significant challenge compared to the four-stroke engine in which fuel/air mixing in the inlet manifold and cylinder during the intake stroke occurs. Even slight problems with mixture formation can lead to high HC emissions, although not as high as the carburetted two-stroke.

Today, the industry is engaged in intense development of this engine. Most work is highly proprietary with little public discussion. A very few organizations such as the Orbital Company from Australia have, however, been aggressively attempting to market their technology and consequently, been very vocal.

The two-stroke engine can be operated with several variations. The simplest uses the downward stroke of the piston as a pump to scavenge the cylinders, while others use an external blower. Valving, in the most basic design, is accomplished by the piston alternately covering and uncovering inlet and exhaust ports in the cylinder wall, while others use conventional type poppet valves. In any case, all elements of the operating cycle (intake, compression, power, and exhaust) are accomplished in 360 degrees of crank rotation compared to 720 degrees in the four stroke. This gives rise to the basic size and weight advantage of the engine; it uses its internal displacement volume twice as effectively as the four stroke. Potential advantages of small size, light weight, and probably lower cost in vehicle applications are substantial and indeed could bring a revolution to vehicle design. From a strategic standpoint if a given manufacturer were to conclusively resolve key problems, the competitive advantage could be significant.

Fuel economy could be about 10-20% greater than a four stroke due to significantly lower friction (no valve train, lower ring tension, and reduced number of components) and vehicle size and weight reduction.

However, serious problems remain. The exhaust gas contains oxygen (from scavenging) which would make a chemical reduction reaction to control NO_x very difficult. Furthermore, excessive HC emissions may be difficult to control due to lower exhaust temperatures and higher initial HC content. Long term durability and engine lubrication are also tough but probably not fundamental barriers. Orbital has demonstrated compliance with Federal emission standards in prototypes but tougher emission standards could be a serious challenge.

Blowby gases sometimes are directed to the airbox and oil consumption may be relatively high. This could cause problems with HC emissions. Without variable valve port timing, blow down losses are high compared to four-stroke engines. Also, the nature of HC emissions may be different from four-stroke designs, suggesting a need to conduct AMES tests to determine exhaust gas mutagenicity.

It is extremely difficult to assess the probability that the two-stroke will emerge as a viable alternative, but optimism is growing even among many skeptics. The odds for development of a commercially viable automotive two-stroke may be around 50%.

Diesel Engine

The diesel engine is hardly a stranger to light-duty vehicle applications throughout the World, with extensive use in most areas other than North America. Diesel use has been prompted by its excellent fuel economy and frequently by incentives such as lower fuel cost.

We are pessimistic about prospects for the use of diesels in North American light-duty vehicles during the next 20 years. Enthusiasm for the diesel has faded dramatically since the early 1980s for a variety of reasons, including poor execution on several automotive diesel engines. However, the primary reasons for loss of interest include high initial cost, smoke, odor, noise, excessive weight, poor performance, and reduced customer value of better thermal efficiency.

There is no question that the diesel offers significant fuel economy advantages, particularly in an open chamber or direct injection (DI) diesel configuration. The prechamber or indirect injection (IDI) diesel, which has been the standard automotive diesel, is generally superior to the spark-ignited engine, but is no match for the DI engine. It appears that the DI engine is on the threshold of light-duty vehicle commercialization in Europe.

A significant part of the diesel's fuel economy advantage is derived from the greater density of diesel fuel, leading to about a 10% efficiency advantage over an S.I. engine. The IDI diesel appears to be about 10% better than an S.I. engine, discounting fuel density considerations, and the D.I. an additional 10% greater. Further significant efficiency improvements are possible if a low heat rejection (LHR) diesel can be perfected, but little incentive seems to be evident for use in light-duty applications. Special materials, processes, and generally more sophisticated componentry, suggest this technology is more likely to be applied to heavier-duty commercial applications. Tough barriers remain that call for considerable effort before the LHR diesel can be commercialized.

Perhaps the most basic long range challenge facing light-duty diesels is emission considerations. The engine produces a far higher level of soot or particulate matter than the gasoline engine, although external control (traps) with an optimized injection control strategy and/or fuel property adjustment may provide acceptable results. Fundamentally the diesel must operate lean (excess O_2) which creates an almost insurmountable problem for after-engine treatment of NO_x. It does not appear the diesel will be able to meet the tough proposed NO_x standard. Even the expected tighter HC and CO standards may be very difficult to meet because of durability problems with using oxidizing catalysts and lower exhaust gas temperatures despite plenty of O_2 available for oxidation.

Today there is little diesel interest in North America. The light-duty diesel research is largely in Europe and Japan. Unless a significantly different energy price, availability, or emission regulatory scenario emerges, the diesel is an unlikely alternative for light duty vehicles in the next twenty years.

Gas Turbine

Twenty years ago, the gas turbine or Brayton cycle engine, was viewed as being 10 years away from application in light duty vehicles. Today the turbine is at least 15-20 years away in the opinion of most engine specialists. Despite important developments in materials, heat exchangers, and other factors, the conventional S.I. engine is a formidable moving target. The downsizing of passenger cars and engines has proven to be a particular challenge for the turbine, since it is not readily downscaled. Below 200 bhp engine size, aerodynamic losses are significant and micro-precision manufacturing is needed.

Several different configurations have been proposed for the gas turbine engine, including a single and twin shaft designs. The twin shaft appears to be the most practical. It consists of a gasifier turbine (for compressing air) which is driven by one shaft. The hot gases continue to expand through a second turbine stage (power turbine) which drives the output shaft. To achieve even modest levels of thermal efficiency the low pressure ratio automotive gas turbine requires a heat exchanger or regenerator to recover exhaust heat which is transferred to the compressed air exiting the gasifier turbine. Advanced ceramic materials in the gasifier turbine have permitted higher peak cycle temperatures, resulting in improved efficiency. Problems remain and the technology is not yet commercial. Furthermore, even with an excellent regenerator and high temperature turbine alloys, fuel economy is still a problem, particularly at light load. The typical passenger car driving cycle consists of relatively little high load operation, where the turbine is at its best. Variable geometry turbomachinery

14

aids both partial load economy and throttle response, but even in advanced concept designs fuel economy is a serious practical limitation.

Additional concerns with the turbine include significant transmission speed reduction to accommodate the high shaft speeds and the high cost associated with the complicated, micro-precision components and generally expensive materials and processes.

The turbine, of course, possesses some important advantages, including multi-fuel capabilities (no cetane or octane needed), only coolant as working fluid and developing maximum torque at stall. Furthermore, emissions are low in comparison with an S.I. engine without external emission control. However, meeting proposed future emission regulations appears to present a potentially fundamental challenge. This is particularly true with NO_x emissions which are very difficult to reduce chemically in the oxygen rich exhaust characteristic of the turbine. Hydrocarbon emissions during engine transients are a problem, and low exhaust gas temperatures cause difficulty with cleanup. Catalytic exhaust treatment does not seem to be feasible.

While a modest level of research on light duty turbines continues throughout the world (sponsored by both private and public sources), there is little enthusiasm for even small scale use in passenger vehicles. The general uncertainty of future automotive-related environmental regulations is precluding any consideration of serious investment in alternative power plants.

Spark-Ignited Stratified Charge

History. Since the 1950s, low level but continuous work has been going on to develop a spark-ignited stratified charge engine. Major players have been Texaco, Ford, and General Motors. While the concept of stratified charge is quite old (Otto's engine was stratified), the work of Mitchell at Texaco brought it to the attention of the engine community in the 1950s. In the Texaco engine direct cylinder injection was used with a single hole nozzle. The air charge was caused to swirl about seven times faster crank than speed by intake port shape. There was no throttle, and fuel was injected to produce the desired load. Since there was no end gas (theoretically), there was no knock or octane requirement. Thus somewhat higher compression ratios of about 11:1 were attempted. Significant economy gains were realized due to minimal

pumping losses and higher compression ratios. Some octane requirement was noted, apparently due to in-cylinder air/fuel mixing. The problems were:

- High HC emissions from lean flame-out zones
- Low bmep, due to smoke limits and volumetric efficiency loss from the shaped port
- Some bad news from the AMES test.
- Some aldehyde emissions.
- High cost of injection equipment
- Erratic ignition

The problems (except ignition) were similar to those of the diesel, and for the same reasons. Heterogeneous combustion at the low compression ratios of the Texaco engine did not produce complete burning, and the lean mixtures did not lend themselves to exhaust treatment devices due to low temperatures. The ignition problem resulted from the combustible mixture not being in the spark gap when the spark occurred. The mismatch was different at different speeds, since the air swirl changed, but the plug location relative to the injector was fixed.

Around 1960, Ford became interested and much development work was done by Bishop. In an attempt to reduce cost, a lower cost injector (about 100 psi pressure) was developed for injection early in compression. A second spark plug was added to improve reliability of ignition. Finally, some throttling at light load was added to increase exhaust temperatures so that a catalyst could be used. Still, HC emissions were high, and in an era of new emission regulations the program slowed. In 1979, Ford announced that a production version would be forth coming. However, the problems of manufacturing with the required precision to meet emission standards were never solved.

While the stratified engine was moving in the direction of the conventional engine (less stratification, throttling) the homogeneous four-stroke gasoline engine was improving. The addition of EGR lowered manifold vacuum and thus pumping losses, achieving some benefits of stratified charge. This further lowered the incentive to work on stratified charge.

General Motors worked on stratified charge of the Texaco type for many years and still has a modest effort. HC emissions were always a problem and there never seemed to be much enthusiasm at GM. UPS and Texaco developed a prototype fleet of delivery trucks. Fuel economy and low fuel octane requirement were the likely incentives.

The preceding discussion has concentrated on the direct injection, open chamber type of design. During the 1970s several groups worked on prechamber engines. Here stratification was easier to achieve. The Honda CVCC is the best example. Extremely lean operation was not achieved and the fuel economy and emissions were similar to existing engines. The cost was higher, however. Apparently, the greater heat losses of the prechamber design almost balanced any economy gain from lower pumping losses. With the oil embargo of 1973, interest in this engine disappeared.

Recent Developments. In the mid-1980s Toyota and General Motors and several others discovered that the charge in the poppet valve engine could be stratified using port fuel injection. High HC emissions and smoke were early problems. It was learned that if the fuel were injected near the end of the intake stroke, the richer mixture was concentrated near the head end of the cylinder, with the piston end lean. This stratification was easy to achieve as opposed to the Texaco type which was circumferential. The poppet-valved engine has much mixing circumferentially, but not axially. Thus, circumferential stratification is not really practical (with this type of valve) whereas axial stratification is possible. This is the principle behind the Toyota lean burn engine.

Future Prospects. HC emissions will limit the application of the Texaco type process. The Toyota process will be limited by the application of a catalyst which operates at the lower temperatures of the unthrottled engine. With good port heat conservation, and a catalyst placed close to the engine, the axially stratified charge is a possibility. Catalyst life is always a problem in such configurations. The benefits of axially stratified charge would be:

- Elimination of EGR system, for NOx is low with lean mixtures
- Probably some gain in octane requirement
- Some greater ability to burn methanol, a fuel with low volatility which does not burn with a sooty flame
- A modest gain in fuel economy because of reduced pumping loss

Concluding Comments—Stratified Charge

The conventional gasoline engine has been a moving target over the years. There is much less pumping loss today than 20 years ago due to EGR. But advances in fuel injection equipment, electronic fuel controls, ceramic insulation and precision manufacturing may make axially stratified charge production possible and even desirable. The direct injection, open chamber and prechamber types of stratified charge engines are not of much interest today. The development of an alternative to the poppet valve could revive interest in the Texaco type engine, if circumferential mixing were less strong. The prospect for further tightening of

emission standards is likely to reduce the incentive for stratified charge engines. From a fuel economy standpoint, a good stratified charge engine could yield efficiency gains on the order of the diesel, 10-20% over today's "good" spark-ignited engines.

Section Two: Barriers and Driving Forces

Summaries of the future prospects of the alternative engine technologies and further developments to the traditional four-stroke technology reviewed in Section One are shown in Tables One and Two.

Table One reviews likely improvements in fuel economy and emissions, and the status of current and future research activities for developments of the traditional 4-stroke internal combustion engine. Four of the listed developments are rated as "certain" in the next ten years, not only in terms of further development, but also in terms of market application to light motor vehicles. The remaining improvements receive at least a "probable," with external boost only limited by its high production cost and declining popularity in the marketplace.

Table Two contains similar ratings for the four major alternatives to four-stroke technology. As shown, major barriers exist for each of the technologies regarding their current and future performance in meeting emissions standards. Emissions performance is so significant as a barrier that it may be the critical factor in the low level of development activity for these alternative technologies, now and in the future. Only two-stroke technology possesses any significant likelihood of commercial feasibility in the next ten years.

An important conclusion, then, is that improved variants of the conventional four-stroke will remain the predominant technology for light-vehicle use well into the 2000-2010 period. The key barriers to the traditional and continued use of four-stroke engines, barring any massive and unexpected increase in fuel cost, are future emission and fuel economy standards mandated at both federal and regional levels. It is difficult to make judgments concerning the effect of these barriers at this point because of the uncertainty regarding final mandated levels or their format. New clean air legislation, of course, has been debated in the U.S. Congress for a matter of months now, with separate proposals issued by the House, the Senate and additional guidance from regulatory officials. One recent version of the Senate bill calls for a first round reduction in tailpipe emissions to the 0.40 gpm level for NO_x and 0.25 gpm for HC by 1993. The questions of which vehicles would be affected by these levels, or whether compliance is only necessary in a specified list of "polluted, high ozone" cities are less clear.

		RESULTS		
DEVELOPMENTS	Fuel Economy (compared to current engine)	Future Mandated Emission Standards	Current Development	Future Development
Engine Structure (reduced weight)	Small improvement from reduced weight.	Small improvement from reduced weight.	Large and ongoing.	Certain.
Fuel Management	Single and multi-point electronic fuel injection may increase fuel economy by 1 to 4% in future.	Small improvement from improved fuel economy. Reduction in HC and NO_x possible with improved cold start vaporization.	Large and ongoing.	Certain.
Ignition System	Some improvement for longer-service vehicles.	Not clear.	Ongoing.	Probable.
Combustion Chamber Improvements	Some improvement in fuel economy (1 to 2%).	Modest improvement in HC and perhaps NO_x.	Ongoing.	Certain.
Variable Valve Lift and Timing	Friction problem. However, fuel economy increases of 5 to 8%.	Modest improvement in HC and NO_x.	Picking up steam.	Probable.
External Boost	Modest improvement over larger engines.	Slight improvement.	Ongoing.	Only 5% operating use by 2000. Expensive.
Advanced Engine Materials	Possible 2 to 4% reduction in fuel consumption.	Some effect to lower emissions.	Ongoing.	Probable.
Improved Electronic Control	Modest.	Modest.	Ongoing.	Certain.

Table One
IMPROVED 4-STROKE ENGINE

	BARRIERS			
TECHNOLOGY	**Fuel Economy (compared to current engine)**	**Future Mandated Emission Standards**	**Current Development**	**Future Development**
Two-Stroke	+ 10 to 20% (maybe more with vehicle changes) increase in fuel economy over conventional 4-stroke.	Excessive HC emissions. NO_x difficult to control to very low levels. Tier II emission standards are a severe challenge.	Prototypes exist. Intensive development effort is occurring.	50% chance of commercial viability.
Diesel (Light-Duty)	No problem. +10 to 20% increase in fuel economy available over S.I. engine. There are issues of high cost, particulates, odor, and noise problems.	High soot and particulate emissions. NO_x very difficult to control. Serious problems with proposed NO_x and even HC regulations.	Active programs around the world. Very little activity in North America.	None projected in North America for light duty use.
Gas Turbine	Problem with fuel economy at light loads. Uses cheaper fuels. Very expensive to produce.	Difficulty in controlling NO_x and HC to very low levels. Catalytic exhaust treatment not feasible.	Modest level of research being performed.	None projected.
S. I. Stratified Charge	Current, advanced versions could achieve 10 to 20% gain in fuel economy.	Relatively low NO_x levels are achievable with axially stratified charge. Tough HC problem. Emission control is difficult, may not meet Tier II requirements.	Modest programs at GM, Ford, Texaco, and Toyota.	Axially stratified charge possible in production in approximately 10 years. Some 2-cycle engines in fact are axially stratified.

Table Two
Alternative Engine Technologies

A useful exercise for this essay, then, is to gauge the likely performance of improved four-stroke technology (ICE) in terms of meeting a consistent proposal for strict emissions levels in the near future. Recent proposals under consideration by the Air Resources Board of the State of California, and even more succinctly, those proposed before the South Coast Air Quality Management District (SCAQMD) may (perhaps unintentionally) prove to be useful, if drastic, yardsticks for this purpose. If four-stroke technology, even with the use of improved fuels, cannot practically meet these proposed and layered standards, then the full implications of ICE non-compliance would have to be confronted by these public agencies.

The future emissions performance of ICE will depend to an important extent upon future developments and applications of catalytic exhaust emission control technology. This essay will begin with a description of the current status of this innovation, and most importantly its likely future development for the purpose of providing improvements in emission performance for four-stroke engines. The essay will conclude with a review of the technical feasibility of four-stroke using the most advanced catalytic technology foreseen, in terms of achieving the TLEV/LEV/ULEV standards proposed by various agencies in California.

Catalytic Exhaust Emission Control

The catalytic converter has been the single most important development in emission control technology. Prior to automotive catalytic exhaust treatment most of the burden of exhaust clean-up was placed on the engine with both design and operating variables optimized for minimum emissions. This generally resulted in significant compromises in fuel economy, driveability, and performance. Even if modern electronics had been available in the early 1970s, these compromises would still have been substantial. Basically the catalyst removed a large share of emission control burden from the engine, permitting optimization for other performance parameters. In fact, the present tough Corporate Average Fuel Economy (CAFE) standards would probably be unachievable in vehicles with the range of attributes available today.

The early catalytic exhaust system was primarily used for oxidation of unburned hydrocarbons (HC) and carbon monoxide (CO). Engines were run lean and/or air injection was used to create an oxidizing environment. With the advent of low nitrogen oxide (NO_x) emission requirements the three-way catalytic system was introduced. It was called three-way because it enabled simultaneous oxidation of CO and HC and chemical reduction of NO_x. To permit both oxidation and reduction in the same environment, the fuel/air mixture must be

controlled in an extremely narrow range around the stoichiometric value. Closed loop feedback control of mixture ratio is necessary. Consequently, sophisticated computer based electronic systems are required and are a fundamental feature in the emission control strategy of modern engines.

Development and implementation of the early catalytic exhaust systems prompted one of the most important shifts in fuel composition in modern times with the mandated introduction of unleaded gasoline.

Early catalysts used either catalyst coated beads in a bed through which exhaust gas flowed or a coated monolithic support. Today's catalytic reactors largely use a monolithic configuration that facilitates packaging in the vehicle and system durability. Refinements over the years have been considerable and modern systems have proven to be quite effective and durable if maintained properly.

The essence of a catalyst is that it functions to enhance desired reactions without (hopefully) being consumed in the process; thus, the need for stable, noble metals. The catalyst is dispersed in virtually atom sized particles which are close enough together to be within the atomic dimensions of the reacting particles. The catalytic material is supported on a ceramic substrate which is in turn supported by either a metal or ceramic base structure.

The automotive catalyst problem is unique in that the testing process requires emissions to be measured from a near room temperature cold start. This is different from most process catalysts which operate continuously at steady state. Since the emission test is of limited duration (about 20 minutes), the total emissions arise from a combination of the initial cold start portion of the test (about 8.5 minutes) and the balance which is basically quasi steady, fully warmed-up. A very large catalyst with great thermal inertia will warm up slowly, thus being relatively inefficient. On the other hand a small catalyst will warm up quickly, but steady state breakthrough is a problem. To further complicate the automotive problem, normal road vibrations can break up the support structure. Thermal cycling is also a problem in this respect. Thus the successful automotive catalyst is of finite size, and must be durable.

The catalytic process is said to occur in seven steps:

1. Diffusion of reacting species from the bulk exhaust gasses to the catalyst pore entry.
2. Diffusion into the pore.
3. The reacting specie "jumps" (is absorbed) onto the surface by attaching to an active site (particle of catalyst).
4. A reaction occurs on the surface between reacting species on nearby active sites.

