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International Assessment of Electric-Drive Vehicles: Policies, Markets, and Technologies

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International Assessment of Electric-Drive Vehicles

Policies, Markets, and Technologies

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Abstract

Motor vehicles generate large benefits for society but also cause large adverse impacts. Many of those impacts can be mitigated with a variety of new and improved technologies. In this report, we focus on electric-drive vehicle technology; we assess their desirability in Sweden, and explore the role of government in guiding investments

The desirability of electric-drive vehicles will vary over time and across regions In the case of Sweden, key factors determining which technologies might be desirable and when, include the following: the small size of the domestic market, inexpensive and clean electricity, Sweden's strong environmental ethic, a strong automotive industry (including buses and trucks), a well educated population, and strong advanced technology and telecommunications firms

In the long term, we find that virtually all versions of electric-drive technology are expected to eventually prove environmentally superior to internal combustion engine (ICE) vehicles, and in many cases also to prove superior in satisfying consumer desires In the short term, we find that major automotive companies

- have mostly abandoned plans to build and market conventional-sized battery-electric vehicles,
- are on the verge of deciding whether to make major investments in fuel cell electric vehicles,
- are tentatively beginning to invest in hybrid electric vehicles

The technology for building competitive electric vehicles is known and available, with the exception of batteries and fuel cells Batteries are expensive and bulky, and expected to remain so into the foreseeable future, though with continuing improvements. Fuel cells are of greater interest for traction energy because they are potentially inexpensive (comparable to ICEs) and superior in many ways to ICEs.

Based on the above insights, and an assessment of Sweden's particular situation, we suggest the following two strategies for Sweden.

1) *An industrial and environmental policy* of designing, manufacturing, and deploying heavy duty vehicles (buses and trucks) powered by electric drive,

2) *An environmental policy* of deploying small electric vehicles for on and off-road transportation applications.

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Abbreviations and Acronyms

AC = alternating current
BEV = battery electric vehicle
BPM = brushless permanent magnet
CAFE = Corporate Average Fuel Economy
CO = carbon monoxide
DC = direct current
EV = electric vehicle
GHGs = greenhouse gases
FCEV = fuel cell electric vehicle
HEV = hybrid electric vehicle
ICE = internal combustion engine
IGBT = insulated gate bipolar transistor
kg = kilogram
kWh = kilowatt hour
NEV = neighborhood electric vehicle
NiMH = nickel metal hydride
NOx = oxides of nitrogen
PM = particulate matter
PNGV = Partnership for a New Generation of Vehicles
SOx = oxides of sulfur
SULEV = super ultra-low emission vehicle
ULEV = ultra-low emission vehicle
VOCs = volatile organic compounds
ZEV = zero-emission vehicle

Problems and Challenges

The world's motor vehicle population is booming. In 1950, approximately 50 million cars and trucks populated the earth, roughly 2 for every 100 persons. Now there are over 600 million, roughly 10 per 100 people. If present trends continue, the vehicle population will soar to over 3 billion by the year 2050, exceeding 20 per 100 people. And even then, world car ownership rates would still fall far short of current Swedish rates of 45 per 100 people (ECMT/OECD, 1998). Vehicle saturation is nowhere in sight People highly value personal mobility and will continue to expand their use of personal vehicles, even with substantially higher costs of vehicle ownership and operation. And businesses highly value the flexibility and accessibility offered by trucks, and will undoubtedly continue to expand their use.

Indeed, transportation is one of the most vital services in modern society. It is essential to most of the other functions of society, such as manufacturing and construction, food and agriculture, energy supply and distribution, safety and security, access to medical care, and tourism and recreation The future of urban societies and regional economies depends critically on systems of transportation that are reliable, efficient, safe and environmentally sustainable. New transportation policies, programs and physical systems must be designed and managed to ensure fast, safe, efficient, and convenient transportation at the lowest economic and environmental cost

The conflict, then, is how to accommodate demands for higher levels of accessibility with demands for clean and safe physical environments and the reality of finite petroleum resources. One solution is to reduce car usage -- by improving access to goods, services, and activities through improved and expanded public transit, walking, bicycling and telecommuting That approach has considerable merit, for a variety of reasons extending well beyond energy and environmental concerns Those approaches merit strong support Here we focus on a different approach. technological options to create more sustainable vehicles

As indicated in this report, cars <u>can</u> be made more benign Indeed, efforts to do so are well underway Motor vehicles are about to be technologically transformed Thanks to rapid innovation in lightweight materials, energy storage and conversion, power electronics, and computing (as well as communications and information management), cars will soon be far more efficient and benign, much safer and easier to operate, and will host a cornucopia of new services and gadgets The implications of these changes are dramatic and far-reaching

While this technological transformation is inevitable. the technological details are difficult to predict Normal uncertainty in cost, performance, and market response will exist, as with all new technologies. but in this case additional uncertainty results from the pivotal role of government Because the marketplace largely ignores energy efficiency and low emissions, government intervenes by adopting rules and incentives to accelerate the commercialization of socially beneficial technologies

In the remainder of the report we examine the international experience with advanced environmental vehicles with an eye toward Sweden's interest in these activities, from the perspective of industrial and environmental policy

Electric Vehicle Policy Drivers

Interest in clean and efficient vehicles is strong and growing aided by the perception and reality of rapid technological advances The principal motivation for developing and introducing more benign vehicles has been, in almost all countries, clean air. Certainly that is the case in the past decade.

Earlier, some countries pursued advanced vehicles and alternative fuels for national security and self-sufficiency reasons. For instance, during the 1980s, Brazil switched almost all new cars to ethanol fuel made from sugar cane, South Africa produced a substantial portion of i transportation fuel from coal, New Zealand converted about 10% of its vehicles to natural gas, and the U.S. provided major subsidies for a corn-to-ethanol industry (Sperling, 1988). Of these, only the U.S. ethanol effort continues to expand, but it is modest in scale, accounting for only about 1% of national transport fuel demand.