5. The products then desorb back into the pore "jump-off."

6. They diffuse out to the pore entrance.

7. Finally, they diffuse back to the bulk exhaust gasses and are swept out the exhaust pipe.

These seven steps occur in series. The slowest limits the entire process. It is important to note that steps 1, 2, 6, and 7 are diffusion processes. These are limited by fluid mechanic considerations such as turbulence and channel geometry. They are weak functions of temperature. Steps 3, 4, and 5 are termed the intrinsic kinetics and are strong functions of temperature. Clearly, during low temperature operation, the intrinsic kinetics are slow and govern the reaction. The free stream concentration can easily fill the pores; and thus there is no diffusion limitation to reaction. At high temperature the intrinsic kinetics are essentially infinitely fast (relatively), and the process is limited by diffusion. The dual nature of the catalytic process coupled with the cold start problem presents another major design conflict.

Many materials are good catalysts for automotive exhaust pollutants including nickel, copper, and iron compounds. The problem is that the sulfur and other trace fuel contaminates (lead, phosphorus, and additives [MMT]) and lubricant additives (phosphorus, zinc, and alkali earths) together with engine wear materials (iron, nickel, chromium, and copper) chemically react with these base metals. The noble metals of platinum, rhodium, and palladium resist chemical reaction and a few grams on a support surface can reduce hydrocarbons, carbon monoxide, and nitric oxides by 70 to 80%. This conversion efficiency, coupled with reasonably good in-cylinder control through design and EGR allows meeting current standards.

Over time, even these noble metal catalytic materials lose activity. One failure mechanism is repeated over-temperature, above $1,500^\circ F$. This causes migration and agglomeration of active sites thereby reducing their number. It may also lead to partial or total pore closure. Very high temperatures in excess of $2,000^\circ F$ can lead to substrate failure and breaking up of the catalyst. Because the catalyst is a good thermal insulator, any excess fuel reacted reaches its adiabatic flame temperature almost instantaneously. Thus excellent fuel/air ratio control is a key to limiting catalyst deterioration. Contaminants such as TEL and MMT deactivate the catalyst by plugging the pores and channels.

Newer design catalysts place the catalyst materials at selected depths within the pore, with each constituent having its own optimal depth. This increases the efficiency of the

.

reaction relative to the mass of catalytic material and minimizes the loss in activity, since there are few active sites near the pore entrance where poisoning is more likely.

Current catalysts tend to be relatively active with more reactive species including higher molecular weight hydrocarbons and not efficient with methane. An approximate reaction efficiency with the different hydrocarbon classes for one feed gas and catalyst composition is suggested below. Feed gas composition varies somewhat with fuel consumption and conversion efficiency with specific catalyst formulation and length of service.

	Exhaust Feed Gas Percentage	Conversion Efficiency Percentage	Remaining Percentage
Olefins	30	100	0
Aromatics	50	90	5
Acetylenes	5	100	0
Paraffins	10	50	5
Methane	5	0	5
	100		15

In the above example, the net efficiency is 85% of which 1/3 is methane. A methane exemption results in a 33% reduction in the remaining hydrocarbon emissions. If the feed gas is 2 g/mi HC, the output after the catalyst is 0.3 g/mi or 0.2 g/mi with the methane exclusion, a significant difference.

Today there is great concern over the supplies of these precious metals, since major sources are South Africa and Russia. If prices rise there will be a move to recycling used converters for both the precious metals and even the stainless steel container. The need for an extremely low contaminate fuel is likely at very low HC requirements to ensure minimum deterioration.

Low Emission Vehicle Possibilities

The State of California has called for future low emission vehicles in three categories: transitional low emission vehicles (TLEV), low emission vehicles (LEV), and ultra low emission vehicles (ULEV). Partial standards are given below in terms of grams/mile on the Federal Test Cycle. Standards are proposed also for benzene and formaldehyde.

	NMOG*	NO$_x$	CO
TLEV	0.125	0.4	3.4
LEV	0.075	0.2	3.4
ULEV	0.040	0.2	1.7
* Non-methane organic gases.			

A significant portion of the aromatics, which include benzene, are thought by some in the technical community to be traceable to the fuel. Thus elimination of the benzene from the fuel may help achieve the stringent requirement of very a low exhaust benzene level. We do not have enough experience with formaldehyde emissions to comment intelligently on the recommended levels, although formaldehyde responds reasonably well to catalytic treatment.

In our opinion, meeting the TLEV levels is likely with an extension of the current emission control system. In fact, good emission control systems today are probably capable of meeting these standards particularly when methane is excluded from the HC measurement. Obviously considerable refinement and attention to detail would be necessary in a typical system and some vehicles may have a difficult time. Deterioration with mileage may also be a problem, but with carefully controlled fuel quality and proper maintenance this should not present an insurmountable challenge.

We are considerably less optimistic with regard to the LEV and ULEV standards. Numerous discussions with industry experts have generally found little confidence that these standards can be achieved in production and even consistently in "one of a kind" special demonstrations. While CO is not likely to present a great challenge we are uncertain about both the HC and NO$_x$ emissions. Even with heroic measures, it may not be possible to meet either HC or NO$_x$ requirements with gasoline type fuels or with the so called "clean" fuels although methane, propane, and the alcohols may permit attaining LEV requirements.

Hydrocarbon emissions from present control systems are primarily associated with the early stages of the test cycle where richer mixtures are required for starting and the catalyst has not reached its "light-off" temperature. Gaseous fuels should greatly aid combustible mixture formation but "light-off" would remain a problem. Even the best catalyst is not perfectly efficient at HC oxidation and some level of HC emissions is likely.

Nitrogen oxide emissions, on the surface, would not seem to present a particularly onerous task since the new standards represent only a 50% reduction from the TLEV levels. However, past experience suggests that this level is indeed a problem. The challenge of

sustaining both an oxidizing and reduction reaction in the same general environment is substantial, particularly at the high conversion efficiencies required. Below are some thoughts on methods of attempting to meet those difficult standards.

Advanced Technology to Meet LEV and ULEV Standards.

While there is considerable uncertainty whether an IC engine powered vehicle can meet the rigorous standards for the LEV and ULEV, it will be necessary to have very low engine out emissions coupled to a very efficient catalyst. Low engine out HC emissions are achieved by much better fuel injection atomization (high pressure, air assist) and attempting to keep fuel out of the top ring land crevice area by axial charge stratification. Obviously a gaseous fuel or external assist with vaporization of a liquid fuel would be helpful. A gapless piston ring could be of value together with the use of a single ring piston. A surface-gap spark-plug could probably help by eliminating the quench region around the center electrode. Elimination of exhaust valve leakage by better valve and seat design will be needed. An engine without a head gasket should be a step in the right direction to further minimize crevice volume. Good heat conservation will also help although octane requirement may be exacerbated. This translates into minimum combustion chamber surface area and probably exhaust port liners of some type. Ceramic coatings have been suggested. A fuel which produces fewer hard to combust hydrocarbons may help, such as lower aromatic content. The engine design changes suggested above are already incorporated to some extent in current engines, but a true systems approach with respect to emissions might yield a considerable improvement over current designs.

Low NO_x is difficult to achieve within the engine. Reducing flame temperature is the conventional means. This suggests more EGR and perhaps stratification of fuel/air charge and EGR. Reducing fuel aromatic content should lower flame temperature a little and the addition of methanol or other alcohols would also help reduce flame temperature.

The catalytic converter will have to be significantly more efficient. This probably means greater precious metal content and larger converter beds. To reduce or eliminate the cold start "light-off" problem, good heat conservation will be required. Probably clever insulation and isolation of the converter could help eliminate the cold start penalty, at least within a 24 hour time span. Electrically heated catalysts have been proposed which would require significant electrical current and time to achieve catalyst warm-up with a cold engine. Molten salt thermal storage is an alternative. Perhaps a combination of an insulated bed and heating

can be used. The technology is not revolutionary but substantial engineering is required to assess both the technical and commercial potential.

With any emission control strategy proposed for LEV or ULEV standards, overall quality control of the engine and fuels must be outstanding. Traditional levels of tolerances would probably be unacceptable if modified IC engines are to even have a chance of meeting the standards. Furthermore, on-board monitoring of system performance will undoubtedly be required.

With substantial reduction of fuel contaminants (primarily sulphur and other non-organic, non-oxygenated fuel components) it may be possible to use more base metals in the catalyst. This may be possible with pure methanol as the fuel. A M-85 blend would probably contaminate a base metal catalyst unless the fuel were cleaned up. Perhaps a "guard" catalyst could help protect a base metal catalyst.

(Caution: HC and CO do not leave the cylinder uniformly. There is a concentration profile. Placing the catalyst too close to the engine to maximize temperature could result in emission break-through.)

Section Three: Summary and Further Monitoring

We believe TLEV requirements can probably be achieved with refined existing technology. Meeting the proposed LEV and ULEV standards may or may not be possible. There are no simple, cost-effective solutions apparent at his time. On the contrary, all of the easy, inexpensive things were done years ago. With the significant uncertainties of the IC engine attaining both LEV and ULEV standards, it would seem desirable to initiate a special joint initiative to demonstrate just how emissions can be reduced and at what cost and complexity. This effort could arise through a refocusing of a portion of the ongoing joint study pact between the domestic automakers and the major refiners, which it is our understanding has been concentrated, to date, on research into alternative fuels. Whatever the source of the initiative, it should use the best of present and advanced four-stroke technology and should preferably involve a joint effort between energy and auto companies, academia, and government.

It is not an easy task to comprehensively monitor key future developments in four stroke and other alternative IC technologies, and their likely performance in meeting future emissions and fuel economy standards. Our final conclusions lead us to believe, however, that

such a monitoring process is critical for the purpose of forecasting significant changes in the use of current and future IC power plants. An effective monitoring of ICE development is also important in evaluating the future prospects of other land transportation systems (EV, IVHS, and Mass Transit). For it is the relative success of ICE technology to meet future regulatory and consumer demands in the market and political arenas that will ultimately determine the need for such substitutes or radical alterations in traditional American transportation.

A practical monitoring plan for keeping current on feasible developments in ICE would contain several elements. There are indeed a number of key organizations, both public and private, with individuals who possess and make it their business to acquire the latest technical and political knowledge on developments in ICE. It is also true that no single organization or individual is aware of all development activities worldwide. We recommend that Chevron establish an ongoing relationship with at least one engineering director from the Big 3 and one similar individual from each motor vehicle industry in Europe and Japan, for the purpose of sharing information on ICE development in these three regional motor vehicle industries. We should point out that these individuals cannot usually impart or reveal advanced proprietary information concerning the actions of their company. They can discuss, however, likely trends in their domestic industries. In addition, we also recommend that similar contacts be established for the same purpose with the Environmental Protection Agency, the Department of Energy and the Department of Transportation in the United States. These latter political contacts should provide a critical government viewpoint on developing environmental and fuel economy regulations, as well as a bureaucratic perception of private sector efforts to balance both consumer and regulatory demands for engine performance.

The identification and cooperation of important information contacts represents only the first step of an effective monitoring process. A second important step is the editing and organization of this information into a useful format or model that can efficiently and thoroughly inform key decision-makers and technical staff at Chevron on a regular basis. We recommend that the status of four-stroke and two-stroke IC technology be updated on an annual basis, and that the status of the other alternative engine technologies be updated on a biannual or longer basis. The status parameters should include such issues as ongoing research, market feasibility and penetration, and likely performance on current and future proposed emissions and fuel economy standards. At some point it would be highly useful to estimate the actual effect the large scale use of these technologies would have on petroleum fuel demand in the United States in the 2000-2010 period.

We do recommend the following contacts for an essential starting lists of key informants in any monitoring process:

- **Environmental Protection Agency**, Emissions Testing Laboratory, Ann Arbor, Michigan. This is the principal federal laboratory that tests engines and fuels on an ongoing basis for emissions and fuel economy performance. Many prototypes are eventually tested here. Charles Gray, the Director of this program, is a suitable contact.

- **Department of Energy.** Robert Larsen or P.D. Patterson are informative contacts for this federal department. Various programs on alternative fuels, heavy-duty advanced diesel engines, and energy conservation are managed or performed by these individuals through the Argonne National Laboratory.

- **Oak Ridge National Laboratory.** The Centers for Transportation and Systems Research and the Energy Division perform and frequently sponsor studies for the Department of Energy's Office of Transportation Systems.

- **Domestic Motor Vehicle Manufacturers.** The directors of the respective engine or powertrain research programs are highly recommended. At General Motors, N. E. Gallopoulous, Manager of Engine Development Research, or Thomas G. Stephens, director of engineering for the new GM Engine Division; at Ford, N. A. Gjostein, Director of the Powertrain and Materials Research Laboratory ; at Chrysler, Thomas Asmus, Advanced Engine Research Department.

- **Foreign Manufacturers and Governments Research.** We certainly recommend the directors of engine development programs at such companies as Toyota and Volkswagen as important contacts. We do not feel that much information about important developments can be gathered from their operations in North America. While European producers such as Volkswagen and Fiat have been relatively open in the past, it can be certainly be said that this is not the general case for the Japanese.

- **Society of Automotive Engineers, Passenger Car and Powerplant Activities, Engine, Advanced Powerplant, Diesel Engine, and Small Powerplant Committees.** A good initial contact is Donald Patterson (co-author of this essay) who is the chairman of the engine committee, passenger cars, SAE. SAE staff contact for passenger car activity is M. J. Asenio Jr., and for powerplant activity, Gordon Wright. The SAE reviews, publishes, and coordinates development conferences and workshop sessions on powerplant development and performance.

- **Office for the Study of Automotive Transportation, (OSAT)**, The University of Michigan Transportation Research Institute, Ann Arbor. Our office is the only active, academic research office in the United States for the sole purpose of research, conference, and liaison activity connected to the motor vehicle industry and automotive transportation. The office regularly interacts and cooperates with all of the contact suggestions listed above, and performs contract and internal research (such as the Delphi Forecast and Analysis of the U.S. Automotive Industry) on future technical change in the motor vehicle industry. The office is partially supported by

corporate sponsors who are now being enlisted as affiliates. This status generally entitles the participating organization to the full range of OSAT publications and products (such as the engine product planning directory), special attention from staff regarding information and contact requests, and an active role in the planning of the OSAT research agenda on an annual basis. OSAT's purpose and goal is to function as an objective, neutral clearinghouse for information, and as a source of original research related to the motor vehicle industry and automotive transportation.

OSAT normally monitors the development of a wide variety of automotive technologies through its Delphi and other research activities. For example, OSAT performs contract research on special topics or issues of interest to Office sponsors. OSAT cooperates on both ongoing or ad hoc bases to meet special information needs for sponsors, either through the internal resources of OSAT staff or through the assistance of Office associates located in the academic, consulting, and industry research areas of activity. Future powertrain development, as well as the development of the automobile in general, are special continuing focuses for OSAT. We would welcome future opportunities for and believe we can make unique contributions to research programs on technical change in ICE development and the special challenge of alternative vehicles such as EV and EHV.

Chapter Three: The Significance of Intelligent Vehicle-Highway Systems (IVHS) for the Future of Motor Vehicle Travel in the U.S.

Robert D. Ervin
Transportation Research Institute
The University of Michigan

Section One: Current Status

Overview

Intelligent Vehicle-Highway Systems (IVHS) represent a concept by which information and control technology will be introduced in many novel ways to make motor vehicle transportation safer and more efficient. In its generic form, it will use electronic communication between vehicles and the roadside—in behalf of automated route guidance, toll collection, hazard warning, fleet dispatch, directory for commercial services, collision avoidance, and other functions and eventually including even automated driving, with full-time automated control. Such features would come into usage on an incremental basis, with a trend to more favorable cost/benefit ratios with each added feature due to economies of synergy.

The concept has growing advocacy from the transportation community as highway systems become increasingly stressed because of travel demands that exceed highway capacity. Because the largest stresses are in metropolitan areas where further road construction is increasingly infeasible, conventional means of solving our major traffic congestion problems cannot be identified. Metropolitan areas will, thus, be subject to increasing distress unless at least the commuting needs of the workforce can be met through new approaches to the congestion problem.

Although a compelling justification for IVHS can be argued simply because of the public need, or "problem" side of the equation, there is also strong private side interest in the IVHS concept among commercial firms who sees business opportunity in new products and services. In Europe the primary driving forces for IVHS come from the private sector; in Japan, the impetus balances between public and private; and in the U.S., the dominant driving force comes, so far, from the public side.

In any world region, the realization of improvement in highway travel via IVHS technologies calls for both new infrastructures and mass purchase of compatible, in-vehicle, packages. The feasibility of IVHS ultimately hinges upon this odd market dynamic. The

enabling infrastructure is presumably financed through public dollars and the in-vehicle elements paid by individuals with their own money. Therefore, attempts to predict the rate of penetration of IVHS implementations into everyday usage are highly speculative.

At a minimum, however, it is fair to say that no nation will adopt IVHS without forming an effectively permanent public/private collaboration to produce standardized, expandable, and popular systems. On the assumption that such collaboration will begin in earnest in the U.S. by 1992, an ad hoc American group called Mobility 2000 has been formed to lay the groundwork for a national IVHS program in this country. The predictions of this group provide a crude view of the possible rate of IVHS deployment and will be briefly summarized later.

Before addressing the development of IVHS, however, it is useful to first consider the magnitude of the highway transportation problem from the perspective of those who are promoting IVHS from within the U.S. DOT establishment as one of very few avenues of solution to the congestion problem.

The Problem with Highways

Motor vehicle travel in the U.S. has increased an average of 4% per year for the last twenty years. Recent projections by the U.S. highway community shows an approximate 2-3% rate of growth in vehicle miles of travel over the next fifteen years. Since even a 2% growth rate is well above the rate of expansion in highway capacity, however (we add about 0.5% more lane-miles in the U.S. each year), expectations are for a dramatic overloading of the U.S. highway system into the next century.

As travel volume approaches the designed saturation limit of a given highway, average travel speeds fall quickly and the total accrued delay to motorists goes up exponentially. Since many large urban areas in this country are approaching the saturation volumes on their freeways during rush hours, it is not surprising that a recent Federal Highway Administration report sees traffic delay on U.S. highways growing 400% from 1985 to the year 2005. Thus, the commuter who experienced 15 minutes of typical delay in 1985 will suffer a 1-hour delay every day, fifteen years from now.

The accident rate is also predicted to rise rapidly although the largest increase will involve the collision-types peculiar to dense traffic, in which lesser risk of death and injury prevails. Although the severity of such collisions is lower, their occurrence in increasingly

dense traffic becomes a feedback mechanism that tends to spawn more accidents and produce tie-ups longer in duration and more extensive in terms of the total highway miles affected by the disruption. .

Ultimately, it is feared that as the delay burden becomes greater and greater, workplaces will move, urban property values will decline, the urban tax base will become stressed, and the search for remedies to highway congestion will become highly politicized. Because the problem will become acute in some, but not all, urban areas, the grasping at remedies may be made more volatile due to the need for local solutions, to the exclusion of national resolutions.

Although the emphasis will be toward congestion relief for commuting, which accounts for only 35% of all motor vehicle travel, this part is toughest to treat since it accounts for the peak loading on the system. Banning of heavy commercial vehicles from Los Angeles freeways during peak-flow hours, for example, is a recent manifestation of this emphasis, though most trucks already avoid the freeway during rush-periods as a matter of choice. It seems inevitable that future steps to treat the problem, without the aid of new urban highway construction, will seek to moderate the peak highway demand, however possible.

The IVHS Option

However, the congestion crisis plays out in a given state or metropolitan region, it seems clear that IVHS-based solutions will be increasingly advocated. However, a key issue resides in the fact that IVHS cannot be applied, like a "Band-Aid." Its real potential for benefit comes when multiple functions are integrated into a robust system—a process which takes deliberate planning and a long time because of the need to penetrate an extant population of vehicles. Thus, it might be asked whether politicized metropolitan environments will be able to sustain the methodical, incremental development of IVHS which is needed for attaining a large payoff. (Of course, it also takes a long time to build urban freeways.)

Investments already being made in Los Angeles, Houston, Dallas, Minneapolis, Seattle, and other large cities will create one element of the urban infrastructure needed for giving motorists route guidance in real time. These so-called "Advanced Traffic Management Systems" (ATMS) will offer, when fully implemented, complete surveillance of the freeway and major arterial street systems to generate motorist advice on the quickest routes. The early means (before the year 2000) by which motorists would become apprised of tieups, with ATMS, is through changeable-message signs along the road or specially-operated local radio broadcast from the roadside.