As concerns about petroleum supply and price subsided after the oil price crash of 1985, air quality re-emerged as a more salient concern, and as the principal motivation for new fuels and technology. Air quality concerns have been motivating OECD countries to impose increasingly stringent emission standards on new vehicles ever since the 1960s, but only California has pushed the emissions requirements to the point where electric-drive vehicles and alternative fuels are required (New York and Massachusetts and other states are in the process of adopting California's requirements). These zero emission vehicle (ZEV) rules are premised exclusively on reduced vehicle emissions, though California regulators are well aware of the associated energy efficiency and greenhouse gas benefits likely to result from these new technologies and fuels.[1]

In recognition of growing world-wide demand for improved environmental quality and with the widespread perception that environmental rules adopted in California will eventually be adopted world-wide, automakers and a variety of technology companies have been investing in a wide range of clean vehicle technologies. Various governments have offered monetary incentives to vehicle buyers, a few European cities have restricted city center streets to vehicles without combustion engines, Taiwan has adopted rules requiring that motorbike and motorcycle suppliers sell a portion of their vehicles as pure battery ZEVs, and some Chinese cities are proposing rules to encourage battery-powered 2-wheelers. In all these cases, the motivation is cleaner air.

A growing concern strengthening the resolve of governments and automakers to develop cleaner and more efficient vehicles is climate change. No country has adopted rules that specifically require electric-drive vehicles as a means of reducing greenhouse gas emissions, but

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[1] Initially adopted in 1990, the ZEV rules called for 2% of car sales in California to be zero emitting by 1998, increasing to 10% in 2003. The 2% rule was subsequently eliminated in 1996, and in 1998 the 10% rule was modified to accommodate a broad range of near-zero technologies, including hybrid electric, non-hydrogen fuel cell electric, and very clean internal combustion engine vehicles. As currently stands, the seven largest automotive suppliers in California (General Motors, Ford, Toyota, Honda, DaimlerChrysler, Nissan, and Mazda) must "make available for sale" 4% of their vehicles as pure ZEVs -- that is, as battery electric vehicles (BEVs) and hydrogen-fueled fuel cell electric vehicles (FCEVs). In addition, those seven companies must accumulate credits for other near-zero vehicles (i.e., non-hydrogen FCEVs, hybrid electric vehicles with combustion engines, and very clean gasoline ICEVs) that aggregate to the equivalent of 6% of vehicle sales (for details on the partial ZEV credit program, see Salon et al. 1999). Other automotive providers can meet the entire 10% quota with partial credits; they do not need to supply 4% as pure ZEVs. With light duty vehicles sales in California at about 1.5 million per year, 4% amounts to 120,000 vehicles per year. As indicated, though, not all companies must comply with the 4% rule, and companies receive multiple credits for introducing the vehicles ahead of the required schedule and for selling ZEVs with long ranges (over 160 km); thus, even if the 4% rule is sustained over continuing industry objections, actual sales of BEVs will undoubtedly be far less than 120,000 vehicles per year in the foreseeable future.

many have proposed to do so. What some countries have done is adopt fuel economy programs to reduce fuel consumption, which have the effect of reducing greenhouse gas emissions. The European Union has a voluntary agreement with automakers to reduce fuel consumption by 25% between 1995 and 2008, the US has its Corporate Average Fuel Economy (CAFE) standards (currently fixed at 27 5 miles per gallon for cars and 20 7 mpg for light trucks); and Japan adopted significantly tighter fuel economy standards in 1999 These voluntary and rule-based fuel economy programs could be readily converted into greenhouse gas reduction programs

While governments remain hesitant to adopt effective rules and incentives to reduce greenhouse gas emissions, automakers recognize the inevitability of having to supply cleaner and more efficient vehicles. Some companies are more aggressive, seeing an opportunity to cast themselves as environmental and technological leaders, others are limiting themselves to monitoring international progress and slowly developing modest in-house research capabilities All remain wary of heightened and accelerated demand for cleaner and more benign vehicles, aware that new evidence of climate change or a series of environmental disasters might motivate governments to expedite the adoption of greenhouse gas emission rules

Still another effective policy driver to introduce electric-drive vehicles is domestic economic growth. In countries with domestic automotive industries, governments typically aid domestic companies by funding R&D and advanced technology demonstration projects The goal is to strengthen the technology capabilities of local companies so that they will thrive in the world market, generating employment and profits for the home country The European Union, various European countries, the U S , Canada, Japan, and others have been supporting the development and demonstration of electric-drive vehicle technology in their respective countries during the 1990s and in some cases for much longer This support has been targeted at a large range of technologies and companies (including batteries)

Other policy drivers for electric-drive vehicles may become important in specific locations and circumstances For instance, concerns about noise in city centers and in ecologically sensitive areas may motivate the use of quiet BEVs – perhaps as part of the movement to create car-free zones. Another policy driver in some cases might be military demands for vehicles without heat and gas traces (to evade heat-sensing and other tracking technologies). indeed, considerable funding in the U S for electric-drive technology was justified in this way and was funded through the Defense Department

An indirect policy driver that could eventually become a powerful agent of change is traffic congestion and efforts to reduce travel. Historical efforts at travel demand management have not been effective in most cities (e g , see Guiliano, 1992) Future efforts might be more successful, as low-cost information and communication technologies become more widespread, perhaps with small personal vehicles playing a central role To be successful, the attitude and behavior of vehicle owners would have to change Most drivers, upon acquiring a vehicle, rarely consider other transport modes as substitutes or complements Their vehicle is intended to serve all purposes Thus people (and businesses) generally purchase vehicles that are large and powerful enough to accommodate the occasional trip that requires large carrying capacity – for individuals, this "marker" trip may be a family outing to visit Grandmother, or it may be to a local store to pick up a large good

The expectation that all vehicles must serve all purposes could change by using information technologies to reduce the inconveniences of intermodal transportation The use of information to facilitate the linking and attractiveness of different travel modes, would create a large new market for small vehicles.[2] Instead of buying and using conventional-sized personal vehicles for all trips, travelers would now find other attractive options readily available, including shared-use vehicles for occasional trips requiring larger carrying capacity or other attributes such as 4-wheel drive, telecenters in the neighborhood for telecommuting to work or regular or infrequent basis; smart paratransit services that promptly pick one up at home or elsewhere; e-commerce that reduces the need for extensive and long shopping trips, and travel planning software that enables quick and easy trip linking By enhancing the attractiveness of these other options, as alternatives and/or complements to the private conventional-sized vehicl a large new market might be created for small, efficient vehicles Indeed, the availability of small, inexpensive, environmentally attractive vehicles could be the catalyst – along with information and communication technologies – for the creation of a more integrated (and efficient) transportation system (Salon et al, 1998)

In other words, the use of small electric vehicles and communication technologies coul facilitate demand management efforts (to create more economically efficient and environmenta benign transportation systems) and, conversely, demand management efforts could facilitate the use of small electric vehicles. That idealized scenario still lies in the future, however.

Sweden's Situation

Every country and company has its own unique set of circumstances, beliefs and values These differences determine which environmental vehicle strategies are most attractive and mos likely to be effective

Sweden is an affluent, industrialized country of almost nine million inhabitants Althoug (or because) the population experiences a relatively high level of environmental quality, the nation is more committed to environmental quality than most Air pollution is not a major problem, even in Stockholm, and large stretches of unspoiled land are within easy reach of all inhabitants Most electricity is produced "cleanly" by domestic hydro and nuclear power, and most other energy – oil, natural gas, and coal -- is imported (SNEA, 1998) Abundant forests an the absence of domestic sources of fossil fuels have led the country to develop an expanding biomass energy industry, mostly to produce electricity Biomass has not been used to produce commercial supplies of transport fuel, however, because of the continuing high cost of converting it to liquid fuels (such as ethanol)

Although a lightly populated country, Sweden is home to several leading industrial companies, especially in the automotive and information technology industries, and its industrial sector is well integrated into the global economy The two domestic car companies, Volvo and Saab, have recently come under control of Ford and General Motors, respectively, but continue t retain some independence The nation's truck suppliers, Scania and Volvo Bus and Truck, are major players internationally, with Volvo ranked third in the world in heavy truck production (over 16 tonnes) and Scania ranked sixth (Bilindustrif_reningen, 1999).

The motor vehicle industry is an important component of Sweden's economy In 1998, 368,000 cars, 100,000 trucks and 15,000 buses were manufactured in Sweden, of which the vast majority were exported (86%, 96%, and 96%, respectively) Exports of vehicles, parts, and

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[2] These need not be electric, but the relatively low cost of small battery vehicles and their environmental attractions make them ideally suited

accessories accounted for 14% of total exports, and the three major vehicle suppliers employed 65,000 people in Sweden (Bilindustriföreningen, 1999)

Sweden is also home to a large telecommunications and information technology industy, which could play an instrumental role in creative "new mobility" transportation system linkages using small and specialized vehicles.

The high level of affluence, combined with large land areas and a strong domestic automotive industry, has led to fairly high levels of car ownership. Car ownership is now approaching 450 cars per thousand capita, greater than the EU average, and is increasing at a faster rate than GDP (ECMT/OECD, 1998; Tengstrom, 1999).

One other attribute of relevance is the country's sense of international presence and leadership Many Swedes have played leadership roles in international organizations and the country has committed itself to international initiatives, well out of proportion to its size and wealth

In summary, Sweden is a relatively small country with a strong environmental ethic, successful economy, strong automotive and electronics industries, limited hydrocarbon resources and abundant hydroelectric power Given these circumstances, Sweden might consider targeting some technological opportunities where it already has strong capabilities, but would probably be advised to curb its desire to be a leader in the use of environmental vehicles In the remainder of the report we examine the international experience with advanced environmental vehicles with an eye toward Sweden's interest in these activities, from the perspective of industrial and environmental policy.

Electric Vehicle Technology Assessment

It is widely accepted that the next generation of vehicle technology will utilize electric-drive propulsion, though there is considerable debate, as indicated below, over the technological details of these propulsion systems, and the rate at which they are likely to be commercialized.

The term "electric-drive vehicle" includes an array of technologies, including but not limited to vehicles powered by batteries Electric-drive vehicles may be sorted into four generic types: 1) pure battery electric vehicles (BEVs) that store wall-plug electricity on board in batteries, ultracapacitors, and flywheels, 2) pure EVs that gain their electricity as needed from a rail, wire or other off-board source, 3) hybrid electric vehicles (HEVs) that generate some or all of their electricity on board using a combustion engine, and 4) fuel cell electric vehicles (FCEVs) that convert chemical energy into electricity on board using a fuel cell system The common denominator for all these technologies is the efficient electric motor that drives the wheels and that can also be used to extract energy from the car's motion when it slows down (known technically as regenerative braking) Internal combustion vehicles, in contrast, employ a constantly-running engine whose power is diverted through a series of gears and clutches to drive the wheels and to turn a generator for the electrically-powered accessories in the car. Electric-drive technologies have major advantages over internal combustion engine (ICE) technology All four types provide potential for large reductions in air pollution, greenhouse gases, oil (and energy) consumption,[3] and noise, and increases in reliability and vehicle life

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[3] Overall energy efficiency varies considerably depending upon the design of the on-vehicle propulsion system and the method for generating and delivering the electricity On-vehicle electric-drive systems are over 90% efficient, versus about 25% for ICE systems However, when the overall energy efficiency of electricity and gasoline

Electric-Drive Propulsion Technology

Major advances have been made in various electric-drive technology components over t past decade. For example, advances in power electronics have resulted in small, lightweight DC to-AC inverters that, in turn, make possible new types of electric motors that have many advantages over the brush DC motor systems that were used in virtually all BEVs through the early 1990s Today's brushless AC induction and synchronous, brushless permanent magnet (BPM) motor drive systems are more compact, more reliable, easier to maintain, more efficient, quieter, and more adaptable to regenerative braking than the previous generation of brush DC motors. AC induction motors in the 30-100 kW range, the size used in vehicles, are currently mass-produced in their basic form at low cost, and then customized for specific purposes, while BPM motors for EVs are currently made in smaller production runs at higher cost, with mass production coming soon

One primary reason that electric-drive vehicles are a more attractive option than they were twenty-five years ago is that the performance of electric motors has increased by nearly an order of magnitude since the mid-1970s [4] These advances have been coupled with advances in power electronics to dramatically reduce the volume, weight, and potential production cost of electric drive systems By one account, the weight, volume, and cost of the electric propulsion motor and associated electronic controller was reduced an estimated 60 percent in the 1980s (CARB, 1992), and continued reductions have occurred through the 1990s As Ford's John Wallace (head of his company's electric vehicle program) notes

> [W]e have gone down in numbers and parts in the controller – it started out quite complicated I can remember the original Ecostar controller, which was quite complex, then there was a two-board controller and now a one-board controller, and perhaps we will go down to a no-board controller basically by mounting control circuitry right on the motor. All that stuff is tearing out cost (Wallace, 1998, p 14)

The motor-controller combination is now smaller and lighter than a comparable internal combustion engine, as well as being cheaper to manufacture (in comparable production volumes) and to maintain [5]