At present, only 6% of the 19,000 miles of urban freeways in the U.S. are covered by some form of ATMS—almost half of which is in the Los Angeles area. Mobility 2000 has estimated that some $18 billion (in current dollars) will be needed to design and build such ATMS installations in every U.S. city over 100,000 population—a figure about equal to the annual federal expenditure on all highway needs. With the more acute areas beginning to deploy ATMS first, Mobility 2000 foresees deployment of robust ATMS installations in at least the 12 largest U.S. cities by 2000.

The benefit of a fully-developed ATMS infrastructure alone has been estimated to provide about 15% reduction in total travel times. This value grows to an estimated 25 to 40% when vehicles become equipped with special electronics that bring the driver individualized routing instructions, given current location and the desired destination. These "Advanced Driver Information Systems" (ADIS) are projected to reach a 50% penetration of the vehicle population by the year 2010. The value of the congestion relief afforded by ATMS and ADIS deployment by 2010 will be nearly $15 billion per year (per federal schemes for appraising the cost of congestion.)

ADIS packages provide utility well beyond congestion relief, however, with safety enhancement features predicted to reduce the annual national accident rate by 20% in the year 2010. This accomplishment alone, if achieved, would yield a national benefit of $22 billion annually in reduced accident costs, again using federal valuation formulas. Further, the penetration curve rises steeply such that, by 2020, the accident toll would be cut in half, saving $65 billion per year.

There is also an intriguing sidelight to the ADIS package of technologies for exercising direct control over highway demand, should the political climate support such a move. Namely, one of the technology categories provides for automatic vehicle identification (AVI) whereby the roadside receiver instrument reads the code number of passing vehicles. Clearly, it would be straightforward from a technical point of view to use AVI as the means to impose road pricing—a system of toll charges for road usage with a sliding scale of rates based upon the chosen roadway and time of day (as in the pricing of electric power or long distance phone service). Commuters choosing to travel on the main freeways at rush hour simply get a larger bill monthly than does the off-peak user. A road pricing law could be made "revenue-neutral" simply by offsetting its total revenue with an equal reduction in, for example, motor fuel taxes.

Over the very long haul, the ATMS infrastructure and the technology base which is built up through ADIS deployment may enable automated driving systems. With California

being the major proponent for developing this "highway automation" technology, the benefit lies in an ultimate doubling or tripling of highway capacity through tight longitudinal and lateral spacing of fully-controlled vehicles. The California Department of Transportation apparently believes that automation is an imperative, given the enormous over-demand situation and the modest levels of congestion relief available through ATMS and ADIS deployment. Delphi surveys done in the U.S. and Europe predict that automated highways are a long way off—with substantial deployment not occurring until the year 2040. But current indications are that California will pursue highway automation with a good deal of vigor while also being an early adopter of the less robust technologies that IVHS will deliver.

The Prospect for Action in the U.S.

Moreover, arguments are being mounted through Mobility 2000 and much of the rest of the American highway community that IVHS is a primary option for our strategic highway policy. Many see some form of IVHS as inevitable, but shrink from the formidable institutional, legal, and technological obstacles. Others, believing that Europe and Japan are determined to develop IVHS (and sell it to us), contend that the U.S. has no choice but to launch a national program in behalf of its national competitive interest—and for the sake of solving its domestic transportation problem.

The strategic path toward launching a national program in IVHS is the Highway Reauthorization Bill which expires at the end of fiscal year 1991. Thus, a substantial legislative push is well under way to gain Congressional adoption of a national IVHS program. Congress itself requested IVHS policy studies from the Office of the Secretary of Transportation (OST) and the Office of Technology Assessment (OTA). Also, the General Accounting Office (GAO) began its own study in 1989 and the Office of Management and Budget (OMB) has become active recently due to its supervisory role over the release of the OST report cited above. A wide array of lobbying groups and professional bodies have already registered support for a national program, but OMB seems to be opposing it because of the Administration's reluctance to make any new long-term funding commitments. Also, resistance is expected from environmentalist groups who may see IVHS as simply prolonging the era in which automotive transportation is the favored mode for individual movement.

One thing seems clear: without a Congressionally-authorized, collaborative R & D program, with nearly $100 million per year in federal funding, IVHS will go nowhere in this country until the urban transportation crisis reaches the acute stage already appearing in Europe

and Japan. At that point, our foreign competitors hope to have so developed their systems for application at home that they will be well positioned for export to us.

Section Two: Barriers and Driving Forces

Notwithstanding the suggested opportunity for IVHS in North America, substantial technical and non-technical barriers exist. These barriers will be discussed, individually, below, followed by a brief discussion of the forecast.

Technical Barriers

In this section, barriers which impact upon the specific configurement of IVHS installations will be discussed. The factors which will influence the configurement, or design, of IVHS include both "soft-side" issues, such as human factors, and hard technological issues such as the need for a traffic surveillance technology. In some cases technical and institutional matters become blended, such as in the issue of radio-frequency authorization which will affect the selection of mobile communications for IVHS. While the following list covers what are seen as major barriers, it is by no means exhaustive.

Human Factors

At the top of the IVHS research agenda, it is generally recognized that very significant human factors challenges must be overcome if IVHS is to be safely and effectively deployed. The problem is simply that IVHS will provide real-time communication to the driver in the midst of the driving task. The primary concern is that these communications will distract the driver and cause accidents. Additionally, the driver's ability to comprehend the displayed or spoken messages will be handicapped by the stresses of driving in heavy traffic. Recognizing the very heterogeneous population of drivers which includes differing levels of age and impairment, illiteracy, inattentiveness, etc., the in-vehicle communication of substantive information is challenging.

Accordingly, both the safety and highway administrations of the U.S. DOT are planning to devote substantial fractions of their IVHS research budgets to human factors research. Both agencies have argued for the development of sophisticated driving simulators (like the flight simulators used to train pilots) as research tools with which to study the tailoring of IVHS to satisfy the constraints on human performance. General Motors is building additional research simulators to augment its two machines already in existence and Ford is seriously examining the need for one or more R & D driving simulators.

36

User Acceptance

At another level beyond the perceptual/cognitive domain of human factors, there is a human behavioral barrier to IVHS that is generally called "user acceptance (or rejection)." This issue simply pertains to whether people will follow advice regarding, say, safety warnings or quicker routes, or otherwise make good use of the provided information. In other words, will people value the IVHS system?

The concern is based upon the axiom that each driver has his or her own objective function. They want what they want—and they don't necessarily want what is good for everyone else in the communal use of the road network. The personal automobile is seen as a private domain into which no one comes without the driver's approval. Thus, the prospect of someone else determining what the driver needs to know while driving poses a risky proposition. Further, the driver's reaction to presented information will always to subject to his past experience. If past information has contained either real or perceived errors, the driver's acceptance of IVHS functions will plummet.

Accordingly, the unknown nature of user acceptance of IVHS poses a barrier because it presents a fundamental risk that could determine the very feasibility of certain IVHS deployments while, perhaps, retarding the adoption of others. Also, this issue may play out rather differently in differing cultures. What is readily accepted by drivers in Japan may not be at all accepted in the U.S., where personal benefit tends to supersede group benefit in determining the behavior of the individual. It is generally acknowledged that a primary purpose of large-scale demonstrations of IVHS concepts in different cities is to assess the level and character of user acceptance that will eventually prevail.

System Architecture

A robust IVHS deployment over a large metropolitan area will involve, perhaps, hundreds of thousands of mobile users and a linking infrastructure. The architecture of the communication and computing system which accomplishes IVHS functions will determine the distribution of "smarts" between the car and the roadside. On the one hand, more intelligence in the car will reduce the communication burden and thus unload the demand for radio frequency bandwidth (see below.) It also increases the cost for the individual car owner and thus reduces the fraction of the driving population that will buy IVHS equipment. Auto manufacturers are both resistant to increasing the cost of the car while anxious to posture themselves should popular demand for new features materialize, especially at the luxury end of the product line. If the IVHS infrastructure is financed largely through public funds,

government bodies want to off-load intelligence onto the car, in order to contain costs, assuring that equipped cars are at least smart enough to transmit their locations back to the traffic control center so that traffic flow can be monitored (i.e., with the vehicle thus serving as a so-called "traffic probe".)

Clearly, the lack of early resolution on the most basic issues of system architecture will delay IVHS. Only when architectural principles are established can interface standards be defined and product development begin in earnest. In the meantime, organizations are working at the level of modular technologies whose packaging, either inside or outside of the vehicle, is yet to be determined.

Traffic surveillance technology

Recognizing that a primary early deployment of IVHS will be to provide real-time traffic advisory to motorists, a fundamental need exists for a technology that can continually monitor the status of metropolitan traffic. This requirement has been addressed, in current practice, only through very limited installations of inductive loops in the pavement for detecting the passage of individual vehicles. At least in concept, a comprehensive network of such detectors throughout a metropolitan street system, with data linkage to a central computer, would meet the nominal requirement. The inductive loop is undesirable from the standpoint of cost and operational problems, however, and is not seen as the ultimate solution.

It is generally assumed that some remote-sensing technology is needed to meet this requirement. If such a technology could be purchased at $10,000 to $20,000 per copy, it would likely become installed at virtually every signalized intersection and every third of a mile along freeways and arterials throughout congested metropolitan areas. The current absence of such a technology certainly constitutes one of the major barriers to the wholesale deployment of IVHS in behalf of traffic control.

An alternative development path, mentioned earlier, involves the use of vehicles as traffic probes. In this concept, vehicles equipped with automatic location equipment can transmit their current location to the traffic control center, thereby permitting a nominal assessment of traffic flow along links throughout the system. The concept obviously depends upon the fielding of many thousands of equipped vehicles in order to achieve reasonable coverage of the network. To get around the "chicken & egg" barrier, (i.e., where no one wants to buy the equipment needed to gain the traffic advisory because not enough probes are deployed yet to make the system work) some suggest the marketing of automatic navigation equipment to attract enough buyers, by itself, to "prime the traffic surveillance pump." The

"priming" achieved through vehicles purchased with navigation capability would hopefully constitute a sufficient fleet of traffic probes to provide at least a skeletal level of traffic monitoring. Then, as more buyers come forward to obtain even crude traffic advisory and route guidance services, the probe density would increase to the levels needed for high quality service. This strategy is being pursued currently in London, UK, by a private consortium under the so-called "Autoguide Demonstration."

A hybrid of the two surveillance schemes can also envision . That is, a given community may deploy ground-fixed traffic detectors over a limited, but crucial, portion of their road network and thereby accelerate the market for vehicles equipped to receive targeted traffic advisories, while also serving as probes. Even another variant on this theme is the City of Toronto which has an extensive network of inductive loops on freeways and is equipping its fleet of 2000 buses to serve as probes on the arterial street network. Although buses may turn out to be somewhat anomalous in the role of probes (because they stop so often) it may be that some calibration of the bus data will serve as a useful measure of traffic on the surface streets.

Radio frequency bandwidth

It is recognized that IVHS will pose an enormously high demand for data transmission by means of radio waves. For a large metropolitan area, one could easily imagine hundreds of thousands of mobile users of the system at a given time. If each equipped vehicle exercises two-way communications, a very robust data radio system will be needed, even after great care is given to minimizing the need for frequent radio contact and the quantities of data transferred at each contact. Since the radio spectrum has already been so heavily allocated through authorizations from the Federal Communications Commission, there is broad concern over the availability of sufficient spectrum for the creation of IVHS. While there are certain frequencies already allocated for mobile usage, the available bandwidths place a severe limitation on the number of users that could be accommodated before the system is saturated. Thus, new allocations are needed, as are innovative approaches toward efficient use of radio communication in the IVHS architecture.

Map data bases

Another barrier that must be overcome is the compilation of the geography of the U.S. road system in a standard form of electronic database. While much has already been accomplished in certain local areas, no standard data format has yet been adopted. There are two generic formats compiling a database representing the road network, namely "digital" and "vector." In the digital approach, one can think simply of a digitization of the coordinates of each intersection and bend in the road directly from a paper map. The digital format is useful

for creating a visual display such as on a CRT screen, but is inconvenient as a data file from which to compute an optimum route.

The vector approach codes each road segment with logical mathematical relationships, citing compass orientation and length of each link. The vector-based data file lends itself readily to navigation and automatic route selection but is not directly suited for visual display.

Various organizations are moving rapidly to compile databases in concert with the development of navigation equipment suited to automotive use. Thus, the expectation is that the map database issue will vanish as a barrier to IVHS within the next few years.

"Normal-traffic" databases

Because the constraints on radio frequency bandwidth will pose such a severe constraint on the quantity of data that can be passed from the ground to the vehicle, it is rather commonly expected that traffic status information will be transmitted only when "exceptional" traffic conditions prevail. An exceptional condition prevails on a given road link when traffic is flowing substantially faster or slower than normal for that time of the day. Thus, in order for the vehicle's on-board equipment to determine an optimum route, it must (a) access a "normal-traffic" database from memory and (b) receive updates from the traffic center so as to make the database current to the moment.

In large U.S. metropolitan areas, however, there is no comprehensive database documenting normal traffic conditions. Thus, another barrier to be overcome involves both the methodology and the direct field activity needed to produce and maintain such databases for U.S. cities. Also, the data must be formatted in a manner which is compatible with the map data itself.

Dynamic modeling of traffic networks

Associated with a traffic advisory function, a more mature IVHS deployment will require that traffic be not only monitored at the moment, but also predicted over the next fifteen minutes to an hour. Especially when incidents occur which tend to block traffic for a limited period of time, and then become cleared, the ability of the control center to anticipate the clearing as well as the associated traffic flow transients must be part of any metropolitan system that attains high levels of performance. Thus, when a motorist on the west side of town queries his system for the best route to the east side, the route selection becomes based upon

knowledge of what the traffic on east-side road links is likely to be when he gets there, and everywhere in between.

There is a generally recognized need for powerful mathematical techniques that can reliably forecast the interactive dynamics of traffic over a very large metropolitan network of roads. When an accident occurs on a given link in the network, the math model must be able to anticipate the implications of the disruption on the other links and modify its predictions accordingly.

Collision sensing/prediction/warning/intervention

Quite apart from traffic guidance issues, the use of advanced electronics to aid the driver in avoiding collisions is also embraced by the broad IVHS concept. Characterized as building-blocks such technologies will (1) sense the near-environs of the vehicle, (2) interpret the sensory data so as to predict when a collision is pending, (3) warn the driver where corrective action is feasible, and perhaps even (4) undertake automatic intervention when no driver-applied correction would suffice. At level (1) there is also interest in simply presenting the sensed, or imaged, environment to the driver as an instructive overlay on the windshield, especially under conditions of obscured visibility. Relative to level (4) and perhaps even level (3) it has been observed that rapidly increasing popularity of anti-lock braking systems will serve to facilitate the more robust collision prevention technologies, making the vehicle inherently more controllable in emergency maneuvers.

The collision-prevention facet of IVHS becomes linked with the interest in traffic flow by the fact that accidents are the largest single cause of traffic delay. Thus, if IVHS implies electronics technology to enable efficient travel over a limited-capacity road system, the unavailability of collision-prevention technology constitutes a barrier to the achievement of the IVHS vision.

Non-technical Barriers

In addition to the technical barriers to IVHS there are also various non-technical factors which tend to either delay IVHS deployment or pose conflicts that may only fully develop after certain deployments have occurred. Each of these items will be briefly mentioned below.

Private investment discouraged by dependency upon government

Clearly, the market for IVHS products will only develop if certain investors choose to accept what at this stage looks like a high level of risk. While IVHS risks come in many

flavors, one prominent risk accompanies the presumption of a publicly-financed infrastructure for traffic surveillance, roadside or central processing, and communications. If the market for vehicle-borne IVHS products is contingent upon such public infrastructure, and if these products require an extended developmental effort, the private investment in product development will come only at a high discount rate. After all, the public agenda is subject to the whim of public sentiment and the unpredictability of elected officials. It will be hard to conclude that a business plan is sound as long as its very feasibility depends upon certain achievements by government. Nevertheless, industry may be convinced by the vigorous initiatives of certain state and municipal road authorities that must respond to crisis-level traffic congestion.

An obvious line of alternative thinking also arises, however,—namely, that of private infrastructure. An organization or consortium that could field a private traffic surveillance network (or fleet of probes) as well as provide communications services and central processing in real time would place itself more or less in control of its own destiny, without dependency upon highway agencies except perhaps for minimal levels of cooperation. This approach could be strategically attractive insofar as it implies a monopolistic market, as in the early era of the telephone communications infrastructure. The public risk in such a development is that an early market success in one metropolitan region might quickly spawn competitors in other cities, each building its own private infrastructure which may be incompatible with those in other cities. Then a market battle for the preeminent protocol would ensue, such as in the VHS versus BETA conflict, at the end of which many of the early buyers must discard their initial purchases.

Social/jurisdictional conflicts when traffic diverts

Perhaps the most commonly-cited scenario of IVHS-style traffic guidance involves the diversion of commuters from a freeway onto surface streets in order to avoid a traffic jam due to an accident on the freeway. Before the high-density traffic stream emerges from the freeway, this scenario assumes that the surface streets are occupied simply by local motorists travelling in the immediate neighborhood. When the diverted stream arrives, the ability of the local clientele to travel on those local streets will be dramatically reduced, even though those diverting from the freeways may be accruing substantial travel-time benefits from the diversion. Thus, there are "winners" and "losers" in the dynamic of traffic diversion. Those who bought IVHS equipment are generally assumed to be among the winners in such scenarios.

Since most metropolitan regions enfold dozens of individual municipalities, each of which has authority over much if not all of its local street system, there is the distinct potential that certain local "losers" in the traffic diversion scenario will eventually petition their municipal governments for an interdiction preventing such diversions. Of course, if the diversion advice to the freeway motorist came simply from the intelligence on his own car, as assisted by a private infrastructure, the municipality may have few options other than simply closing of some of its own roads (or the municipality could even wage high technology war by subscribing to the motorist advisory service themselves and engaging signal lights at the top of each exit ramp to automatically confine freeway diversion traffic to the service drive, right when the traffic is expected to emerge, upon receipt of a "diversion alert.")

Conflict between rural and urban use of highway funds

All those concerned with approaching Congress for federal funding commitments toward a national IVHS Program have recognized that the urban-dominated House of Representatives may readily authorize an effort to relieve urban traffic congestion while the more rurally-sensitive Senate may be unenthusiastic. Even though the benefits of IVHS go beyond the congestion matter to embrace truly national issues such as trucking productivity, traffic safety, and the extension of mobility for the elderly, it is very likely that many will perceive IVHS as primarily intended to relieve urban traffic congestion. Presumably, the U.S. system deals with matters of potential inequity such as this by means of political negotiation, delivering certain concessions to meet rural needs, for example, in exchange for initiatives such as IVHS to address (what are perceived as) predominantly urban needs.

Functionality for both rich and poor urban road users

Another obvious equity issue arises with public investment in a sophisticated infrastructure communicating with road users that have, themselves, invested in expensive optional equipment. Namely, the rich would appear to benefit at public expense. This issue has two interesting sidelights that tend to mute the significance of the concern. Assuming that equipped vehicles eventually perform as traffic probes operating over the street network, the highway authorities gain a data resource that has great value for the planning of highway construction and maintenance as well as in optimal timing of intersection signals. Clearly, such a yield provides public value, even for the "poor" highway user who lacks IVHS equipment. Additionally, there is a concept for inexpensive deployment of "localcast" radio transmitters, using conventional AM or FM frequencies, along major freeways and arterials to provide up-to-the-minute advisory (even to the point of specific diversion instructions) to any road user having a conventional radio. To the degree that the information base for such services comes

from a fleet of high-end road users serving as traffic probes, the low-end user benefits from the public investment that stimulated and sustains the service.

Tort liability

The classic defense in an auto accident litigation is "driver error." That is, as long as the driver is the source of all data gathering, processing, decision making, and control activity, the overwhelming portion of all responsibility for safe driving rests obviously with the driver. But if IVHS begins to offer new data, new processing assistance, new instructions or at least advisories, and eventually even control warning and interventions, the burden of responsibility will tend to be unloaded from the driver and placed upon the organizations responsible for the technology.

The automobile manufacturers, as well as state, county, and municipal highway agencies, have historically borne a large share of the $13 billion annual cost of auto accident litigations, and thus are keenly tuned to the subject. As a result, these organizations are very concerned that IVHS will transfer much more liability onto them, as implied above. They argue that especially for the more ambitious aspects of IVHS to become reality in the U.S., new legislation is needed for placing a cap on liability or providing a more rigorous definition of fault so as to bound the liability and render it reasonably predictable from a business perspective.

Automotive leaders have stated, for example, that liability relief is needed even to begin selling modest control enhancements such as smart cruise control (which reduces speed automatically upon overtaking another vehicle, then resumes speed when the lane ahead is clear). Others recall that the same concerns were raised when cruise control itself first was poised for market introduction. Needless to say, the lure of a rapidly rising market for a profitable option can quickly squelch internal debates over liability risk, especially when competitors go first. Nevertheless, liability concerns will definitely retard the development of IVHS to some degree, more in certain organizations than others, and more in the case of certain technical features, especially those involving vehicle control.

Concern for privacy

A number of IVHS concepts involve automatic vehicle identification (AVI) which raises concerns over invasion of privacy. In the simplest embodiment of AVI, a small transponder device on board the vehicle returns a code number which uniquely identifies itself in response to a coded query from a nearby transmitter. As an example, a cooperative effort of the trucking industry and a group of western states, called the Crescent Project, is preparing to deploy such

a system for tracking truck movements and avoiding unnecessary stops for weighing, collecting fuel taxes, and checking permits. In this case, each truck is uniquely identified and any claims on "privacy of movement" are forfeited.

Other systems have been built, however, which deal with vehicles on an individual basis, but do not acquire a unique identification. Examples exist of systems already installed for automatic collection of tolls, such as at bridges or tunnels. A regular user of the facility purchases a certain number of "tokens", so to speak, by paying cash at the toll booth where the purchased number of tokens is recorded electronically on the vehicle's transponder. On subsequent passes through the automatic lane, the roadside device detects the balance of tokens from the vehicle's transponder and transmits a rewritten balance, subtracting one token. When a zero balance is detected, the vehicle is diverted to a cash-pay lane. The system knows the balance of tokens on each passing vehicle, but nothing else.

In the case of vehicles as traffic probes, it is necessary for the traffic control center to give each probe vehicle a temporary identification code so that the vehicle's progress can be tracked over some period of time as an indicator of traffic flow . This code need not be unique, however, and is assigned to a given vehicle only for the duration of its service as a probe. Of course, the privacy-conscious may worry whether changes in software are possible by which a central authority, or somebody else, could keep track of an individual vehicle, indefinitely. Nevertheless, it is straightforward to design the probe communication feature so that no unique identification of vehicles is possible.

Where an IVHS service is to be charged on the basis of usage, with direct billing to the customer, however, some record of usage is inevitable (as in the analogy of the phone bill.) In such cases, it can be argued that the user participates voluntarily, as do phone customers, and thus assents to the forfeiture of some privacy in return for the services. A somewhat stickier case arises when highway user taxes are automatically billed by the government on a per-mile-of-use basis, with premium rates in force during rush hours, as a strategy for moderating highway demand. In this case every user of the public, regulated, roadway is identified and logged on and off the instrumented roadway. The individual's involvement is not so voluntary and the enterprise is not likely to be seen as a service. Given the highly politicized setting in which such "road pricing" policies would be debated, it is certain that the privacy issue would be raised with vigor.

Section Three: The Forecast

Many believe that IVHS, in a variety of forms, is an inevitable path of development for the highway mode of transportation; the only question is timing and the configuration of deployed systems. Since the concept of a concerted national program in IVHS has only come up for consideration since 1987, however, it is fair to say that little basis exists for any solid forecasting. Nevertheless, we can gain some instruction from a Delphi survey that was undertaken by the University of Michigan in 1988 as a means to predict development of various categories of the IVHS market.

As shown in Figure 1, for example, this survey attempted to predict IVHS progress according to milestone dates for (1) successful lab tests, (2) system introduction (i.e., products for sale), (3) majority use by commercial vehicles, (4) majority use by all automobiles and (5) mandatory use by all road vehicles. The figure plots these developing achievements against a time line from 1988 into the next century for each of three broad categories entitled:

- ATMS, or "Advanced Traffic Management Systems," which refers to the infrastructures for monitoring traffic, detecting incidents, formulating motorist advisories, controlling traffic signals in real time, and implementing automatic tolls and road pricing, if authorized;

- ADIS, or "Advanced Driver Information Systems," which covers all those features which bring information into the vehicle and transmit it out, except for the purposes of vehicle control;

- AVCS, or "Advance Vehicle Control Systems," which pertains only to enhanced control functions, eventually including automatic vehicle control as a complete substitution for driver control.

We see that by the year 2000, the Delphi panel expects majority use of ATMS features by commercial highway users (whose bottom line is impacted by traffic efficiency, for example) as well as a strong level of market development for ADIS features. Automatic control features, on the other hand, are generally retarded in deployment on the grounds of both technological and institutional/legal barriers. The full report on this work entitled, "The Future of Intelligent Vehicle Highway Systems" is available for purchase from the University, having been supported originally by organizations that directly sponsor the Michigan-based Program in IVHS.

**Figure 1   Median Projections of IVHS Market Penetration
(by primary group)**
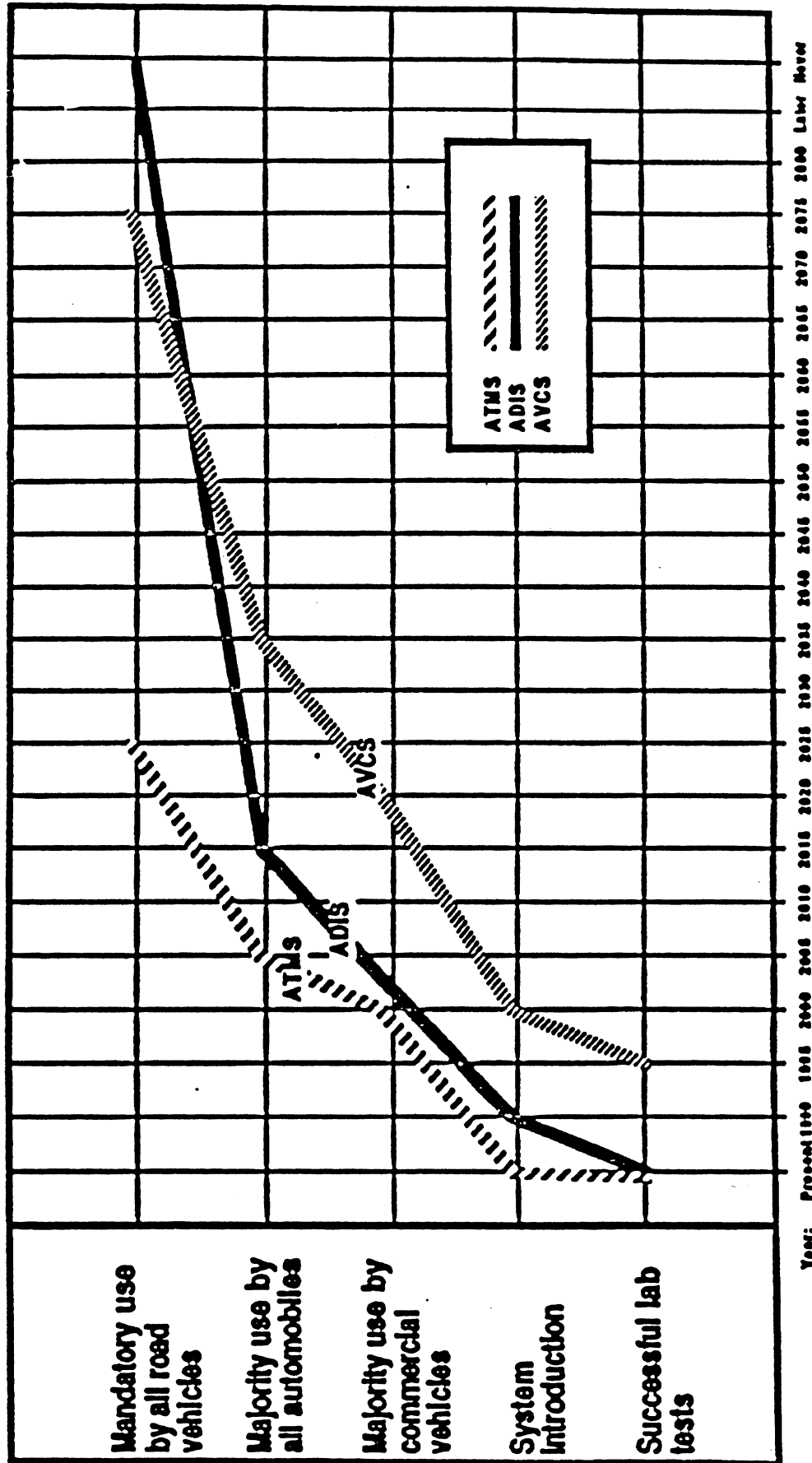
ATMS – (Advanced Traffic Management Systems)
ADIS – (Advanced Driver Information Systems)
AVCS – (Automated Vehicle Control Systems)

The factors that will eventually determine the rate of development of IVHS include the following:

- The incorporation of a National IVHS Program by the U.S. Congress—to be considered in the upcoming Surface Transportation Act of 1991 as well as provision for its support from the Highway Trust Fund through the Highway Reauthorization Act of 1991. Without strong federal support of a National IVHS Program, it is likely that the development of IVHS by the domestic industry will be largely limited to those organizations which have the resources and commitment to pursue a private infrastructure, as discussed earlier. If federal support materializes as a catalyst for state and private cost sharing, IVHS demonstrations are expected to sprout up within the next 2 to 3 years in many regions of the country.

- Initiatives by foreign firms—a number of large electronics firms, telecommunications companies, and auto manufacturers outside of the U.S. have begun to invest significantly in IVHS-related technologies and systems. So far, none of them has made a move to provide any leadership on the U.S. scene or to engage in any systems demonstrations in a U.S. city (although a number of demonstrations are underway in Europe and Japan.) The strong emergence of such a player onto the U.S. scene, perhaps in a joint effort to help a specific urban region deal with its traffic congestion crisis, could conceivably accelerate the interests of both the federal government and the domestic industry.

- The mounting of successful field demonstrations. There are currently three significant field demonstrations of IVHS announced and underway; namely in Orlando (Travtek), Los Angeles (Pathfinder), and in the crescent-shaped string of states in the west and southwest, from Washington to Texas (Crescent, or "HELP" project). Such field demonstrations are seen as being pivotal in IVHS development because they will illustrate in concrete examples the systems-level treatment of technologies, user functionality, institutions, business interests, and socio-political issues. (A complementary initiative in Michigan will enable use of the metropolitan Detroit road system, with associated instrumentation, communication, and central computing, as a multi-function test bed for IVHS development. Called the "Michigan Mobility Center" the test bed infrastructure is currently under design by the University of Michigan and a separate research institution; the control center building is under construction.)

Moreover, field demonstrations and experiments are expected to better enable business and government leaders to make judgements on the wisdom of pursuing IVHS with vigor.

Recognizing that this broad area will change rapidly in the years ahead and that it may have a profound influence on the system of highway transportation in the future, we recommend that Chevron track IVHS in an ongoing way. One effective way for the Corporation to gain a window into these developments is to join the Michigan-based Program in IVHS as a sponsor. The annual affiliation fee is $20,000. The Corporation could also participate, for an additional fee of $50,000, in the group of companies and government

agencies that directs the University's program of basic research in IVHS—studies dealing with the key technological and socioeconomic barriers to IVHS that were delineated above.

In Europe, it is true, that partnerships have developed between government transportation agencies and key developers of IVHS technology in the private sector. Monitoring these activities from the U.S. has been difficult. In the U.S., a voluntary public-private group known as Mobility 2000 has met on occasions to share information on IVHS technology.

Automotive News (June 25, 1990) reported that a new IVHS monitoring and research organization has been proposed at a recent National Leadership Conference on Intelligent Vehicle Highway Systems in Orlando, Florida. The organization would be titled ELECTRANS and will be financed by membership dues and contractual grants. The membership would be comprised of corporations, trade associations, and government agencies from the local, state, and federal levels. It was proposed at the conference that Mobility 2000 operate as the technical arm of ELECTRANS. A major sponsor of the conference was the Highway Users Federation.

Chapter Four: Electric and Hybrid Vehicles

Kan Chen and Richard L. Doyle
University of Michigan

Section One: Current Status

Despite a long history of development, electric and gasoline-electric hybrid vehicles (EVs and EHVs) appear to be unable to seriously compete against pure internal combustion engines in the foreseeable future on strictly technological-economic bases. However, a convergence of socio-political forces are possible in the near future to allow significant market penetration of electric and hybrid vehicles in selected market segments and in selected locations. It is essential that energy and vehicle suppliers maintain a continuing EV and EHV monitoring program in these selected areas.

Brief History

In the early days of automobile development, electric motors powered by lead-acid batteries competed against the steam engine and the internal combustion engine (ICE) for supremacy. In America's first motor vehicle track races in 1896, two of the seven vehicles entered were electrics which finished first and second! In 1900 an electric car completed a 50 mile road race in Long Island, N.Y., in slightly more than two hours, beating both steam- and gas-powered competitors (Sedgwick, 1990). However, the rapid improvements of the ICE vehicles soon outdistanced the electric vehicles (EVs), which disappeared almost entirely from public roads by the mid-1920s (GM, 1990). Detroit Edison was the last manufacturer of electric vehicles and it halted production in 1938.

It was not until the 1960s, driven mainly by air quality concerns, that EVs resurfaced beyond such off-road applications as golf carts and indoor factory and air terminal transport. In 1964, GM introduced its "Electrovair I," basically a Chevy Corvair with an electric motor. In 1967, General Electric announced the development of an electric car with a top speed of 55 mph. In 1967, Ford demonstrated an experimental commuter car which it claimed could achieve a top speed of 138 mph. (Sedgwick, 1990). However, the small size and limited performance of the EVs made them noncompetitive with other vehicles on public roads. The energy crises of the 1970s, the prospect of gasoline priced at $2 per gallon or more, and the combined concerns of environmental quality and petroleum shortage caused a serious revival of electric vehicles (EVs) and gasoline-electric hybrid vehicles (EHVs) in the 1970s. General

Motors announced at one point that it would have electric cars in production by the mid-1980s and estimated that 10 percent of GM production in 1990 could be EVs. However, the oil glut since the early 1980s altered that scenario.

The University of Michigan series of Delphi forecasts by North American automotive industry experts projected in the 1979 edition that by the year 1990 there would be 600,000 electric vehicle units produced in the U.S. Later forecasts of unit production by 1990 fell dramatically to 300,000 units in the 1981 Delphi II and to under 10,000 units in the 1984 Delphi III (Cole & Harbeck, 1984).

This brief historical review of EVs and EHVs suggests that their future will be tied closely to gasoline prices and availability, and to environmental concerns and regulations forces more socio-political than technological-economic in nature.

General Current Technology and U.S. Status

Although EVs have made substantial progress in the past century, there has been no revolutionary change in the key technology, namely that of the batteries. Despite years of research and development efforts on advanced batteries such as sodium/sulfur and zinc/bromine batteries (Patil *et al.*, 1989), the most advanced EVs for demonstration today still use lead-acid batteries because of their proven reliability and available technology (GM, 1990). The basic disadvantage of excessive weight/energy ratio of electric batteries, versus ICEs, has remained relatively unchanged.

Note that the above statement does not imply that significant progress has not been made in advanced battery technology. In fact, as a result of intense R&D in recent years, there is now a plethora of battery types contending for consideration in EV applications (see Table 1).

Other practical problems with battery-driven EVs include limited acceleration, frequent battery replacements (about every 15,000 miles), lengthy charging time (about 2 to 8 hours), and reliable metering for energy level. It appears that the most significant advances made in EVs are in their accessory technologies, such as the use of silicon controlled rectifiers or transistors for power conversion and mechanical design to improve vehicle aerodynamics and tire resistance. Power conversion devices are used where AC instead of DC motors are used to transduce electric energy stored in batteries into mechanical propulsion. The advantages of AC over DC motors are in the lower costs of AC motors and their smaller sizes (and thus lower weights) especially when higher frequencies are used. However, these advantages are offset

by the complexity and costs of electronic converters and controllers needed for AC motors. Moreover, since the semiconductor controllers are not very efficient, the cooling of the power semiconductors presents a design challenge. Parallel approaches using AC versus DC motors for EVs, are being developed and tested, a clear cut winner is another deterrent to the practical acceptance of EVs.

Table 1 — Overall Suitability of Candidate Battery Technologies for the EV & EHV Applications					
Technology	Specific Energy Potential	Specific Power Potential	Life-Cycle Cost Potential	Overall Suitability for Application	Major Technical Limitation
Developmental Systems					
Na/S	Good	Good	Fair	Good	Life, Cost
Li/FeS	Good	Good	Fair	Good	Life, Cost
Ni/Fe	Fair	Fair	Good	Fair	Cost
Ni/Cd (sintered)	Fair	Good	Fair	Fair	Cost
Ni/Zn	Fair	Good	Marginal	Fair	Life
Ni/Cd (non-sintered)	Fair	Marginal	Fair	Marginal	Power, Life
Pb-Ac (flow-thru)	Fair	Marginal	Fair	Marginal	Life
Ni/H$_2$	Fair	Good	Unlikely	Unlikely	Cost
Pb-Ac (non-flow)	Marginal	Good	Unlikely	Unlikely	Life
Zn/Cl	Fair	Unlikely	Fair	Unlikely	Power/Cost/ Volume
Zn/Br	Fair	Unlikely	Fair	Unlikely	Power/Cost/ Volume
Al/Air	Good	Unlikely	Fair	Unlikely	Power/Cost/ Volume
Fe/Air	Good	Unlikely	Fair	Unlikely	Power/Cost/ Volume
Zn/Air	Good	Unlikely	Fair	Unlikely	Power/Cost/ Volume
Exploratory Systems					
Na/S (glass)	Good	Good	Unknown	Good	Life Unknown
Li/FeS$_2$	Good	Good	Unknown	Good	Life Unknown
Bipolar Li-FeS	Good	Good	Unknown	Good	Life Unknown
Bipolar Pb-Ac	Fair	Good	Unknown	Good	Life Unknown
Source: Miller and Christianson (1986).					

However, other schools of thought maintain that technological progress of R&D programs and practical operational programs for EVs and EHVs in the U.S., Japan, and Europe are at a stage whereby strategic planning of future highway operations should include consideration of these vehicle types in the process (Akikawa, 1986; Brusaglino, 1986; O'Connell, 1987; US-DOE, 1989).

One of the most advanced EVs shown to the public recently is GM's Impact, a two-seater powered by two AC induction-motors each driving one of the front wheels. The Impact is capable of accelerating from 0 to 60 mile per hour (mph) in 8 seconds and has a top speed of 75 mph. The high-power lead-acid battery is completely sealed for life, and the 870-pound battery pack can be almost completely recharged in 2 hours. With the special design for aerodynamics and tire resistance, the car has a 0.19 coefficient of drag (compared to about 0.3 for conventionally designed cars) and a cruising range of 120 miles. This is certainly a substantial jump over the performance of previous EVs, which typically accelerate 0-60 in over 20 seconds and with a cruising range well below 100 miles. However, the battery pack for the Impact still accounts for one third of the total weight of the car, and the projected life of 25,000 miles is only a target. The cruising range of an equivalent ICE vehicle is at least twice that of the Impact, and even more for the same coefficient of drag. Furthermore, the cruising range of the Impact is likely to drop substantially from 120 miles in the winter and under unfavorable driving conditions.

But, EVs are not inferior to ICE vehicles in all applications. Beside the distinct advantage of very low or no emission, EVs also have relatively low maintenance costs compared to equivalent ICE vehicles for multiple stop-and-go operations. Cautious analyses of several applications showed that EVs may have their best chance to compete favorably against ICE vehicles in the light-duty commercial fleet market. If mass-produced, electric vans with lead-acid batteries could compete, on a life-cycle cost basis, with conventional vans used in local service fleet applications (Hamilton and Bevilacqua, 1985). However, this is only possible if the performance of the electric vans is suitably restricted—limited range, frequent stops, and parked overnight in a central company site. If advanced batteries became available and reliable in the next decade, range enhancements of 60-300% and cost reductions of 30-40% appear possible over lead-acid battery driven vans (Marr et al., 1989).