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production and distribution are considered, the differences are much smaller For instance today's battery-powered EVs, with electricity from fossil sources, are typically only slightly more energy efficient than equivalent ICE counterparts Future advances in electricity production efficiency, shifts to non-fossil sources, and use of other electric-drive vehicle systems could lead to significant improvements in fuel cycle efficiency Some improvements are likely with ICEs also (for instance with direct injection gasoline and diesel engines), but these likely improvements are of a smaller magnitude

[4] The early DC motors used in BEVs had torque densities of about 3 1 newton meters (Nm) per kg, while permanent magnet motors with ferrite magnets introduced in about 1975 improved the density to over 4 0 Nm per kg Beginning in about 1980, BPM motors with rare earth samarium-cobalt magnets demonstrated torque densities of 6 0 to 8 0 Nm per kg and improved samarium-cobalt magnet formulas (Sm2CO17) produced densities as high as 12 5 Nm per kg Modern BPM motors of the 1990s, with neodymium-iron boron (Nd-Fe-B) rare earth magnets, have demonstrated torque densities of up to 25 0 Nm per kg (Ragone, et al , 1995)

[5] Both AC induction and BPM systems are good choices for use in electric-drive vehicles and it is not clear which system will prove to be the most popular Most vehicles in pilot-scale production today (particularly by the U S

The control systems needed for both AC and DC motors are costly and complex at present. As noted above, however, their size and weight have been reduced significantly in recent years, and they are now expected to be produced at relatively low cost in high-volume production. In particular, the costly insulated-gate bipolar transistor (IGBT) power switching devices used in the motor inverter have been improving rapidly in performance and cost. Continued progress in IGBT technology is expected, particularly with regard to the saturation characteristics of the devices and their switching energies Inverters in general are expected to progress not only in terms of cost and performance of the IGBT silicon chips, but also in packaging, controls, processors, and transducers (Hodkinson, 1997)

Battery and Other Electricity Storage Technologies

The single largest hurdle holding back BEV commercialization is battery development. Batteries typically account for one-third or more of vehicle weight and one-quarter or more of the lifecycle cost of a BEV. They also play an important role in HEVs and potentially in fuel cell EVs. In HEVs, battery systems act as peak-power devices, so that the combustion engine can be relatively small and can be supplemented with the electric motor In such a configuration, the small internal combustion engine can operate near its peak efficiency point or not at all (i e , be switched off), thereby maximizing its efficiency. Also, the presence of a battery pack in the vehicle allows regenerative braking energy to be captured, further improving efficiency.

A variety of research efforts are underway to develop and commercialize advanced batteries. The most prominent is the U.S Advanced Battery Consortium (U S. ABC) (NRC, 1998). Launched in 1991, U S. ABC's goal is to increase the energy and power capability, extend the life, and reduce costs of batteries as they are scaled up to sizes suitable to power vehicles Funding for its first five years was $262 million, split evenly between government (U S Department of Energy) and industry (electric utilities, GM, Ford, Chrysler, and battery companies), but has been greatly decreased since then Advanced battery development efforts in Europe and especially in Japan have been at least as active, but have received less publicity and less public scrutiny.

Many different types of traction batteries have recently been or are currently being investigated These include batteries with solid, liquid, and gaseous electrolytes, high and low ambient temperatures, replaceable metals, and replaceable liquids In fact, at least 20 distinct battery types have been suggested as candidates. Unfortunately, what looks promising in a small cell often disappoints when scaled-up for a vehicle The reality is that the underlying science of battery technology is highly complex and not entirely well understood, rendering the engineering of large batteries tricky

At present, leading candidates for BEV and HEV batteries include nickel-metal hydride (NiMH), lithium polymer, and lithium-ion, with a few other types still under consideration Several other types, such as sodium-sulfur and sodium disulfide, have been abandoned as vehicle

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automakers) use AC induction systems, but some vehicles, such as the Toyota RAV4, use systems based on BPM motors Both AC induction and BPM systems offer similar advantages over conventional direct-current (DC) brush motors These include lighter motor weights higher efficiencies, and lower service requirements (the brushes in DC brush motors wear out and require replacement) In general, AC induction motors provide high efficiencies over a wide range of operation, while BPM motors provide higher peak efficiencies BPM motors also tend to be lighter, but they use rare earth magnets that are somewhat costly at present Both of these motor types require complicated control systems relative to DC brush motors in order to operate from a DC source traction batteries because of problems with consumer acceptance, efficiency, and/or cost. Ni and the lithium batteries are achieving many of the necessary performance criteria required f both BEV and HEV batteries, but continue to be too expensive. Even future performance improvements are likely to result in batteries with costs in excess of the established $150 pe kWh cost goal of the U.S. ABC, although $200-$250 per kWh may be achievable by NiMH batteries in high volume production (Kalhammer, 1999, Lipman, 1999a) Manufacturing cos for lithium polymer batteries are projected to be in the $250/kWh to $300/kWh range, based technology developed by Hydro Quebec and 3M, although a French partnership between Electricite de France and Bollore Technologies has identified a cost goal of $200 per kWh fo lithium polymer batteries in mass production (Kalhammer, 1999) Lithium ion batteries are q expensive today, with costs in excess of $1,000 per kWh, but they have the potential for long cycle lives of 1,000 or more cycles and costs are expected to drop significantly SAFT has identified an optimistic cost target of $150 per kWh for lithium-ion batteries in high volume production (Kalhammer, 1999), but this will require manganese or nickel to be substituted fo cobalt in the battery electrodes while maintaining satisfactory performance, along with cost reductions in other cell components

These projected costs would represent considerable improvement over the much high costs of the pilot-production batteries in use today, but they are still too high for BEVs to compete effectively on a first-cost basis with comparable ICE vehicles, particularly when markups associated with battery integration, testing, and overhead are considered However, economics of BEVs would improve greatly on a lifecycle basis if batteries could be designed last about 10 years (about 1,000 battery cycles), rather than 4-5 years that is currently expecte for the NiMH and lithium EV batteries that are in use at present Thus, given the problem of high initial costs for EV batteries, battery manufacturers such as SAFT, Ovonics, and Hydro Quebec have identified a goal 10 years for the cycle/calendar life of future generation batterie (Kalhammer, 1999).

It is also important to note that even though progress in battery technology performanc has been slower than the industry would like, considerable improvements have been made in recent years The progress has been particularly noteworthy with regard to specific energy (i e. Wh/kg) for batteries to be used in BEVs, and specific power (i e , W/kg) for batteries to be use in HEVs and FCEVs These improvements have come as a result of improvements in batter design and material utilization Continued improvements are expected for two reasons (Kalhammer et al , 1995)

- considerable progress has been made in developing new and improved small batteries for the rapidly expanding consumer products industry – for portable computers, camcorders, cellular phones, etc .
- relatively little effort has been put into the technically difficult process of upscaling those (and other) batteries to the size needed for vehicles

The continuing high cost of batteries has motivated the development of other energy storage media Among the substitutes being developed are ultracapacitors, which store large amounts of electricity and can charge and discharge quickly, and flywheels, which store energy in a spinning rotor Ultracapacitors owe much of their development to the U S Strategic Defen Initiative ballistic-missile defense program Ultracapacitors can store about 15 watt-hours in a one liter volume, and a one-liter device can discharge at a rate of three kilowatts Flywheels firs saw use in transportation in the 1950s. Flywheel-powered buses traveled the streets of Yverdon, Switzerland, revving up their rotors at every stop. Since then, designs have changed substantially. Now composite rotors spin at 100,000 revolutions per second, a speed limited only by the tensile strength of their rims. Magnetic bearings have reduced friction so that a rotor can maintain 90 percent of its energy for four days

Since ultracapacitors and flywheels can provide power very rapidly, they would be paired with batteries -- the batteries supplying basic driving needs, and the capacitors or flywheels handling peak requirements when accelerating rapidly or climbing a hill. This combination would allow the use of smaller battery packs and extend battery service life – in BEV, HEV and FCEV applications. However, ultracapacitors and flywheels both remain too costly for use in vehicles, and flywheels still face safety concerns.

Hybrid Electric Vehicles

HEVs are one solution to the battery cost problem HEVs combine an electric motor with a combustion engine, thereby providing a hybrid propulsion system By severing the direct connection between engine and wheels, the engine can operate at steady load near its maximum efficiency, as with stationary engines The engine can be downsized, with onboard energy storage devices such as batteries, ultracapacitors, or flywheels providing the power surges needed for hill climbing and passing. Toyota was the first company to market a mass-produced HEV, launching its Prius in Japan in late 1997 (with sales to Sweden beginning in 2000) Honda followed in early 2000, selling its two-seater Insight in the U.S market, Renault intends to sell its Kangoo battery electric vehicle with a small ICE range extender later in 2000, and many other manufacturers are displaying hybrid concept vehicles and announcing future production plans.

HEVs are not a single, uniform technology They encompass a wide range of designs and technologies. Like fuel cells, they build upon electric-drive technology developed for BEVs They may use a variety of combustion engines, including Otto-style spark ignition, diesel compression ignition, gas turbines, Stirling, and Atkinson engines They may store energy in a variety of batteries, ultracapacitors, or flywheels, as well as in a liquid or gaseous fuel These various components may be combined in a variety of ways to achieve a variety of goals The principal HEV design strategies and goals include the following. 1) minimize emissions by incorporating large battery packs and operating mostly in a zero-emissions mode, 2) minimize energy consumption by operating a small combustion engine full time, 3) minimize changes in conventional petroleum-powered ICEV by using a very small battery pack mostly just to gain the energy benefits of regenerative braking, or 4) achieve some mix of cost and performance goals In practice, a variety of hybrid designs will likely be commercialized, reflecting differing corporate goals, local government rules and subsidies, and decisions about which market segments to target

In some sense, hybrids are a middling technology They do not have a distinct superiority along any dimension and present a muddled image to consumers Compared to ICE vehicles, hybrids have better energy efficiency, easier-to-control emissions (since engines are operating at a steady load) and, like all electric-drive vehicles, a superior driving feel (the result of high torque and smoother acceleration at lower speeds) But due to redundant powerplants, they are inherently more expensive and possibly less reliable than ICE vehicles Hybrids have longer range and smaller batteries than battery EVs, but are technologically more complex, generally lack home recharging (which appears by many consumers), and present a less pure environmental image.

The most successful full-size mass-produced electric vehicle of any type is the Toyota Prius, put on sale in Japan in December 1997 Priced competitively at about US $17,000, Toyota planned for 1,000 sales per month. Faced with much stronger demand than expected, they expanded production in February 1998 to 2,000 per month, though demand seems to have leveled off at less than that level. The vehicle uses an Atkinson engine operating most of the time and a small pack of nickel-metal hydride batteries Fuel consumption is about half that of a comparable gasoline ICE vehicle on a Japanese driving cycle, but less than 50% better on standard US driving cycles.[6]

Hybrid technology is readily accessible, as indicated by the Toyota experience. Most major automakers have built advanced hybrid prototypes and a few have sold limited numbers of hybrid vehicles In general, though, automakers are reluctant to make major commitments to any type of electric-drive technology Doing so implies a major transformation of their company· a restructuring of manufacturing processes and supplier relationships away from their core technology (combustion engines), an accelerated shift away from their mechanical engineering culture, a reformulation of retail strategies and service and product distribution systems, and possibly the use of different fuels

HEVs have an important attraction to automakers, however. they are less disruptive and carry less risk in the near term than battery and fuel cell electrics HEVs allow companies to cling to their core technology (combustion engines) and previous ways of doing business, and to proceed incrementally.

Will others automakers follow Toyota, Honda, and Renault? If government regulations and incentives were designed to encourage hybrid vehicles (which, for the most part, they do not at present), HEVs would likely come into the marketplace in large numbers But are hybrid vehicles likely to dominate? Should they be singled out for strong government support? Are they a clever amalgamation of advanced technologies, or a middling compromise doomed to failure? Are they a second-best option that will be delayed in the near term and succumb to fuel cells and other technologies in the long term? While definitive answers are not possible, it appears certain that a variety of HEV technologies will find their way into the marketplace in the foreseeable future – and that they will provide clear, strong benefits

HEVs in various forms may well come to dominate the motor vehicle industry But, with fuel cell and other technologies also becoming available, it is not certain at present how successful HEVs will be Only with time, money, and experience will we know

One application where HEV technology may prove particularly attractive is heavy duty buses, currently operated on diesel almost everywhere in the world As elaborated upon later in the report, increasing concern over particulate emissions and the fact that buses tend to operate in densely populated areas is leading to demands for much cleaner buses Hybrid electric buses may prove a leading solution Sweden, with its strong heavy duty vehicle manufacturing industry, might treat this as an opportunity (or threat).