Within this category of EVs, the Chrysler Caravan has been fitted with nickel-iron storage batteries under the floor and an electric powertrain to produce an experimental urban delivery vehicle. Because of its minimal speed requirements and overnight access to a

centralized recharging facilities, an electric urban delivery van is a viable solution to the smog problems of some areas of the U.S. Also, the Electric Power Research Institute (EPRI) has sponsored prototypes of an EV cargo-carrying GMC Vandura. The so-called "G-van" uses conventional lead-acid batteries.

Gasoline-electric hybrid vehicles (EHVs) try to combine EVs and ICEs in single vehicles. For more than two decades, the potential impact of EHVs to reduce air pollution and to reduce dependence on fossil fuels was recognized (Hoffman, 1967). There are many possible configurations for EHVs. Figures 1 and 2 show the block diagrams of two basic configurations: series hybrid and parallel hybrid, respectively (Wouk, 1987). In the series configuration, the vehicle wheels are always driven only by an electric motor while the ICE is used to run an electric generator which charges the batteries as well as running the electric motor. By contrast, in the parallel configuration, the wheels are driven by both a dynamotor and an ICE which is coupled to the dynamotor through an electrically operated clutch. Thus, the torques of the ICE and the dynamotor add directly on the in-line shafts. The extra output from the dynamotor is used to charge the batteries from which the dynamotor also draws its power when needed. The best configuration of EHV is dependent on the specific application. A typical strategy is to provide electric operation for most of the daily driving needs with a simple, reliable system—i.e., operating the EHV on the electric system for 50 miles, then switching to the ICE for longer distances, an "either/or" strategy (Hardy and Roan, 1985). Generally, the initial costs of EHVs are higher and the life cycle costs could become competitive depending on the specific application specifications. Some futuristic EHV designs include such configurations as an all-electric module that can be detached from the full vehicle for driving in the core city or campus areas. The smaller module has a limited capacity than the full vehicle but consumes less energy, emits no pollutants, and can be parked more easily.
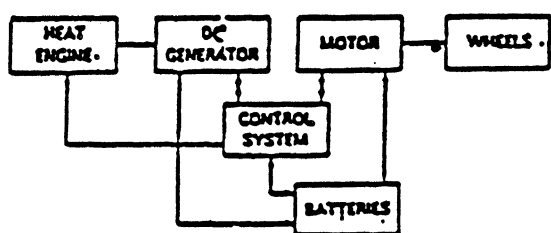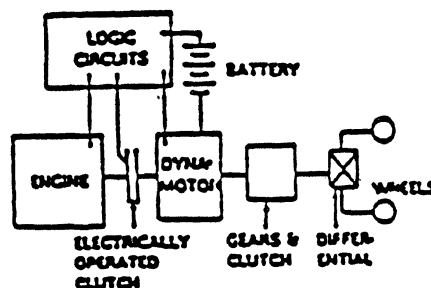

Figure 1

Figure 2

A major player on the EHV R&D scene is the U.S. Department of Energy's "Electric and Hybrid Vehicle Propulsion" program, in place since 1976 because of congressional mandate. Aside from EHV R&D, the DOE program has been expanded to a variety of projects aimed at developing EV manufacturing and service industries, including full-scale demonstration projects and financial incentives (DOE, 1989). DOE EHV propulsion research has been concentrated on the dual shaft electric propulsion system (DSEP), a single shaft AC system (ETX-II), and a methanol-fueled, phosphoric acid fuel cell/battery system.

International Developments

A number of other countries, spurred by high gasoline prices and increasing environmental concerns, have been aggressively pursuing EV and EHV programs. The following is a brief synopsis of basic strategy, technological developments, and types of vehicles, by country.

United Kingdom

The United Kingdom has a tradition of electric vehicles with an estimated 35,000 electric delivery vehicles in operation in 1986, with ongoing research efforts more or less dedicated to electric commercial vehicles. Four major vehicle manufacturers have developed different types of electric vehicles: Bedford Commercial Vehicles (electric van), Freight Rover - BL (electric van), Renault Truck Industries (Dodge 50 series), Leyland Trucks ("Electric Roadrunner"). EHV vans and minibuses have also been manufactured by Electric Vehicle Hybrid, Ltd. and placed in operation as part of a demonstration programs.

West Germany

Activity on EVs and EHVs has been conducted mainly by "Gesellschaft fur Elektrische Strasenverkehr mbH" (GES) in collaboration with vehicle manufacturers Daimler-Benz, M.A.N., and Volkswagen, and electrical equipment manufacturers Bosch and Siemens. The Ministry of Research and Technology and the Ministry of Transport are also heavily involved with ongoing research and demonstration programs.

In the category of passenger cars, the Volkswagen EV "CitySTROMer", derived from a VW Rabbit, was developed within a program started in 1981. VW also introduced an EHV version of the Golf in 1986. Within the category of commercial vehicles, Daimler-Benz has produced over 200 units of their "Electric Transporter 307E" and VW has produced an "Electric Transporter E-lt-35." These vehicles have been operating in practical service in

various German cities since 1974 under GES management. Seventy units have been operating in Berlin and Bonn within a program co-sponsored by the Ministry of Research and Technology and the Ministry of Transportation. Within the category of buses, there are several versions by MAN that have been in practical operation since 1974. Daimler-Benz has had EHV (diesel-battery) buses in operation in Stuttgart and Wesel since 1979 under a government-sponsored program. In general, the German government appears to be deeply involved in the development of batteries and integrated propulsion systems R&D programs.

France

France has produced a considerable number of EVs through consortiums coordinating the activities of automobile manufacturers and suppliers. The PSA Group has developed the EV passenger car model Peugeot 205 and the EV delivery van models "J9" and "C25." The PSA Group has also produced other prototype vehicles for demonstration programs sponsored by the European Economic Community (EEC) in France and Belgium. Additionally, in the category of commercial and utility vehicles, Renault has developed EV versions of their "Express" and "Master" models. An important part of the EV program in Frances appears to be dedicated to vehicles for public mass transit. A fleet of various versions of trolleybuses have been in operation in several French cities since 1977.

Italy

EV activity in Italy has been developed under the sponsorship of the National Electricity Authority (ENEL) in collaboration with Telephon Company (SIP) and the Italian "Consiglio Nazionale delle Ricerche" (CNR). Fiat has introduced both passenger car and commercial/utility EV models. In the category of vehicles for public transport, two different approaches have evolved. One is the development of an EV minibus by Fiat from an IVECO model; the other is an experimental EHV bus, again derived from an IVECO design.

Other European Countries

Other European nations involved in the development of electric and hybrid vehicles are:

- Denmark - Electric passenger cars and commercial vehicles

- Belgium - As headquarters for both the EEC and AVERE, Brussels is
  a major center for meetings related to EV and EHV vehicles. In
  addition, the Belgian company "Elenco" is involved with VW on
  a R&D program on alkaline fuel cells and tests on a VW electric
  van.

- Netherlands - The Netherlands also has a tradition of EV delivery van
  usage as well as ongoing fundamental research in this area.

- Switzerland - This country has a particular experience of EV usage in mountain tourist areas. The result has been the satisfactory operation of over 500 EVs within these very cold climatic tourist areas.

- Austria, Sweden, and Finland also have on-going EV R&D program under both governmental and private enterprise sponsorship.

Japan

R&D work on EVs was initiated on a large scale in 1971 when the Japanese Agency of Industrial Science and Technology under the sponsorship of the Ministry of International Trade and Industry (MITI) implemented an on-going EV program. These activities are substantially augmented through the activities of private enterprise. At the present time, emphasis appears to be placed on off-road vehicles, with over 13,500 such vehicles in operation as of 1986. The number of EVs in use in Japan (as of 1985), broken down by type is presented in the following Table. Additional information regarding Japanese EV, EHV, and advanced battery systems is proprietary.

Table 2 Holdings of Electric Vehicles in Japan (as of March 1985)		
On-Road Vehicles		
Classification	Types	Units
Light Vehicles	Passenger Cars	42
	Trucks	440
	3-Wheeled Vehicles	142
Small Sized Vehicles	Passenger Cars	4
	Trucks	18
Busses	Small and Ordinary Busses	8
Motor Bicycles		188
Mini-Cars, Special Cars, Others		8
Total		861
Off-Road Vehicles		
Off-Road EV and Other EV		13,500
Total		13,500

Source: JEVA Survey on EV ownership and Automotive Inspection and Registration survey on EV ownership

U.S. and European Government Programs

Recognizing the driving forces and infrastructure barriers to EVs, the U.S. Department of Energy (DOE) has supported the Electric Vehicle Program for a number of years. Understandably, the support level has gone up and down with the fluctuation of oil prices. The federal policy since the beginning of the Reagan administration to leave civilian technology demonstration programs mainly to the private sector has also affected the federal funding level. Currently DOE's EV research and development program includes the following components and major industrial contractors (DOE, 1988):

Propulsion System Design
- Dual-shaft electric propulsion system for light vans (Eaton)
- ETX-II system for light vans (Ford & GE)
- Fuel cell/battery powered bus (Energy Research Corp./Los
- Alamos/Bus Mfg; and Booz-Allen/Chrysler/Engelhard)

Battery Options
- Advanced lead-acid (Johnson Controls)
- Nickel-iron (Eagle-Picher Industries)
- Sodium-sulfur (Chloride Silent Power, Ltd.)
- Zinc-bromine (Johnson Controls)
- Lithium alloy/iron sulfide (Electric Power research Inst.)
- Iron-air (Westinghouse)
- Nickel-cadmium (Energy Research Corp.)

Testing and Evaluation
- 4 private-sector fleets with 71 EVs
- 5 public-sector fleets with 249 EVs (mostly by U.S. Navy)

The Europeans also have a substantial EV program, supported by the European Community and COST (Scientific and Technical Cooperation among European Countries) involving 11 nations (Brusaglino and Mazzon, 1988). An assessment of the various features of EVs that affect their production and applications has been performed within the European study COST 302. A variety of vehicles (passenger cars, light vans, medium vans, different batteries, hybrid vehicles, dual-mode vehicles, etc.) have been evaluated. The results appear to corroborate U.S. findings. There is no evidence that EVs and EHVs have found substantially

higher practical use at present in Europe than in North America even though gasoline prices there are roughly twice those in the U.S..

Section Two: Drivers and Barriers

Driving Forces

The immediate driving force behind EVs and EHVs is environmental concerns, which are particularly acute in certain states like California and in core city areas (including crowded foreign cities such as Singapore and Hong Kong). The most specific and serious driving force is Rule 1601 proposed by South Coast Air Quality Management District (SCAQMD) which covers California's most populous regions—Los Angeles, Orange County, Riverside County and part of San Bernadino County. Some 12 million people live in this 13,350 square-mile area, in which there are almost 8 million vehicles operating today. If the proposed rule is adopted, any fleet of 15 or more vehicles registered in the District would be required after July 1, 1993 to have an increasing percentage of their fleet vehicles to have increasingly low emission, until the year 2000 when all their fleet vehicles should be "ultra-low emission vehicles" (SCAQMD, 1990). Understandably this serious proposal has given a major impetus to EVs and EHVs as well as vehicles operating on methanol, propane or CNG.

In the longer-term future, the increasingly powerful driving force would include higher gasoline prices, which could jump unexpectedly, as they did in the 1970s due to political forces. In general, breakeven fuel prices for EVs and EHVs range from 150% to 350% of the current level on a life-cycle cost basis.

For the past two decades, the environmental driving force emanated from the concerns about ICE emissions: HC, CO, NO_x, SO_x, and PM (particulate matter). The substitution of ICE vehicles by EVs would reduce these emissions practically to zero. However, EVs derive their energy from electric power plants, which have their own emissions. Fair comparisons should be, and have been, made on the basis of total emissions from the two basic alternatives of (1) ICE travels and (2) equivalent EV travels with power plants. Of course, such comparisons have to make assumptions regarding electricity consumption per mile of EVs, emission control technologies for power plants, and the mix of primary energy sources for electricity generation. A recent study to analyze the emission impact of EVs in California for two target years, 1995 and 2010, concluded that the use of EVs would dramatically and unequivocally reduce carbon monoxide and hydrocarbons. Nitrogen oxide emissions decrease in most scenarios. Particulate and sulfur oxide emissions generally increase, but only slightly.

Because other areas of the U.S. tend to use more coal in electricity generation and have less stringent emission controls on power plants, EVs may have less emission benefits outside California (Wang et al., 1990). As California traffic gets heavier and more congested in the future, such study results would certainly provide powerful driving forces for EVs. Policy decisions will have to be made on the use of economic incentives versus governmental regulations to encourage or require the substitution of ICE vehicles by EVs and/or EHVs.

A new emerging environmental force in the last couple of years is the concern of carbon dioxide (CO_2) emission that has been blamed for global warming. Although the concern about global warming has added momentum to the environmental force pushing for EVs and EHVs, the ultimate effect is either uncertain or minimal. In spite of definite scientific evidence to show the steady increase of CO_2 concentration in the earth's atmosphere over the past decades, the impact of such increase on the global climate due to greenhouse effect is highly uncertain, as recent modeling work has indicated. Furthermore, increase of CO_2 has been contributed by a diversity of human activities, and significant curtailing of CO_2 emission will require global cooperation, which is highly unlikely especially since some countries may even benefit from global warming. Thus, any unilateral action by any country, such as the substitution of ICE vehicles by EVs and EHVs in the United States, will not produce any appreciable impact on the greenhouse effect (Chen *et al*, 1980).

It should be noted that EVs also have another environmental advantage over ICE vehicles; namely, substantial reduction of noise pollution. In fact, EVs are so quiet that some kind of noise makers have been suggested to be installed on EVs to warn blind pedestrians who might inadvertently step in front of EVs. However, noise considerations do not seem to be a major driving force behind EVs. On the other hand, EVs and EHVs could have negative environmental impacts of their own, emitting hazardous gases during the battery charging period (Smith, 1983). This could be a factor in selecting batteries and operating EVs and EHVs. For example, certain advanced batteries such as nickel-iron generate more hydrogen than lead-acid during the charging period. However, with proper venting, any potential harm to human health caused by these gases can be minimized or avoided.

Barriers

Infrastructure

Even if environmental forces, coupled with a sudden increase of gasoline prices, could provide impetus for either the EV and/or EHV market, the widespread use of these vehicles would not be possible until the necessary infrastructure is built up. There are several major

components in the infrastructure supporting large-scale application of EVs and EHVs. First of all, there need to be battery chargers available in a large number of locations for EVs (and for those EHVs designed to be plugged into the wall for battery recharge) that can accommodate many types of batteries. To avoid EVs and EHVs getting stranded with exhausted batteries, there should be "filling stations" for rapid refueling of EVs and EHVs through battery exchanges. At these stations, fully charged battery packs will be quickly mounted onto EVs and the exhausted battery packs will be removed for recharging during the night or at relatively low cost during low load periods. However, a battery exchange would cost about twice as much as an equivalent amount of petrol from natural crude oil. This is due to the high capital cost of the stations and battery stocks and the high labor cost (Weeks, 1978).

Other components in the EV and EHV system infrastructure include the maintenance facilities; a trained human resource pool for sales, operation, manufacturing and maintenance, parts suppliers, and aftermarket development. If certain areas, such as core cities, are restricted to EVs only, there need to be mechanisms for policing and keeping ICE vehicles out of those areas. All of these components are potential barriers and will need time and resources for development and implementation.

Note that the infrastructure barriers exist for any alternative fuel vehicles—vehicles operating on methanol, propane, compressed natural gas (CNG), as well as electricity. Since many fleets are fueled at central locations and train their own maintenance people, the infrastructure barriers for fleets (both public and private) are easier to overcome than those for individual vehicles. This has motivated South Coast Air Quality Management District (SCAQMD) to propose mandates for fleet purchase of "clean fueled" fleet vehicles as a practical strategy to get the momentum started in southern California (NAPA Fleet Executive, 1988) practical strategy to get the momentum started in southern California (NAFA Fleet Executive, 1988).

Accessories

An additional and not inconsequential impediment for all EVs is the problem of heating and cooling of the passenger compartment. With heat engines at least one-half of the energy in the fuel is dissipated through the radiator and exhaust pipes. However, at colder temperatures this heat is not wasted as it is used for heating the passenger compartment. With electric engines there is no heat loss. It is, therefore, necessary to use some of the primary energy of the batteries to heat the passenger compartment, resulting in a decrease of vehicle range. The same is true of air conditioning to cool the passenger compartment. Given the level of comfort

expected by the American consumer, these considerations take on increasing importance and should not be dismissed.

Review of Battery Technology and R&D

Present battery technology research is focused primarily on battery-types suitable for utility van and commuter car applications. An assessment of non-proprietary data suggests that advanced lead-acid batteries (with efficiencies almost double those of existing batteries) along with zinc-bromine, sodium sulfur, and lithium alloy-iron sulfide battery systems present the best opportunities for improved performance, reliability, and safety. R&D on nickel-iron technology consistent with the dual-shaft electric propulsion system (DSEP) is also being pursued with satisfactory results. However, the recent announcement by Isuzu Motors, Ltd., and Fuji Electrochemical Company of the development of what is termed by Isuzu as a "revolutionary" new type of electric storage that is smaller, more powerful than existing batteries, can be recharged in 30 seconds, and will be on the market within two years (*Automotive News*, 1990 and *Metalworking News*, 1990), could radically alter the situation. Isuzu terms this technology based on activated charcoal "electric power storage" rather than a battery and claims its starting power is 40 times greater and its output is 20 times greater than a conventional lead-acid battery.

Lead-Acid

Lead-acid batteries are at present and will continue to be in the foreseeable future the predominate battery system for automotive vehicles. The announced GM "Impact" will use an 870-pound battery pack developed by the Delco-Remy Division of GM. Fiat will market a conventional lead-acid battery powered Panda model ("Elettra") in its domestic market by the the middle of 1990 [a nickel-cadmium battery will be offered as an option] (*Automotive Industries*, 1990).

The lead-acid battery is one of the oldest battery types. Although they are experiencing a period of dramatic technological evolution,—e.g., segmented electrodes and improved adhesion for increased cycle life (Clough & Pinsky, 1990)—they have conceptually remained unchanged since the 1860s. There are some basic advantages to the lead-acid battery: they have a proven track record and are comparatively inexpensive to manufacture. At present it is essentially the only battery type commercially available with applicability to commercially viable electric vehicles. However, there remain significant impediments to increasing commercial application of lead-acid batteries in electric vehicles. Primary among them is power

density versus energy density which is indicative of speed versus range. Because only a small portion of the total amount of materials (lead, lead dioxide, and sulfuric acid) used to initiate the basic chemical reaction to store electrical energy are actually utilized in the reaction, total battery weight becomes a formidable factor in vehicle propulsion. Heavy duty lead acid batteries are currently used in power source applications in forklifts, golf carts, etc. (Powell & Brennan, 1988). In these applications, however, high power density and low weight are not considered a high priority. In fact, for forklift trucks the batteries need to heavy to counterbalance the load on the forks.

Another important consideration is durability or power density. Under the average existing light-duty conditions of starting a car, present lead-acid batteries can have a life span of up to five years, which would be 1500-2000 very light discharge-charge cycles. However, under the extremely strenuous duty of repeated heavy discharges in an electric powered vehicle, estimates of the durability of a battery designed for that purpose decline significantly to as low as 100 cycles. Two hundred cycles appear to be more typical, although given continued R&D some estimates have gone as high as 1000 cycles. Given the considerations of weight and power density, performance and economy become formidable factors in the electric vehicle equation. A disadvantage of present state-of-the-art lead acid batteries is that regardless of the speed-range ratio, they will wear out and the cost of replacing them averages more than the cost of the electricity to charge them.

A number of alternatives to the present state-of-the-science lead-acid battery are being subject to intensive R&D efforts. While each of these systems offer unique advantages, there are also unique problems associated with each type. It is clear that major technological improvements in each of these systems will be necessary before they become economical practical and therefore commercially viable. A comparison of the more likely alternatives must be reviewed vis a vis the characteristics of the present lead-acid battery along the following parameters: energy and power potential, life-cycle cost, and practicality or suitability for EV or EHV application.

A review of Table 1 indicates that there are a large number of candidate battery technologies for EV and EHV application. For the purposes of exposition and education, battery technologies that present the "most likely probability" for commercial application in the near future (considering governmental and private enterprise R&D efforts) will be discussed.