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[6] The relatively better fuel economy on the Japanese driving cycle is because internal combustion engines do not operate efficiently at low revolutions per minute (rpm) ie, low speeds and stop-and-go traffic The Japanese driving cycle contains much more low-speed driving than the standard US cycles

Fuel Cell Electric Vehicles

Perhaps the most promising option for powering electric drive vehicles is fuel cells. Many researchers and several of the major automakers see them as the most likely successor to the internal combustion engine. In a major speech on 19 January 2000, William Clay Ford, Chairman of Ford Motor Company, said:

> [I] believe fuel cell vehicles will finally end the 100-year reign of the internal combustion engine as the dominant source of power for personal transportation. It's going to be a winning situation all the way around - consumers will get an efficient power source, communities will get zero emissions, and automakers will get another major business opportunity - a growth opportunity.

Fuel cells are devices for generating electricity. The electricity powers an electric motor, which turns the wheels In the most simple fuel cell system, a fuel cell oxidizes hydrogen to water vapor. If another fuel is used, such as methanol or a petroleum product, then carbon dioxide and other trace gases will also be emitted Although fuel cells are best known as power sources for spacecraft, the first commercial fuel cells found their way into an experimental farm tractor in 1959 Prototype fuel-cell buses built in the early 1990s have demonstrated that the technology is workable, now the central issue is cost Fuel cells in commercial production for stationary applications employ a phosphoric-acid electrolyte to carry current, and cost about $2,000 per kilowatt, compared to perhaps $30-50 per kilowatt for a typical internal combustion engine (though these fuel cell systems are designed to have much longer operational lives).

Proton exchange membrane (PEM) fuel cells are now being developed for automotive and residential-scale applications, and are rapidly nearing commercialization These PEM fuel cell systems have the benefit of operating near ambient temperature Manufacturing costs remain an issue, but efforts are underway to develop key system components out of low-cost materials, and to continue to reduce the amount of expansive platinum catalyst needed. By one estimate, these efforts may result in manufacturing costs of fuel cell systems of as little as $35-100 per kilowatt, in high volume production (Lomax et al., 1997)

Today's commercial and pre-commercial fuel cell systems all operate on hydrogen. If another fuel is used, that fuel must first be converted to hydrogen At present, the most economically attractive means of producing hydrogen is via steam reformation of natural gas Because scale economies are large, this process will occur at large stationary facilities or neighborhood refueling stations In the near term, the other principal fuel options for fuel cells are on-board conversion of methanol (or petroleum products) to hydrogen

When fossil fuels become more scarce and expensive, hydrogen will likely be made from water using electricity from solar cells (a process known as electrolysis) If such solar-produced hydrogen were widely adopted, the entire transportation-energy system would be environmentally nearly benign and the energy would be fully renewable. While electrolyzers and solar cells are relatively expensive at present, costs are expected to decline and the cost of solar hydrogen fuel should ultimately not exceed one dollar per liter-equivalent of gasoline

Fuel cell electric vehicles (FCEVs) have many of the same advantages as BEVs -- including the potential for zero tailpipe emissions of criteria pollutants and GHGs and the advantages of maximum torque from zero speed and shift-free acceleration to maximum speed -- without the disadvantages of limited driving range and long refueling time

As with HEVs, there are many different configurations possible for FCEVs.[7] First of all, there are several different types of fuel cells -- including PEM, alkaline, solid oxide, and phosphoric acid -- though PEM fuel cells are considered the best choice at present for transportation applications, primarily because they operate near ambient temperatures. Second, FCEVs could be powered with different fuels -- with hydrogen loaded and then stored on-board the vehicle, hydrogen produced on-board from a liquid fuel such as methanol or gasoline, or powered directly with methanol. Third, the fuel cell power system could be hybridized with a peak-power battery power system, in order to reduce the size of the fuel cell system and to capture regenerative braking energy, or a simpler system could be used with a somewhat larger fuel cell system and no peak-power battery.

As recently as the mid 1990s, FCEVs were considered impractical as a near-term option for ZEV technology. But rapid developments in fuel cell component, stack, and system performance and design have made near-term introduction of FCEVs possible. World leaders in FCEV development include the DaimlerChrysler Corporation, which has produced four generations of prototype FCEVs known as NECAR I-IV (Daimler-Benz, 1996; Veit, 1998), Ford Motor Company, Toyota Motor Company, General Motors, and perhaps Honda. These companies have all announced plans to introduce commercial FCEVs in the 2003-2005 time frame. Virtually all of the world's other major automakers are also investigating fuel cell technology, although many will decide to follow the leaders to market with their own designs in later years (probably with fuel cell systems purchased from other manufacturers or suppliers, rather than manufactured "in house"). Such companies include Volkswagen, Nissan, Renault, Peugeot, Volvo, BMW, Fiat, and Mazda.

The most advanced prototype to date, unveiled in 1999, is the DaimlerChrysler NECAR IV. It is a Mercedes-Benz A-class vehicle that uses a liquid hydrogen storage tank, a compact fuel cell system with no battery hybridization, and a 55-kW electric drivetrain. The NECAR IV represents substantial progress in reducing the size and weight of fuel cell system components. The complete fuel cell system (not including hydrogen storage) in the NECAR IV has a power density of 200 W/kg (i.e., 5 kg/kW), but DaimlerChrysler engineers believe that this can be increased to 250-333 W/kg (3-4 kg/kW) in the near term (DaimlerChrysler, 1999). These power densities compare with about 48 W/kg (21 kg/kW) in the NECAR I prototype vehicle that was built in 1994, demonstrating a four-fold improvement in five years.

Due to improvements already made in reducing fuel cell stack size and weight and integrating auxiliary systems, efforts are now shifting away from the technical issues associated with designing fuel cells for vehicles (although technical issues still remain), and toward reducing system costs. Cost reduction efforts are focusing on design modifications, use of lower cost materials, and techniques for automated mass production.

Electric Transit Bus Technology

One attractive niche for electric-drive technology is transit buses. It's attractive because vehicles operate on fixed routes with known power demands in urban areas where pollutant emissions are most damaging. Growing concern over high emissions of particulate matter and oxides of nitrogen from diesel engines is drawing heightening interest in clean

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[7] Technically speaking, FCEVs will likely be hybrid vehicles, in the sense that fuel cells will be hybridized with batteries or other energy sources, but rarely with combustion engines.

alternatives. As with smaller vehicles, electric buses can be battery, hybrid, or fuel cell powered. Only small numbers of electric-drive buses are in use, but their popularity seems to be growing

In Sweden, 17 electric-drive buses are in use and being tested. Ten of these are from Neoplan, a medium-sized bus manufacturer in Germany, six are from Scania and one from Volvo. Twelve of the buses are HEVs, half of which burn bio-ethanol in their internal combustion engines.

In the US, purchase subsidies available in conjunction with programs such as the alternative fuel vehicle (AFV) fleet mandates and the Clean Cities initiative are slowly boosting market penetration of electric buses. The cities of Santa Monica, Santa Barbara, and Chattanooga each have been using battery powered electric buses since the early 1990s, particularly for routes that serve popular tourist destinations, the performance has been good and the municipalities have had a favorable experience with them (U.S DOE, 1999). Additional electric buses are now being used in San Francisco by AC Transit, and as passenger shuttle buses at the San Jose Airport and at the San Bernardino commuter train station (CALSTART, 1996) Electric and hybrid electric buses and drive systems are being developed by several companies around the world including Lockheed Martin, Northrop Grumman, Orion Bus Industries, NovaBus, and DaimlerChrysler, along with several smaller companies Some companies are focusing on "ground-up" designs that include lightweight chassis designs and full component integration, while other companies are developing retrofit kits that allow conversion to electric drive at lower total cost. This is the commercializing strategy adopted by the New York State Energy Research and Development Authority who along with Alternative Fuels Technologies Corporation is developing a series of hybrid-electric power train system retrofit kits. The kits will primarily be produced for use in light and medium-duty urban delivery vehicles (which commonly undergo re-built engine replacements and can readily have a hybrid drive system installed instead), but they can also be used in small transit and shuttle buses. This results in a usable vehicle at a much lower cost than a new hybrid electric bus purchase (NYSERDA,1999)

With regard to designs for completely re-engineered vehicles, Northrop Grumman has produced six prototype buses, known as Advanced Technology Transit Buses (ATTBs), for the Los Angeles County Metropolitan Transit Authority These buses have been undergoing testing in trial use, and one of them is being retrofitted with new wheel motors, an electro-mechanical suspension system, and a flywheel peak power device (U S DOT, 1999a) The ATTB may also serve as a future platform for fuel cell system testing, in parallel with the program to test Ballard/Xcellsis fuel cell buses under the California Fuel Cell Partnership (see section on Demonstration Projects below)

Also, the GPX Corporation has begun to produce a hybrid electric bus design known as the 4080 (40 feet long, 80 passengers) based on years of research and development The company decided that heavy conventional bus technology was poorly suited to hybrid bus mass and strength requirements, and redesigned the bus chassis using advanced materials The bus uses low-cost lead acid batteries to gain an 80-kilometer (50-mile) range in ZEV (battery only) mode, while also allowing operation in hybrid mode with a 100-kilowatt, gasoline-fired auxiliary power unit The bus is expected to be comparable with conventional buses on a first-cost basis, and equivalent in lifecycle cost and performance (Moore, 1998)

Additional hybrid electric buses are being produced by Orion Bus Industries and NovaBus, both of which are beginning to supply buses for use in metropolitan New York City (with Orion supplying an initial order of ten buses, and NovaBus five) Also in New York, bond money has been approved for the purchase of electric shuttle buses in Manhattan and Albany (NYPA, 1998).

Finally, fuel cell buses are also beginning to be designed and tested, led by efforts of Ballard Power Systems and its affiliate Xcellsis (formerly dbb), in partnership with DaimlerChrysler, but also including a program by the U.S Federal Transit Administration (FTA) and U.S. Department of Energy (DOE). This government program has produced three 30-foot fuel cell buses and two 40-foot versions, the latter to compare the use of phosphoric acid and proton-exchange membrane fuel cell technology. Emissions testing on the 30-foot methanol-fueled bus demonstrated that it emitted nearly non-measurable levels of nitrogen oxide, no particulate matter, low levels of hydrocarbons, and acceptable levels of carbon monoxide (U.S. DOE, 1999b) The FTA/DOE effort has also been monitoring the fuel cell bus demonstration programs by the Chicago Transit Authority and BC Transit in Vancouver, British Columbia For the past few years, these authorities have been experimenting with the use of Ballard hydrogen-fueled fuel cell buses in their fleets, and comparing fuel, maintenance, and repair costs to those of their other buses

Environmental Impacts of Electric-Drive Vehicles

Vehicles have a deep and far-reaching effect on the quality of social and physical environments, especially in urban areas Indeed, during the twentieth century, vehicles played a central role in the evolution of human settlements – toward lower density and a more mobile lifestyle In areas with rapid growth, human settlement patterns are far more dispersed, largely a response to the speed advantages provided by cars and trucks In this report we limit ourselves to the direct environmental impacts of replacing ICE vehicles with electric-drive vehicles

We limit ourselves primarily to air pollutant and greenhouse gas emissions of electric-drive and ICE vehicles Other impacts include noise, water pollution, and solid waster disposal Generally speaking, electric-drive vehicles are inherently quieter and will cause less water pollution (because they use less fuel and engine lubricants that leak from vehicles on to roads, and from storage tanks into water supplies). Vehicles with large battery packs are environmentally problematic if toxic materials are used, as is the case with nickel-cadmium and lead-acid batteries, but these battery technologies are not likely to gain widespread usage and even if they did, recycling systems are relatively easy to create and operate and could prove reliable

In general, the introduction of electric-drive technologies are not likely to have more far reaching (positive) impacts than those listed in the above paragraph One possible exception, addressed earlier, is the creation of new mobility systems premised on the application of advanced information technologies that integrate smaller electric vehicles, smart paratransit, smart car sharing, telecommunication substitutions, and e-commerce deliveries The environmental implications of this "new mobility" approach to transport could be very large, resulting in reductions in energy use, air pollution, noise, space devoted to parking and roads, and a variety of related phenomena

Air Pollutant Emissions

Air pollution impacts of vehicle technologies are difficult to specify Impacts depend upon the specific attributes of the vehicle, how and where the vehicle is used, and how the different impacts are valued In general, though, in most regions of the world and in most situations, FCEVs and HEVs will tend to produce considerably less air pollution than ICE vehicles, while BEV impacts are more site-specific, depending upon the source of electricity. Except where BEVs rely mostly on coal-derived electricity, all electric-drive vehicles will be far superior to ICE vehicles in reducing pollution.