Zinc-Bromine

R&D data suggests that zinc-bromine batteries compare quite favorably with both lead-acid batteries and other battery types. Basically, the operation of the zinc-bromine battery is predicated on a circulating electrolyte. This electrolyte circulation is useful for feeding reactants, removing products, thermal management, and homogenizing the electrolyte. Although the circulation of an electrolyte increases the intrinsic complexity of the system, it does provide for higher specific energy and improved performance. Also the structural members of the battery, including electrodes, can be almost entirely plastic. This extensive use of plastic can, of course, allow for a lighter weight and easier mass production. In addition with the use of a circulating electrolyte, maintenance can be simplified by working on the the entire battery as a whole in comparison to the the maintenance of each individual cell in a system such as lead acid. This modularity facilitates inexpensive partial repairability versus complete battery replacement.

At the present time Johnson Controls, Inc., and Exxon Research and Engineering have ongoing R&D programs on zinc-bromine electric vehicle batteries under a DOE sponsored program. The Exxon R&E laboratory model was loaned to the Ford Motor Company for testing in conjunction with a DOE sponsored drivetrain development program. After FMC testing it was then sent to Johnson Controls for additional parametric testing, teardown and analysis.

Results of these tests appeared to indicate some reduction in capacity which was attributed to zinc shorting resulting from poor electrolyte flow distribution; which was in turn caused by adhesive restrictions in the flow channels. Poor flow distribution may also have been the result of warpage of the electrodes, although to a lesser extent (Zagrodnik & Grimes, 1986). In-use test results also revealed a reduction in power of the zinc-bromine battery. This reduction in power was attributed to severe corrosion of the terminal electrodes (Zagrodnik & Grimes, 1986). Johnson Controls, Inc. is continuing work on this battery system, concentrating primarily on design modifications to overcome the problems encountered in testing.

Nickel-Iron

The nickel-iron alkaline battery, which uses a hydroxide electrolyte, presents only a very modest improvement in energy density over the lead-acid battery. The lead-acid battery has an energy density of 40 Watt-hr/kg, with a cycle life of about 200 deep cycles. The energy density potential of the nickel-iron battery is only approximately 60-90 Watt-hr/kg. This is not really a significant improvement over lead-acid. However, the primary advantage of nickel-iron

batteries is in the extended cycle life, with a potential estimated to be approximately 2000 cycles (Powell, 1988). An additional advantage is that the chemical reaction producing the energy appears to be reversible, which means that the battery can remain idle for long periods of time without injury. In addition it operates at ambient temperatures and therefore does not require expensive, heavy housings. The gases it produces are not noxious or corrosive and it is extremely durable, being able to withstand ordinary mechanical and electrical abuses. The primary disadvantages are relatively low energy values and power density. This translates into a rather heavy and bulky system for a simple four-passenger vehicle.

In a U.S. DOE program, a nickel-iron battery with a specific energy of 57 Watt-hr/kg with a life cycle of more than 1000 has been demonstrated (Brown, 1988). Research and development is continuing on increasing the thickness of the sintered electrodes from from 2 to 4 times the thickness of conventional electrodes. Full vehicle sized batteries are being tested both in the laboratory and on the road.

Sodium-Sulfur

The sodium-sulfur battery is essentially a high temperature system. Operating temperatures must be maintained at approximately 570 degrees F. The electrodes are in a liquid state and the separator is solid; this is a reverse configuration from most conventional batteries. The separator is usually made of beta alumina, a solid ceramic membrane that allows passage of sodium ions, but not electrons or liquid. The primary appeal of sodium-sulfur batteries is a very high cycle life, estimated to have a potential of over 3000 cycles (Powell, 1988). There are, however, formidable disadvantages that make application in passenger vehicles appear unlikely in the near future. There is, of course, the high operating temperature and the need for safe packaging of the molten materials. Also there is the safety hazard of a reaction between sodium and air, particularly moist air. Critics point out that the slightest crack in the system provides the potential for a veritable bomb.

A number of groups have researched sodium-sulfur battery systems, among them Dow Chemical, Ford, GE, U.S. DOE, and Sandia National Laboratories. In an effort to resolve the problem of ceramic membrane cracking after a short number of cycles, Dow utilized very thin-walled, boron glass tubes instead of a ceramic membrane for the passage of sodium ions. Using this process Dow has achieved an energy density of 200 Watt-hr/kg. Sodium-sulfur batteries tested by the DOE have achieved a specific energy density of 136 watt-hr/kg and over 600 cycles. Ford Aerospace and Communication Corp. has a one-third scale vehicle battery which is undergoing testing with a vehicle. The Sandia National Laboratories, Chloride Silent Power Ltd. (CSPL) is also in the process of developing a sodium sulfur battery for EV

applications. The developmental goals are aimed at a battery that will provide a 125 mile range under urban driving conditions in an ETX-II van.

While sodium-sulfur battery technology is promising for EV applications because of its favorable energy, power, and projected cost characteristics, impediments remain in the areas of cell reliability and battery life, and the development of an optimal cell interconnection strategy and a thermal management system.

Lithium alloy-Iron Sulfide

Li-Al/FeS couples were first developed at the Argonne National Laboratories (ANL) in 1973. Within three years they were selected for intensive development for EV applications. These efforts were supported by the U.S. DOE, ANL, Eagle-Picher, Inc., and Gould, Inc. Development programs on various versions of Li alloy/FeS batteries are currently underway in Great Britain, Canada, Japan, Korea, West Germany, and the USSR (Chilenskas, et al, 1989). This system operates at a temperature of 700-840° F; therefore, the outside housing must be an excellent insulator. In addition, the cells must operate under near-vacuum conditions. Never-the-less, an energy density of 80-100 Watt-hr/kg at various discharge levels make it an interesting candidate for EV applications, in spite of the fact that this value within this system assumes a 25% added weight for peripheral devices needed to maintain proper operating temperatures.

A Li/FeS battery system developed by the ANL achieved a cycle life of 125-150 cycles. This was considered unacceptable for intended EV application. The ANL outfitted a Chrysler T-van powered by a 567 kg Li-alloy/FeS battery and it was estimated to have a 109 miles range for a single discharge.

Section Three: Monitoring R&D and Emerging Technologies and Forecasts

Monitoring R&D programs for EVs, EHVs and advanced battery systems is of critical importance in maintaining a perspective on developments that could affect petroleum demand. The following is a listing of major governmental and private enterprise facilitators of ongoing projects related to EV/EHV and battery R&D programs.

U.S. Department of Energy—Office of Transportation Systems

The U.S. DOE—OTS is involved with facilitating many governmental R&D programs aimed at increasing energy conservation, improving energy efficiency, and developing alternatives to petroleum fuels. An integral part of this strategy is to ensure transfer of the results of OTS R&D programs directly to private industry for commercialization. The OTS manages the congressionally mandated "Electric and Hybrid Vehicle Program." It is part of OTS program strategy to ensure technology transfer from researcher to manufacturer for commercialization (DOE, 1989). It is worth noting that 20% of funding dollars for OTS programs comes from cost-shared contracts with the transportation industry (including OEMs and suppliers, battery and component companies; universities, EV users from private enterprise, utility companies, state and local government agencies, as well as the U.S Navy) with industry retaining patent rights (DOE,1989). Current R&D and evaluation programs within the OTS include:

EV Propulsion System Design

The purpose of this program is to oversee the development of commercially viable EV technologies.

The Dual-Shaft Electric Propulsion (DSEP) System

This program, in conjunction with powertrain technology developed by Eaton Corp. and nickle-iron battery subsystem technology from Eagle-Picher Industries, Inc., focuses on the development of light-weight electric vans for an urban/suburban environment. Vehicle modifications necessary to accommodate any realized system will be performed by ASC, Inc.

ETX-II System

This program focuses on the development of light-weight EV vans. Major contractors for powertrain development for this program are the Ford Motor Company and General Electric. Battery subsystem contractors are Powerplex (through Ford) to develop a sodium-sulfur battery system; Chloride Silent Power, Ltd. (through DOE) to also develop a sodium sulfur battery; and Johnson Controls, Inc. (through DOE) to develop a zinc-bromine battery system.

Fuel Cell/Battery Powered Bus

This two-phase program is jointly funded by DOE and the U.S. Department of Transportation (DOT). Phase I consists of cost-shared contracts with Energy Research Corporation, the Los Alamos National Laboratory, and Bus Manufacturing, USA, Inc., to develop an air-cooled, phosphoric acid fuel cell/battery system. Booz-Allen & Hamilton, Chrysler Corp., and Englehard are also contracted to develop a liquid-cooled system. These contracts are for two years after which one the the technologies will be selected for phase II development (DOE,1989).

Considering the opportunity for high-risk technology transfer information in this area, the OTS should be considered a valuable resource. See Appendices One and Two. To facilitate appropriate monitoring, an organization chart of the the OTS Electric and Hybrid Propulsion Division is provided below.
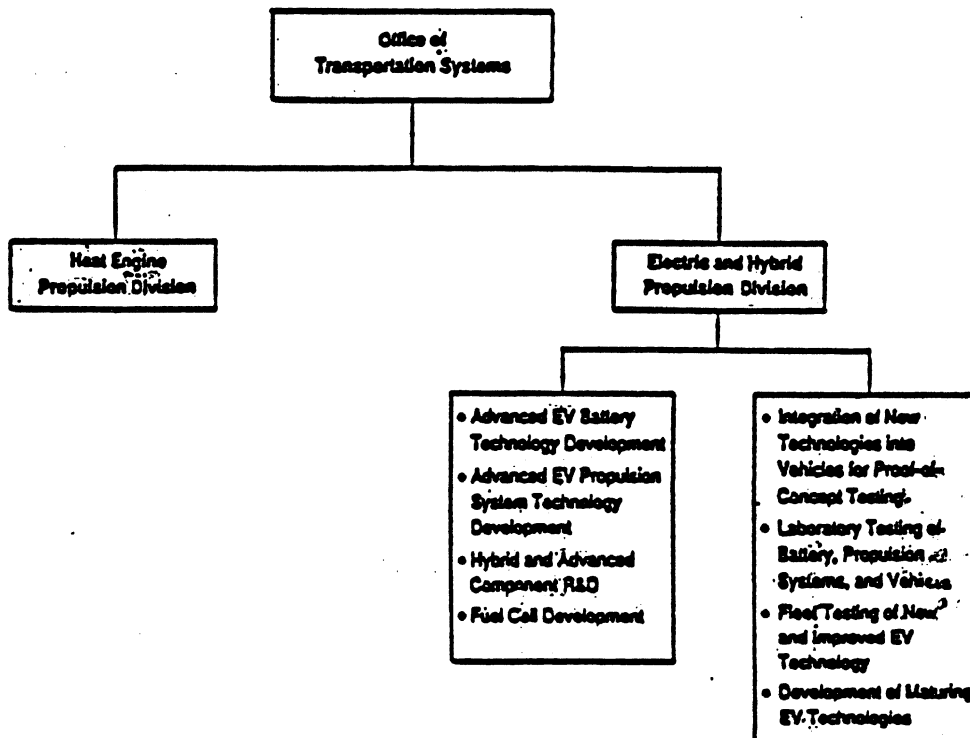
Argonne National Laboratory: Center for Transportation Research, Argonne, IL

Environmental Drivers of Transportation Technology

Project # 49786-40

Study for EPRI (with DOE) of the impact of electric vehicles in the South Coast Basin as part of the South Coast Transportation Plan. As of December, 1989 to begin doing a matrix to focus on which cities are good sites for EVs.

Alternate Fuel Policy Analysis

Project # 49223-00

As part of a study of the Administration's proposed "Clean Fuels Program" (with DOE), develop estimates of selected costs and benefits associated with the use of EHVs; particular emphasis placed on estimating the gasoline displacement levels which can be achieved with EHVs and their comparability to the displacement levels of natural gas and methanol fueled vehicles.

Johnson Controls, Inc.—Battery Group

Johnson Controls—Battery Group is a major supplier of lead acid batteries for automotive applications. It is also the largest U.S. manufacturer of automotive replacement batteries. The headquarters of their Automotive Systems Group is located in Ann Arbor, MI and the Engineering Technology facility is located in Plymouth, MI. In addition there is an Advanced Battery Business Unit located in Milwaukee, WI. This unit is charged with developing battery technology from concept to commercialization. In-progress rechargeable battery system R&D within this unit includes advanced lead acid batteries, lithium solid state electrolyte, lithium solvated electron, and lithium/niobium selenide batteries; as well as hydrogen/nickle oxide and zinc-bromine batteries.

In 1989 Johnson Controls was awarded a cost-shared, three-year contract by the U.S. DOE—OTS to develop a proof-of-concept, zinc-bromine electric vehicle battery

Forecast

Traffic congestion, safety, driving comfort and convenience, environmental pollution, and petroleum shortage are the major concerns related to ground transportation, especially in urban areas. These problems are expected to become more acute in the future decades as traffic demand grows unabated. The push to develop EVs and EHVs is driven mainly by problems of

environmental pollution and potential petroleum shortage. Because of the lack of revolutionary changes of the key technology (i.e., batteries) for EVs, it is very unlikely that EVs and EHVs will find widespread applications in the next 5 to 10 years.

If the unlikely events of a sudden increase of oil prices and a substantial increase of air quality regulations should converge, then it is conceivable that EVs and EHVs will find significant applications in the core cities, especially in such states as California and in such cities as Singapore. A widely accepted scenario would have an increasingly large portion of the urban vehicles first going hybrid, which reduces the objection to EV of inadequate range and performance, and eventually going to dedicated electric vehicles. Meanwhile, even without the convergence of the above-stated events, EVs and EHVs will be developed for certain market segments such as the light-duty electric vans in commercial fleets. Thus, it behooves energy and vehicle suppliers to maintain a vigilant EV and EHV monitoring program in these selected areas; namely, urban cores in California and Singapore, and light-duty commercial vans.

APPENDIX I

Major Participants in OTS Electric and Hybrid Vehicle Programs

Automotive Companies

Ford Motor Company

Component and Propulsion System Companies

Delco/GM
Booz-Allen & Hamilton (BA&H)
Eaton Corporation
Energy Research Corporation (ERC)
General Electric (GE)

Battery Companies

Beta Power, Inc.
Chloride Silent Power Limited (CSPL)
Eagle-Picher Industries (EPI)
Johnson Controls, Inc. (JCI)

Universities

Georgetown University (GU)
Massachusetts Institute of Technology (MIT)
University of Alabama (UAH)
Virginia Polytechnic Institute (VPI)
University of Florida

Fleet Testing Site Operators

GTE
Long Island Lighting Co. (LILCO)
Detroit Edison (DECO)
Arizona Public Service (APS)
University of Hawaii
City of Alexandria, Virginia
United States Navy

Source: 13th Annual Report to Congress for Fiscal Year 1989: Electric and Hybrid Vehicles Program. U.S. Department of Energy/Office of Transportation Systems, p.3, April, 1990.

APPENDIX II

OTS 1989 Program Accomplishments

Significant progress was made in each of the Electric and Hybrid Vehicles (EHV) Program areas during FY 1989. The following are highlights of achievements.

Research and Development

Johnson Controls, Inc. (JCI) fabricated and delivered two flow-by cells and a 6-volt flow-by module based on the use of a forced electrolyte flow. Test results obtained at Argonne National Laboratory (ANL) indicated that the performance of these cells are able to meet the peak power requirements of the Simplified Federal Urban Driving Schedule (SFUDS) at up to 96% depth-of-discharge.

Testing if a 36-volt lithium/iron sulfide module manufactured by Westinghouse Ocean Systems Division and vacuum-insulated case developed by Meyer Tool and Manufacturing, Inc. was completed at Argonne National Laboratory.

DOE initiated a joint program with the Electric Power Research Institute (EPRI) to complete the development and evaluating of a full-scale proof-of-concept lithium-alloy/iron sulfide battery for an electric van.

Westinghouse Electric Corporation directed its iron-air battery research and development (R&D) efforts at increasing the power and extending the cycle of practical bi-functional air electrodes. Cycle life was doubled-from 150 to 300--for 40 cm^2 air electrodes operating at constant current in half-cell tests.

A 64-volt, sodium-sulfur EV battery fabricated by Chloride Silent Power Limited (CSPL) successfully completed over 200 test cycles at ANL. Results of simulated electric vehicle driving tests indicate a projected range of 148 miles for an electric van on the Federal Urban Driving Schedule.

Johnson Controls, Inc., continued the engineering testing of the zinc-bromine battery and began the fabrication of a flow frame specific for EV applications. The R&D program encompassed the development of almost every component of the battery and included studying efficient means of battery packaging for an EV.

A cost-shared, one-year contract for a design study of high-performance sodium/metal chloride batteries for electric vehicles was awarded in August 1989 by DOE to Beta Power Inc.

DOE awarded a two-year, 50% cost-shared, contract in September 1989 to the Delco Remy and Hughes Division of General Motors for the development of a thermoelectrochemical (TECH) system for transportation applications.

The electric vehicle analysis software package (MARVEL) developed by ANL was upgraded with additional battery and vehicle data sets to reflect recent progress attained in battery and EV technologies.

The second Dual-Shaft Electric Propulsion (DSEP) vehicle successfully underwent limited durability and system reliability and compatibility testing in all weather

conditions at the Chrysler Chelsea Proving Grounds in Chelsea, MI. Also, the vehicle either met or exceeded the program goals during performance testing.

The third vehicle in the DSEP Technology Development Program was completed and delivered to Idaho National Engineering Laboratory (INEL) for extensive test and evaluation. The completion an delivery of TB-2 marked the end of the 64-month development effort with Eaton Corporation.

All subsystems developed in the Single-Shaft Electric Propulsion System (ETX-II) Technology Development Program were integrated into the test bed Aerostar minivan and extensive control software development was initiated.

A sodium-sulfur battery developed for electric vehicle application was evaluated successfully in the ETX-II test bed vehicle. Chassis dynamometer test indicate that this battery (in combination with the energy efficient powertrain) will provide a range of over 160 km (100 miles) on the Federal Urban Driving Schedule (FUDS).

The team of Booz-Allen & Hamilton, Chrysler Pentastar Electronics, and Fuji Electric completed the design and fabricated a brassboard system of a liquid-cooled phosphoric acid fuel cell/battery propulsion system for an urban bus.

The team of Energy Research Corporation (ERC), Los Alamos National Laboratory, and Bus Manufacturing, Inc. completed the design and fabrication of a brassboard system of an air-cooled phosphoric acid fuel cell/battery propulsion system for an urban bus.

Test and Evaluation

Project and contract management of the Site Operator Program was moved from Booz-Allen and Hamilton, Inc., to Idaho National Engineering Laboratory. Each of the Site Operators was issued a new contract with E.G.&G. Idaho to continue their fleet testing of electric vehicles.

New software was developed by DOE for the Site Operators field test data. The software placed the actual database in the hands of each fleet manager for entry and access of data. INEL will maintain a master field to be used for analysis.

The test period for the six GM Griffon vans located at Detroit Edison was extended to 1991. The vans continue to operate reliably in a variety of missions including commuting, demonstrations, delivery and special testing. Detroit Edison also completed the testing of the Chloride EV Systems Indirect Battery Heating System and the Aachen Range Prediction Device.

The Energy Research Corporation completed the DOE contract to develop and build an electric vehicle sized nickel-cadmium battery based on their roll-bonded technology. Two battery modules were delivered for testing and a final report was submitted to INEL.

The University of Alabama at Huntsville (UAH) successfully tested a single wire data collection system to replace a multi-wire harness used by the charge controller to monitor module voltages and the ability of their system to control the simultaneous charge of multiple vehicles.

Experimental nickel-iron batteries constructed by Eagle-Picher Industries (EPI) with fiber electrodes successfully completed over 800 cycles in tests conducted at Argonne National Laboratory.

INEL conducted a series of performance tests on a DC powertrain in an electric passenger car, incorporating an inverter driven air conditioner and electric heater/defroster. The vehicle was built by the Soleq Corporation and purchased for use in the Site Operator Program by Arizona Public Service.

A series of acoustic noise tests conducted by INEL determined that interior and exterior noise levels in an electric passenger vehicle were noticeably lower than comparable internal combustion engine (ICE) vehicle during acceleration and idle conditions, while essentially equivalent at constant speeds.

INEL conducted a series of performance tests on a DC propulsion system developed by the Soleq Corporation with partial DOE sponsorship and installed in a full size van. The system incorporated two parallel battery packs for enhanced reliability and a modified automatic transmission with no torque convertor.

The INEL battery laboratory tested a number of near-term of commercially available batteries to determine their suitability for electric vehicle applications, including sealed lead-acid batteries built by Johnson Controls, Concorde and Sonnenschein.

Source: <u>13th Annual Report to Congress for Fiscal Year 1989: Electric and Hybrid Vehicle Programs.</u> U.S. Dept. of Energy/Office of Transportation Systems, pp. 5-7, April, 1990.

References

Akikawa, Y., State of the Art and Overview on R&D and Demonstration for EHV in Japan. In: Proceedings of Eighth International Electric Vehicle Symposium, Washington, D.C./Edison Electric Institute, New York, NY. Report No. CONF-8610122. pp.20-24. 1986.

Automotive Industries, Batteries Included, p. 18, May 1990.

Automotive News. Battery Jolt: Isuzu Cell Shocks Industry, p. 202. April 23, 1990.

Automotive News. Autopower in the 90s: Energy & Power; Fuels of Tomorrow. p. 202. November 29, 1989.

Berg, M.R., et al. Electric Vehicles Market Assessment and Demonstration Planning for Commercial Applications. University of Michigan, Institute for Social Research, Ann Arbor. PhD Program in Urban, Technological, and Environmental Planning. 117 p. 1983.

Brusaglino, G., Electric and Hybrid Vehicles Status and Development in Europe. In: Proceedings of Eighth International Electric Vehicle Symposium, Washington, D.C./Edison Electric Institute, New York, NY. Report No. CONF-8610122. pp.7-19. 1986.

Brown, P.J., et al. Potential or Electric Vehicles in Present and Future Transportation Systems. In: Proceedings of XXII FISITA Congress, Automotive Systems Technology: The Future, Vol. 2, Dearborn, MI, SAE P-211, pp. 2.658-2.660, 1988.

Brown, P.J., Overview of the U.S. Government's Electric Vehicle Program. In: Proceedings of Eighth International Electric Vehicle Symposium, Washington, D.C./Edison Electric Institute, New York, NY. Report No. CONF-8610122. pp.4-6. 1986.

Chen, K.; Winter, R. C.; Bergman, M. K. Carbon Dioxide from Fossil Fuels: Adapting to Uncertainty. 13 p. Energy Policy, Vol. 8, No. 4, 1980, pp. 318-330.

Clough, T. J., and Pinsky, N., Durable Bipolar Plates for Lead-Acid Batteries, NASA Technical Briefs, p. 22, 1990.

Cole, D., & L. Harbeck, Delphi Forecast and Analysis of the U.S. Automotive Industry through 1992 - Delphi III. The University of Michigan, Ann Arbor, MI, 292 p., 1984.

DeLuca, W. H., et. al. Temperature Effects on Ni/Fe Battery Characteristics. In: Proceedings of Eighth International Electric Vehicle Symposium, Washington, D.C./Edison Electric Institute, New York, NY. Report No. CONF-8610122. pp.4-6. 1986.

General Motors Corporation. Impact. News release, General Motors Technical Center, Warren, Michigan. January 3, 1990.

Hoffman, G.A. Hybrid Power Systems for Vehicles. Symposium on Power Systems for Electric Vehicles, Columbia University, New York City, April 6-8, 1967.

Metalworking News. Isuzu Motors, Fuji Plan Commercial Production Of New Storage Battery, p. 10. April 23, 1990.

Miller, J.F., & C.C. Christianson, Batteries for Hybrid Vehicles or Other High Power Applications. In: Proceedings of the Eighth International Electric Vehicle Symposium, Washington, D.C./Edison Electric Institute, New York, NY. Report No. CONF-8610122, 1986.

NAFA Fleet Executive, California Proposal Mandates "Clean Fueled" Fleet Vehicles. December 1988.

O'Connell, L., Electric Vehicles: Their Future Role in Transportation, In: Technology Options For Highway Transportation Operations. Institute of Transportation Studies, Berkeley, CA./ California Department of Transportation, Sacramento. Report No. UCB-ITS-P-87-1. pp.148-156. 1987.

Powell, J.D., and R. P. Brennan, The Automobile: Technology and Society, Prentice Hall, New Jersey. 1988.

Programs in Energy Conservation: Transportation Systems, U.S. Department of Energy, Washington, D.C., 13 p., 1989.

Roberts, L., Global Warming: Blaming the Sun. 2p. Science, Vol. 246, 24 November 1989, pp. 992-993.

Saridakis, N., and W. Josefowitz, Hybrid Petrol-Electric Power System in the VW "GOLF" - Vehicle Conception and test Results. In: Proceedings of Eighth International Electric Vehicle Symposium, Washington, D.C./Edison Electric Institute, New York, NY. Report No. CONF-8610122. pp.241-247. 1986.

Sedgwick, D., GM Readies Electric Impact, The Detroit News, pp. 1 - 3 D, April 15, 1990.

Smith, G.E., Impact of Electric Vehicle Use on Environmental Problems, Appendix A in K. Chen, P.P. Appasamy and M. Donahue, Environmental Problems Anticipatory System, Report to the U.S. Environmental Protection Agency (CR-807332-01-0), December 1982.

South Coast Air Quality Management District, Public Workshop Notice. Proposed Rule 1601 - Fleet Conversion for Passenger, Light-Duty, and Medium-Duty Vehicles. February 26, 1990.

Wang, Q.; DeLuchi, M. A.; Sperling, D. Emission Impacts of Electric Vehicles. University of California, Davis. 40 p. Preprint paper No. SAE 890682. 69th Transportation Research Board Annual Meeting. January 7-11, 1990.

Wouk, V., Two Decades of Development and Experience with Hybrids. Victor Wouk Associates, New York City. 1987.

Zagrodnik, J., & P. Grimes, Testing of a 30 kWh Zinc-bromine Electric Vehicle Battery, In: Proceedings of the Eighth International Electric Vehicle Symposium, Washington, D.C./Edison Electric Institute, New York, NY. Report No. CONF-8610122. pp. 344-349, 1986.

Chapter Five: Mass Transit Innovations—2000 To 2010

Charles Wright, University of Brasilia

and

Howard M. Bunch
University of Michigan Transportation Research Institute

Section One: Current Status

The term "mass transit" will be used to include bus transit, guided transit, and rail transit, avoiding an overly restrictive use of the term to only rapid rail transit. A more complete description of the individual technologies and their variations is presented in the appendix. Herein we will summarize the chief attributes of each generic class and the state of the art in research and applications for the period 2000-2010.

Bus Transit

With the exception of a few fuels and their respective propulsion systems, bus transit technologies are well defined and at least reasonably well tested in several countries around the world. In most urban settings, the chief innovations are likely to be of an organizational nature; i.e., learning to use bus transit systems better in different urban contexts.

Rights-of-Way Classification

Organization systems may be classified on the degree of exclusiveness of their rights-of-way (ROWs).

Lanes reserved for high occupancy vehicles (HOVs). A lane in an avenue or freeway is reserved for carpools, vans, and buses. Usually, no physical separation is used, with the lane being identified with paint on the lane itself (e.g., a white diamond painted on the surface of the lane) and by signs. Such lanes are easily invaded by other vehicles and are often ignored or short-lived. They work best on freeways (longer routes with several lanes) and are useless on city streets. Examples of the first category include a section of I-66 near Washington, D.C., and on I-5 in Seattle; and of the latter, a short stretch on Glen Avenue/Fuller Road in Ann Arbor and the "Little Axes" in Brasilia (the Brasilia version was formally abandoned a few months after implementation).

Bus-only lanes. Like above except only buses allowed. These are rare because of reactions of other drivers who are tempted to use the lane and the reduction of road space

77

available for other vehicles. When bus traffic is intense enough to justify an exclusive lane, there is a tendency to provide physical separation of some sort, transforming it into a busway.

Busways. These may be roadways specially built for buses or lanes separated by curbs or other devices. An exclusive busway will have its own access and exit facilities including a special roadway or physically separated lane. Pittsburgh, Los Angeles (El Monte), and several Brazilian cities, such as Sao Paulo, Rio de Janeiro, and Curitiba operate examples of these systems.

Guided Busways. Prefabricated concrete slabs are placed on compacted soils on each side of the busway with a "L" on each side approximately 7 inches high. Lateral wheels mounted on all-steerable wheels press against the up-side of the "L" and guide the bus (or trolleybus) along a perfectly defined path. At least three types of lateral wheels are available, two are extended by the bus driver upon approaching the guided section while the third is permanently attached to the wheels and slightly extended to the outside. Such systems are being researched in Japan and are in operation in Adelaide (Australia) and Essen (West Germany). The Adelaide system operates much like a train and enjoys a specially prepared exclusive busway, but it is possible to insert sections of a guided busway on city streets, with reduced levels of efficiency. Mercedes-Benz has been involved in these developments and makes buses equipped for this type of operation. Most research of this sort and the practical experiences use simple and reliable, mechanical lateral wheels.

Fuels and Propulsion

Conventional buses can now be run on methanol, ethanol, natural gas, and LPG, aside from gasoline and the predominant diesel fuel. Both spark-ignited engines (the MAN D2566 FMUHO) and diesel engines using glow plug assist (the DDAD 6V-92TA) have been successfully run in bus operations, and meet forecast regulations on particulates. Alternative systems using natural gas and ethanol have been extensively used or tested in heavy truck and bus operations in Brazil and a few other countries by multinational companies such as Mercedes-Benz, Scania-Vabis, and Volvo and smaller local firms. Electric-drive buses are a proven technology, although little-used presently in the United States and with much higher capital costs and lower flexibility than diesel buses. If electrified roadways come into being (a topic outside this research) a bus using a battery for propulsion would be possible as well. A 35-passenger prototype has been developed by Systems Control Technology for the city of Santa Barbara. The battery would be charged by an inductive power transfer system built into the roadway and is to be tested on a 400-foot electrified test track. Mercedes-Benz has been

exploring the use of hydrogen as fuel, a concept that, if viable, would obviously be an alternative for buses.

Functions of Transit and Roles of Transit Authorities

The limits of mass transit technologies can be partly compensated for by integration of traditional bus and rail services with vanpooling, carpooling, and private transportation. Efforts by transit authorities to promote the mobility of the population instead of merely administer a static public mode are occurring in some centers. Examples of such trend setting innovations include Houston's integrated systems connector framework, now in the implementation stage. Light rail transit, automated rapid transit/advanced rail transit, HOV lanes, busway transit, and traditional buses are all linked to strategic connector and transfer facilities, in a city whose growth occurred with very little public transport and led to extended gridlock areas. Washington Metro's integrated system is built around the rapid rail transit system with automated control and significant amounts of HOV lanes and active encouragement of carpooling and vanpooling.

Use of Various Bus Sizes and Combinations

Unlike other countries, American buses have typically been of a near standard size and little experimentation has been done with articulation. Mini-buses are better suited for such tasks as serving low density routes, transporting the handicapped and for flexible route transit while articulated buses (one driver in the first bus, with a trailer or even two trailers attached behind) offer high-capacity service on more dense routes, especially during peak hours. Articulated buses can be seen in many European cities (e.g., Hamburg) and are quite frequent in Brazil's major cities. They can be built by almost any bus manufacturer, with Mercedes-Benz, Scania-Vabis, and Volvo versions available, among others. Swiss transit authorities have been working with industry to decrease tracking and stability problems encountered with towing a two-axled vehicle, and Mercedes-Benz has been involved in investigations of configurations of towing two vehicles behind the main bus.

Guided Transit

This category includes a wide variety of systems, many of them proprietary, whose distinguishing characteristic is full automation without drivers or attendants on-board. They may be somewhat arbitrarily classified in the following manner.

Monorail Transit

A monorail system operates on an exclusive ROW composed of a single rail, usually as a concrete beam. The vehicle/train either is suspended from the beam or rides astride it, with several different systems of traction and propulsion being used. The most common systems to date are the straddle-type monorails, since full-sized suspended monorails ordinarily need more costly support systems and have problems with wear at the points where they are suspended. Straddle-type monorails typically use rubber tires on the concrete beams, resembling elevated train systems in other respects. To keep the vehicle from falling off the beam, counterpendular pressure is applied to the sides of the beam through horizontal wheels. This has the disadvantage of increasing the cost and weight of the vehicle, along with friction and energy losses in its operation. However, the chief technological limit is the need to move the entire beam to complete a switching operation, a time-consuming process and one which makes it difficult to develop a network of monorails. So, their applications tend to be limited to loops or shuttle-type services, such as airport to downtown, within downtown, or at amusement parks and expos, where almost all those now in operation are found (e.g., Disney World, Yokohama Dreamland). Japan, however, has 8.4 km of double track in Kitakyushu in use as an urban transport mode and has several others in various stages of planning or implementation.

The chief reason for the growing popularity of monorails in Japanese urban transport is that the monorails can be built in the median of highways and being considered as part of the roadway, qualify for subsidies from highway funds in that country. Although higher capacities are possible, most straddle-type monorails operate, at best, with maximums of nearly 6,000 persons per hour per direction. Despite having no costs to obtain their ROWs in Japan, such systems are very costly: the average cost of four systems came out to about US$60 million/km, with half of that cost for the guideway. Japan has a group of firms engaged in monorail development, including Hitachi, Kawasaki, Toshiba, and Mitsui.

An interesting variation on the monorail is the Coester Aeromovel (or "airtrain") which has overcome most if not all the R & D problems in the last few years. This experience started with a short experimental stretch in the Brazilian city of Porto Alegre in the early 1980s with governmental support, but is now essentially a commercial enterprise with a realistic 3.2 km line in operation in a large park in Jakarta (Indonesia). Unlike the rubber tired versions of monorails with their heavy motors and suspension systems, the airtrain runs on two steel rails (1.6m gauge) and has no motor or other heavy appendices on board, reducing the weight of the car to about a third of that of a conventional railcar while retaining about the same capacity. Power is supplied by an inverted sail or plate placed in the hollow beam (monorail) which

provides the system's support and guideway. Large industrial fans are used along the beam to provide low-pressure eolian power on the sail or plate. The openings around the plate and the shaft which connects the plate to the railcar above cannot be completely sealed, so that energy losses do occur, roughly compensating for the decreased weight, so that the airtrain is about as energy efficient as choices such as trolleybuses or light rail systems. Switching is carried out by opening and closing ducts with computer activated hydraulic levers with efficiency at or above that of conventional rail systems. Each car or articulated car operates as a unit, supplying high frequency service. The cars can go up steep grades (10%) and make sharp turns (radius of 25m).

Today there are no urban transportation experiences with the airtrain technology (several cities are considering it with other options), it is difficult to say what the actual capacity and cost of the airtrain in an urban setting will be. It appears possible, however, that 10,000 persons per direction/hour can be attained, and the cost of the Jakarta airtrain (which involved no ROW costs) for guideway, station, vehicle, and other components were U.S.$4 million/km. This is, however, a loop-type system, so that a two-way line would cost nearly double that amount and additional requirements (stations in urban areas, elevators for the handicapped, etc.) would add expense onto those figures. The proprietary airtrain system is being developed by a Brazilian consortium (US office: Sür Coester Aeromovel, Suite 221, 2025 I Street, NW, Washington, D.C. 20006, Telephone 202-223-3805). The firms involved have considerable knowledge in production of navigational instruments, elevators, and mechanical engineering, with some experience and applications in marine systems, aviation, and other areas.

Mini-Metro Systems

Mini-metro systems are similar to rapid rail transit except for full-automation and shorter trains and platforms (in some cases smaller cars as well). Capacity is approximately 10,000 to 20,000 passengers/hour/direction. Linear induction is an alternative (Vancouver Skytrain, German, and Japanese research), with conventional steel-wheel-on-steel-rail rather than linear induction with magnetic levitation, as is being considered for intercity transportation in Germany and Japan.

Automated Guided Transit

These systems share the airtrain characteristic of being proprietary systems. They have, at the upper end, capacities that approach 10,000 persons/hour/direction and monorail type operation, and at the lower end, very low-capacity cable car systems which operate at low speeds and with room for only about three passengers per car. The proprietary aspect means

that a city interested in one other these systems would have to purchase it from the manufacturer. Some of these include Walt Disney, LTV-Vought (Dallas-Ft. Worth airport), Westinghouse (Atlanta airport; Busch Gardens, Va., amusement park; Miami airport), Otis Elevator (Duke University campus) and Boeing (Morgantown campus), Soulé Corp. (Paris-Nord expo) and TAXI 2000 Corp. Most of these systems (including the planned versions) are loop or shuttle-type operations with obstacles to networking. Some low-capacity systems such as TAXI 2000 attempt to introduce flexibility with the use of small units and networking through off line stations. To date, however, none of the very low-capacity small car systems has ever ventured outside the expo or amusement areas into an urban traffic setting. The cost of the Soulé version is estimated by the manufacturer at US$5 to US$12.5 million/km without civil works. The closer these systems come to monorail-type capacities, the closer they approach the monorail costs.

Rail Transit

Other than the aforementioned changes in organization to provide them with greater integration with other modes and some enhancement of passenger attraction features, most rail systems have a modest inventory of expected innovations. The modest agenda includes phasing out diesel-electric on-board drive and other non-electric systems (a continuation of a many decades long trend) and some use of lighter materials. However, linear induction (a linear motor in the car with magnetic plates in the railbed providing attractive and/or repulsive force to drive the vehicle) will be experimented with on some more modern systems, probably with conventional steel-wheel-on-steel-rail support and guidance systems on shorter routes and those with frequent stops. Magnetic levitation (a lighter vehicle subject to magnetic repulsion floats on an air cushion) will be experimented with on longer routes. This latter version may or may not continue to be considered as outside the scope of urban mass transit as longer distance commuting becomes more important.

Commuter Rail Systems

These are composed of conventional rail systems, with long (e.g., to 10 car) trains and requirements for long stations and often low degree of automation and low frequency service. Some systems still have diesel-powered locomotives. Altogether, users have very negative perceptions of commuter rail services, although it is often characterized by high speeds (130 km/h cruising and to 70 km/h average). Upgrading will probably be limited to electrifying a few diesel operations with significant demand and to improvements in track and geometry. Meaningful changes would place most of these systems in regional high-speed rail connections (see below).

Light Rail Transit

This technology varies from streetcars to more sophisticated rail systems with exclusive ROWs liken to rapid rail systems, differing only in number of cars per train (fewer than rapid rail) and the frequency of service (lower in the non-streetcar versions of LRT). Higher degrees of automation are likely to be sought as a way of reducing, operating costs on these systems, with attempts to better integrate them into the overall transportation picture. Sometimes, they may also become targets for the employment of linear induction propulsion.

Rapid Rail Transit

High-speed, high-capacity systems, capable of carrying 40,000 to 60,000 persons/hour/direction under conditions of crush loading. Examples include the subway/metro systems of New York, Chicago, and Philadelphia. Again, this is a proven technology with little innovation expected, with some older systems (e.g., New York) in need of upgrading facilities. These are, however, very high cost systems. The metros of Sao Paulo, Rio de Janeiro, and Japan have cost nearly US$85 million/km, US$115 million and up to US$160 million/km for stretches built in recent years. A major cost involved is that of obtaining ROWs and station space in highly valued urban areas.

Regional High-Speed Rail Connections

It may become possible—at a high cost—to have high speed connections with few stops between major nodes/cities, substituting for air travel. Presently the fastest AMTRACK express train on the Northeast Coast attains speeds of up to 200 km/h on some stretches while mag-lev systems have cruising speeds of nearly 500 km/h and even this does not approach the possible limits of this new technology. Today Transrapid International (composed of the German firms of Krauss Maffei, MBB, and Thyssen Henschel) has plans to link Disney World to Orlando's airport with the world's first commercial mag-lev system at a projected cost of US$20 million per km, much less than many freeways. This cost, however, does not include ROWs and is probably underestimated, and recent problems with the concession may delay or otherwise endanger the project. Many other sites in California, Nevada, Texas, Florida, and other states are also in various stages of studies and plans for construction of mag-lev systems. Prototypes have, however, included a shuttle which carried 50,000 passengers at a transport expo in Hamburg in 1979 and another which has reached speeds of 495 km/h. Their reduced noise levels make them preferable to steel wheel/steel rail technologies in urban and suburban areas.

<div align="center">

Section Two: Barriers and Drivers

</div>

The barriers to use of the mass transit technologies by the 2000-2010 period are divided for the purposes of this report into technical, economic and political/social barriers.

Technical Barriers

Relatively few of the innovations described above appear to be subject to major technical barriers, although many questions remain as to what cost are involved and in what circumstances they can be used, given their technical characteristics.

Bus Transit

All innovations described above appear to be technically feasible, excepting the novel/dangerous propulsion systems (electrified roadways and hydrogen) which remain very much in doubt. Since the electrified roadway concept is not included in the scope of this report, a convenient observation is that if it ever becomes practical for cars it will be viable for buses as well (the same comment is also applicable for hydrogen as a fuel). Indeed, the electrified roadway idea may be valid for busways even if it cannot be safely employed in a general way on city streets, but could be on specific, grade/horizontally separated, high density routes. Technologies for ethanol, natural gas, LPG, and electric buses are now commercially available as part of technologically proven systems. Some environmental doubts may of course emerge regarding ethanol, methanol, and any of the other fuels (including electricity from thermal or nuclear sources).

Mini-buses and vans present no important technical problems, and tracking and stability problems with articulated buses also have solutions, either specific to bus operation or available by borrowing from experience of multi-unit operation in the road haulage industry. The guided busway systems have some problems when the busways have to be placed in the street system with at-level crossings and parallel car traffic. These will require additional construction to reinforce the upright part of the "L" providing lateral guidance to avoid breakage by other vehicles which would otherwise accidently come into contact with the guideway, and will place limits on speeds and reduce somewhat the quality of service. The basic concept and presently available steering wheels appear to be sound, however.

Guided Transit

The monorails have inherent disadvantages in switching operations which limit their ability to form a network (These are least in the case of the airtrain). Otherwise they may be

<div align="center">

84

</div>

regarded as a proven technology. Mini-metro systems may also be thus regarded, with some question regarding the reliability of proposed linear induction systems in heavy, demanding commercial use. The risks appear to be rather modest, however, for the linear induction systems which run on the steel wheel/steel rail combination, as appears to be appropriate for use in urban transportation with frequent stops and short distances. The proprietary automated guided transit systems usually face same barriers as the monorail to efficient networking, but otherwise several of the currently available systems may be regarded as proven technologies. Several, however, have inherent capacity barriers, in that they have low-capacity cars, necessarily low average speeds and minimum headways which, while lower than the other systems, do not compensate fully for the other limiting factors.

Rail Transit

No technological barriers apply to upgrading the commuter rail systems, or in expanding marginally improved versions of light rail and rapid rail systems. There are, however, practical limits on minimum radius of curvature and maximum grade, along with substantial requirements of space for stations which constitute inherent limitations on the areas they can be placed in without incurring very high costs of obtaining ROWs and station space. Linear induction with conventional steel wheel/steel rail configurations for support and guidance appears capable of reducing the limitations on grade and curvature substantially, and also require less space for tunnels and other clearances. The high speeds of maglev systems cannot be utilized in urban settings since the tolerances of passengers to acceleration and deceleration near closely spaced stations are quite low and energy requirements also quite high. Those systems appear to be fully capable of use, however, on longer routes and from airports to downtown areas.

Economic, Political, and Social Barriers

The long standing trend toward suburbanization restricts the population and trip densities that are the most important variables for mass transit. Although in 1980 half of the US population lived in metropolitan areas with over a million residents and a third of the population in metropolitan areas of over 2.5 million, most of the growth in both population and jobs occurred in the suburbs rather than in the central cities. The work trip now most important in these areas is suburb to suburb, the trip type least susceptible to transit, particularly rail and guideway technologies. Only some 23% of personal trips are to/from work or work related, and the other 77% are less compatible with transit than the journey to work.

Private car ownership in the US now exceeds both the number of licensed drivers and the number of workers. Once the fixed cost of owning a car has been incurred, out-of-pocket costs are usually comparable to subsidized transit fares (a typical calculation involves gasoline versus fare).

Additional barriers to the more widespread adoption of rail mass transit include:

• The lack of flexibility of transit systems;

• User acceptance of transit is hurt by fear of violence, along with the presence of begging which occurs in the vicinity of many stations and the entrance of the homeless in some systems, most notably New York;

• The excessive time necessary to implant rail systems, which tends to erode public support for their construction (plans for the Washington Metro were advanced in the early 1960s, but the system is still not complete);

• The very high capital construction costs, which are unlikely to be below US$40 million/km for any high capacity rail system and can easily reach the range of US$85 to US$160 in some urban settings;

• The high operational cost of most rail and bus systems in the United States in relation to farebox revenue and other non-subsidy income. Transit is seen as sort of a "black hole" for tax dollars, since no transit authority in the US covers its operating costs, much less pays for its capital costs (the same holds for most other Western countries, such as West Germany);

• Recent negative experiences with predictions for mass transit in American cities, with ridership far below levels predicted by prior cost-benefit studies (these experiences include Washington, Atlanta, Portland, Baltimore, Pittsburgh, Miami, and Sacramento);

• HOV lanes are always opposed by private car owners and in some cases have been challenged in court;

• Overall negative attitude of governmental officials with respect to mass transit. An example is Secretary Skinner's declaration in the January meetings of the Transportation Research Board that state and local governments had in the past been encouraged to make bad decisions due to the availability of federal funds and that they would be required in the future to "up the ante"; i.e., there would be less federal participation in mass transit;

• The poor financial situation of most state governments and municipalities in face of the investments needed to significantly upgrade and marginally extend existing systems (US$15 billion sought for New York City alone over a five-year period);

• Although environmental concerns generally favor transit with respect to private automobiles, emissions standards for buses are scheduled to go into effect before those of other vehicles and are very stringent. If actually put in place at an early date, these requirements could have a devastating effect on the economics of local transit authorities and result in reduced service in many locations, further eroding ridership and citizen support. Other concerns include noise for buses and steel wheel/steel rail

86

modes and any mode which includes elevated structure (considered unsightly or inappropriate in many urban locations);

• Availability of electric energy.

As seen in Step 1 of this report, with the possible exception of buses, transit options rely heavily on electric energy. The lack of easily harnessable watercourses not already in production in the United States and concerns about the safety and environmental effects of nuclear energy and reservations about thermoelectric plants may result in substantial increases in the price of electricity and in enhanced competition from residential and industrial/commercial sectors, as has in fact occurred in Brazil, for example. This restriction could of course be relaxed by innovations not considered in detail herein, such as solar energy production on a commercial scale and commercial nuclear from cold fusion, both highly speculative concepts at the present time.

Section Three: The Forecast

Present Status of Mass Transit

From 1960 to 1980 transit lost 50% of its share of urban passenger trips, along with a small decline in absolute numbers as well. In 1980 there were only 6.2 million daily commuting trips by transit taken in the United States, compared with 83 million commuting trips for private automobiles. One third of all transit trips occurred in New York and the bulk of the remainder in metropolitan areas of over one million population, typically in the central cities. The movement of population toward the suburbs of metropolitan areas—at times with the decline in absolute numbers of central city population—put transit in an even poorer competitive position. Commuting is the strongest market for transit, accounting in 1980 for 6.2 million of 14.3 million round trips (42%), against 83 million private car commuting round trips (23% of private vehicle trips). The low percentage of commuting trips in the private car trip total shows the extent to which social, educational and recreational trips now predominate among car trips (77% of all car trips). With respect to the commuting trips, the figures do not change appreciably if distance figures are used instead of trips, since average distance for transit and private car are similar (a bit shorter for buses and streetcars and somewhat longer for RRT and commuter trains). Carpooling and vanpooling are now of very reduced importance in commuting. Private vehicle occupancy on commuting trips has fallen below 1.15, indicating that even workers of the same household are travelling separately by private car in the vast majority of cases. However, in 1980 there were about 1.8 million commuters in vans with at least four passengers, a fairly recent phenomena.

Continuing Trends Status Quo Scenario for Transit

Given the weak position of transit options with respect to current trends, the status quo scenario for transit in the US would imply continued growth in private car usage which will hold transit in check, with decreases in transit's already low share of the personal transport market and possibly even some decreases in the absolute numbers of transit riders. However, given that a number of new transit systems in larger American cities have been implanted recently or are now being implanted or upgraded, a "most likely" forecast would be an increase in ridership to the order of 8 million daily passengers by the 2000-2010 period. This level would represent an increase of nearly a third in absolute terms and approximately enough to stabilize transit's percentage share at its current level of some 7% of motorized commuting trips and perhaps some 1-2% of overall motorized urban trips (excluding walking and cycling).

External Shocks Scenarios

Although the pattern is clear for transit's limited role in the scenario which projects current trends of relevant variables into the future, some scenarios could give transit a substantial boost in absolute ridership levels and even its percentage share. These scenarios include: (a) strict environmental regulations on emissions and the continued lack of availability of satisfactory alternative fuels in the automobile market; (b) very drastic increases in the price of petroleum based fuels in constant dollar terms (placing gasoline in the $4.00-10.00/gallon range); (c) critical gridlock situations in most urban areas; and (d) some combination of the above, such as alternative fuels which meet emissions standards and which are channeled to mass transit, including buses, due to limited availability/high cost, with very high prices used to discourage use of petroleum based fuels.

If such shocks occurred, the rail-based modes using traditional technologies with minor innovations could not respond to a need to increase transit's share in total urban travel or commuting to levels approaching those of South America, Europe or Asia. Through some expansion and upgrading, with additional rolling stock and increased use of automatic traffic control on systems where it is not already in place, they might be able to double their current number of riders.Such an option would involve considerable public expense and might not be politically feasible. Newer and as yet still unproven technologies (linear induction with steel wheel/steel rail) would be even more expensive (probably involving US$30-60 million/km to build). They could, however, more easily overcome restrictions on physically fitting a rail system into the urban fabric, due to their less rigorous requirements for grades and turning

radii. New but traditional technology rapid rail systems would be at least that expensive due to the need to overcome the turning radii handicap and consequent right of way costs. Even streetcar options would be very expensive to create and would provide low performance.

The monorail and proprietary automated guided systems are even more limited due to the restrictions on formation of networks and would typically involve US$30-60 million/km to build as well. The only technology which at present appears to be fully viable for immediate commercial application and to offer medium high capacities with networking possibilities is the Sür-Coester Airtrain, at some $10-15 million/km of double lane routing. Even this innovation, however, is likely to find only special use applications (airport to city center, loops in central business districts, etc.).

The most favorable technological options for responding to shock scenarios involve bus systems and improved transit administration in which buses play a major role (see description in Step 1 of this report). Most buses have low loading factors and do not reach crush capacity even at peak hours, permitting a significant short term response with given rolling stock. Although this is also true of most rail systems, bus operations require only additional vehicles and drivers to extend and intensify transit, while rail and proprietary AGTs may require a decade or more to actually begin to transport passengers. The magnitudes of the above cited capital costs for new rapid rail and AGT infrastructure make it doubtful if sufficient funds may ever become available for them to vastly expand their services. Over a long time frame such as 1990-2010, there would be no barriers to obtaining sufficient numbers of buses (with or without cleaner fuels) or electric buses to respond to large percentage increases in US transit ridership. Integrated facilities (park and ride, foot/bicycle to bus stop, bus/train transfer points could significantly increase ridership as well.

Carpooling and vanpooling offer the most logical and far-reaching responses to external shock scenarios. Although not traditionally considered transit, they could receive special public policy treatment and even coordination, via use of an increased number of HOVs and parking priorities. These options involve very little public investment and are a very efficient way to combat the problems listed in the external shock scenarios, at least initially.

Combined Effects of Responses to External Shock Scenarios

There are obviously a very great number of assumptions implicit in constructing external shock scenarios, and the assumptions influence in a very direct and significant fashion the magnitudes of the estimates obtained regarding modal split. The shock phenomena

considered above (emissions regulations, real price increases of 4-10 times in fuel costs and expanded gridlock) are extremely serious but perhaps not entirely catastrophic. It is worthy of note that the most serious shock considered would probably be the extremely large real price increase without the availability of alternative fuels in realistic quantities and competitive prices.

The most significant response to such a scenario would be a decrease in non-commuting, non-work related travel, which now accounts for some 77% of private car trips and only some 57% of transit trips. Given the constraints imposed by geographical location, the most logical response for maintaining essential travel would be the formation of carpools and vanpools. Thirdly, bus transit would receive a significant boost, possibly tripling its current total number of passengers. A distant fourth response would be renewed interest and investment in rail and proprietary AGT systems, and even in such a case the assumption must be made that the economic shocks induced by such a large real price increase would still allow vast investments of public funds in these transit systems.

The combined effect of such scenarios for the period considered would be something like the following:

- A doubling of rail and AGT combined number of commuting trips and commuting passenger x km;

- An increase of over two times the absolute numbers of bus trips and passenger x km, resulting in the tripling of total commuting transit passengers to the order of 18 million/day;

- Total transit trips (including trip purposes other than commuting to work) would increase much less, probably only by a factor of 2 or 2.5;

- There would be a very great reduction in private car use, due primarily to decreases in non-work related trips which now constitute the bulk of private car travel (77%). This, along with an increase in private car loading figures, would solve the gridlock problem and go a long way toward reducing the emissions problem;

- Vanpooling and carpooling would increase exponentially as a relatively fuel and emissions efficient alternative to transit, with low investment costs and considerable flexibility. Although not traditionally considered as transit, it is clear that pooling serves many of the same purposes and would be so treated by public authorities.

External Shocks in the Other Direction

From the preceding discussion, it is clear that the residence and job location patterns in the United States and the almost universal car ownership patterns among workers make it very difficult for transit to vastly expand its current and rather insignificant role in the urban transportation picture. Even under shock scenarios favorable to transit, it could not easily

approach the levels of use which are common in other countries. The converse also applies: if fuel continues to be low priced, if environmental restrictions are applied first and most stringently to buses, and if alternative fuels become available at low cost for private cars (say a hydrogen or solar powered, high performance car), the future of transit in this country will be very bleak indeed.

High-Speed Rail Transit

Steel-wheel-on-steel-rail technologies promise little innovation in the Japanese/French tradition, and are unlikely to be attractive on corridors other than the Northeast, where a low grade form of the high speed technology is already in operation. It cannot be emphasized too much that the high speeds in themselves make such transportation inviable for most intra-urban trips, so that their potential usefulness is limited to intercity routes. In these cases, linear induction and particularly maglev technologies (only these provide ultrahigh speeds and stable rides) may become an alternative for longer distance commuting and on special routes of intermediate distances (such as airport to city center). Due, however, to the need to integrate the widely spaced stations with other forms of surface transportation (e.g., rental cars or privately owned cars for business or home-based travel) it appears unlikely that such an alternative will become popular in the period studied. If implemented at all, this technology is likely to be limited to intermediate length intercity routes where it can offer a substantial time savings with respect to all other forms of surface transportation and not loose significant amounts of time with respect to air travel (including the loading/unloading and scheduling delays associated with air travel).

Monitoring Key Developments

Throughout the earlier sections and steps on mass transit, the names of companies and agencies have been given to facilitate future contacts should a need arise. Clearly, however, there are few scenarios in which mass transit would be likely to become responsible for a substantial share of motorized urban travel in the US by the 2000-2010 period.

In terms of total travel, the best transit strategies include improving bus services and encouraging vanpools and carpools (i.e., by taxing parking space and considering as business expenditure company disbursements for bus tickets and van provision). HOV lanes are to be encouraged. These are typically low-tech and administratively dispersed, with no single company or agency that can be contacted for monitoring. The more interesting possibility from the viewpoint of monitoring would seem to be alternative fuels for buses, including the possibilities of adapted diesel motors for CNG, LNG, ethanol, methanol, and other fuels.

Mercedes-Benz and Scania-Vabis, along with Detroit Diesel and Cummins, would be appropriate initial contacts.

Rail systems are very unlikely to make any significant impact on US urban transportation in the next 20 years. The only innovation which may have some substantial increased attractiveness is linear induction with steel-wheel-on-steel rail technology.

The monorail and proprietary systems are even less likely to have a major impact, even if a number of these small but expensive systems are adopted in a variety of American cities. The most interesting of the lot is the hybrid monorail/steel-wheel-on-steel-rail/proprietary airtrain (US office: Sür Coester Aeromovel, Suite 221, 2025 I Street, NW, Washington, D.C. 20006, telephone 202-223-3805).

REFERENCES

American Public Transit Association, 1989, Transit Fact Book. Washington, D.C.: APTA.

_____, 1989, Transit 2000. Washington, D.C: APTA.

American Association of State Highway and Transportation Officials, 1989, New Transportation Concepts for a New Century. Washington, D.C.: AASHTO.

Anderson, J. Edward, 1988, "The TAXI 2000 Personal Rapid Transit System". Journal of Advanced Transportation 22 (Spring): 1-15.

Bloch, Arnold J; Pignataro, Louis J., 1982, "Public Transportation and Urban Decentralization: Conflict or Accord?". In: Urban Public Transportation Planning Issues, Transportation Research Board/National Academy of Sciences, Washington, D.C.

Coester, Oskar H., 1990, "Aeromovel: Porto Alegre's Aeromovel Development". Washington, D.C.: Paper accompanying exhibit at TRANSEXPO 1990 - US DOT, Sheraton Washington Hotel (January).

Hoel, Lester A.; Koltnow, Peter G., 1988, "Transportation: Coming Changes and Strategies". TR News, July-August, p. 2-8.

Johnson, Larry R., et al., 1989, "Maglev Vehicles and Superconductor Technology: Integration of High-Speed Ground Transportation into the Air Travel System". Argonne: Center for Transportation Research, Argonne National Laboratory, Report ANL/CNSV-67.

Kikuchi, Shinya; Onaka, Akira, 1988, "Monorail Development and Application in Japan". Journal of Advanced Transportation 22 (Spring): 19-38.

Krause, Robert A.; Patel, Dinker I.; Gathy, Brian D., 1987, "Financing for the Future: Changing Roles in Mass Transit". Washington, D.C.: Report Prepared for Office of Planning Assistance, Urban Mass Transportation Administration.

Nice, David C., 1989, "Consideration of High-Speed Rail Service in the United States". Transportation Research, A, 22A (5): 359-65.

Pisarski, Alan E., 1987, Commuting in America. Westport, Conn.: The Eno Foundation for Transportation.

Rice, R. G., 1988, "The Future of Transit Technology: Lessons from EXPO 86". Journal of Advance Transportation 21 (Winter): 239-53.

Rogers, Lee H., 1989, "Aeromovel: Urban Transport Within Jakarta and Potential for New Technologies". Jakarta: Paper presented at Indonesian - UK Business Association Meeting, Mandarin Hotel (14 Sept.).

_____, 1990, "Aeromovel Technology Sür Coester S.A.: Project Issues within USA Urban Transit". Washington, D.C.: Paper accompanying exhibit at TRANSEXPO 1990 - US DOT, Sheraton Washington Hotel (January).

Smith, Frank A., 1989, Transportation in America: a Statistical Analysis of Transportation in the United States. Westport, Conn.: The Eno Foundation for Transportation.

Straddle-type Monorail Group, 1985, Urban Transit Monorail System. Tokyo: STMG (Publication in Commemoration of the Inauguration of the Kokura Line of the Kitakyushu Monorail System).

Sür Coester S/A, 1988, Aeromovel. Washington, D.C.: The Match Institution.

Transportation Alternatives Group, 1990, "Future Federal Surface Transportation Program: Policy Recommendations". Washington, D.C.: TGA.

Transportation Research Board, National Research Council, 1987, New Organizational Responses to the Changing Transit Environment. Washington, D.C.: Transportation Research Board, Special Report 217.

White, Robert M, 1988, "Beyond the Millennium: Transportation and the Economy". TR News, Sept.-Oct., p. 3-6.

***   FOR YOUR INFORMATION   ***

To: Bunch
From: UMTRI Research Information and Publications Center
Date: 07/16/90

The document(s) listed below may be of interest.   If you would like it (them)
sent to you, return this form to the library.

    57677
    See Journal
       PORTS, WATERWAYS, AND INLAND WATER TRANSPORTATION.   Transportation
       Research Board, Washington, D.C. 1989.   57 p.   Transportation Research
       Record, No. 1222, 1989.

           Subjects: Ships/ Boats; Ferries; Freight
           Transport/ Goods Movement; Waters; Economic Impact;
           Level of Service