These air pollution benefits could be very important, given the heavy contribution of motor vehicles to air pollution in many regions. For example, in the European Union around 1990, motor vehicles accounted for approximately 49% of total volatile organic compound emissions, 78% of total carbon monoxide emissions, and 52% of nitrogen oxide emissions (OECD, 1993)

As indicated in Table 1, BEVs would practically eliminate emissions of carbon monoxide and hydrocarbons (also known as reactive organic gases and volatile organic compounds) and would greatly diminish nitrogen oxide emissions -- regardless of the type of power plant, fuel, and emission controls employed (Wang et al, 1990; Dowlatabadi et al, 1990, OECD, 1993. IEA, 1996). BEVs would add sulfur oxides and particulate matter to the air in areas served by dirty coal-fired powerplants, but this will usually not be a critical concern since gasoline-powered vehicles generally account for only a few percent of total urban emissions of these two pollutants

Table 1: Emissions from Advanced-Technology BEVs Vs State-of-Art Gasoline Vehicles

Country	Est. Electricity Mix for 2000			Percentage Change in g/km Emissions				
	Coal	Gas	Oil	VOCs	CO	NOx	SOx	PM
Australia	0.804	0.076	0.012	-97.9	-98.8	-28.3	1797.6	274.1
Belgium	0.360	0.099	0.007	-99.1	-99.4	-61.4	49.0	49.5
Canada	0.172	0.029	0.057	-99.2	-99.6	-59.5	40.5	-12.3
France	0.081	0.006	0.016	-99.8	-99.9	-90.8	-58.4	-59.2
Germany	0.438	0.129	0.026	-98.2	-99.0	-65.8	96.1	95.7
Greece	0.705	0.104	0.082	-97.7	-98.8	-8.4	297.0	290.0
Italy	0.290	0.265	0.235	-98.5	-99.0	-51.1	100.7	105.3
Japan	0.187	0.166	0.143	-98.8	-99.3	-66.2	-40.4	9.9
Norway	0.000	0.083	0.004	-99.9	-99.8	-92.0	-98.3	-95.2
Spain	0.431	0.012	0.123	-98.6	-99.3	-48.7	327.5	133.6
Sweden	0.028	0.005	0.020	-99.7	-99.9	-96.5	-77.3	-69.3
UK	0.552	0.130	0.061	-98.4	-99.0	15.9	407.2	165.1
United States	0.501	0.180	0.050	-97.8	-98.8	-52.0	401.5	41.9

Source: OECD, 1993

Note: See source for details

The air pollutant emissions impacts of HEVs are somewhat difficult to assess because they will depend on the configuration of the hybrid vehicle and type of engine used, as well as on the emission control system. HEVs will not have emissions as low as BEVs, except perhaps where electricity is generated with coal, but should be superior to ICEVs. The Toyota Prius and Honda Insight both have very low emissions, both meeting the Ultra-Low Emission Vehicle

(ULEV) levels specified by the California Air Resources Board; with tighter controls on their evaporative emissions, they probably could meet the more stringent Super Ultra-Low Emission Vehicle (SULEV) requirements. Furthermore, HEVs with substantial battery packs and relative large electric motors could be designed to have a certain amount of "zero-emission range" by switching to a pure electric mode when beneficial, such as when operating in dense urban areas

FCEVs will have very low emissions, though there will be some variation. FCEVs fuele with hydrogen have essentially zero emissions. The amount of upstream emissions associated with these FCEVs will depend upon how the hydrogen is produced For hydrogen produced fro natural gas, these emissions are quite low but vary somewhat depending on the scale of hydroge production For hydrogen produced with electrolysis, emissions can vary greatly from near zero for solar electrolysis to relatively high emissions for electrolysis using electricity from coal-fired powerplants.

FCEVs fueled with other fuels will have some small amounts of direct "tailpipe" emissions, plus upstream emissions The on-board emissions result from chemical reformation c the fuel – likely to be methanol or a gasoline-like liquid in the near term – into hydrogen Preliminary emission data from methanol fuel reformers suggest that emissions from these vehicles will be very low, almost certainly below ULEV levels (Prabhu, 1999)

The fuel cycle NOx emission reduction levels for a few types of BEVs, HEVs, and FCEVs, relative to late-1990s conventional vehicles are summarized in Table 2. These emission estimates are based on analysis using the GREET emissions model of Argonne National Laboratory. NOx emissions are highlighted here because they are the most challenging to reduc from internal combustion engines Table 2 shows that in the U S in general, NOx emissions would be expected to increase significantly with the use of BEVs, although there would be great reductions in urban areas The increase in overall NOx emissions is because these comparisons are made with a late-1990s era gasoline vehicles, with heavily controlled NOx emissions While California has tight NOx emission controls on its power plants and no coal-fired plants. the U.S national power mix contains generating technologies with much higher NOx emission levels Thus, in California, NOx would be reduced both in urban areas and in total. but in other U.S. areas some net increases in NOx would be expected in the absence of additional NOx emission controls In the case of Sweden, the emission impacts of BEVs would be similar to those of California, since neither burns coal to generate electricity The total NOx reductions shown in the table for California -- 95% reduction for near-term technology and 75% for long-term technology – are similar to the NOx reduction estimate of 96 5% for Sweden shown in Table 1

Table 2: NOx Emission Impacts of Electric-Drive Vehicles Relative to Late-1990s Era Gasoline-Powered Vehicles

Vehicle Type / Fuel / Feedstock	Percent Change Urban / Total
Near-Term Technology:	
BEV, California mix	-95% / -56%
BEV, U.S. mix	-96% / +65%
HEV, spark ignition engine, reformulated gasoline	-3% / -19%
Long-Term Technology:	
BEV, California mix	-75% / -38%
BEV, U.S. mix	-80% / +103%
HEV, spark ignition engine, reformulated gasoline	-15% / -41%
FCEV, hydrogen (gaseous H2 storage), natural gas	-23% / -41%
FCEV, hydrogen (liquid H2 storage), solar	-75% / -70%
FCEV, methanol, natural gas	-80% / -63%

Source: Santini, 1999

Electric-drive vehicles often provide greater pollution benefits than indicated by calculations of total fuel cycle reductions of emissions. Some vehicles, especially BEVs and direct-hydrogen FCEVs, shift the source of the pollutants away from population centers. Conventional cars emit carbon monoxide, particulates, and other pollutants from their tailpipes wherever they travel -- which is usually where people live and are exposed. In contrast, pollution associated with electric powerplants or hydrogen production facilities are located at a few generation stations, usually at a distance from urban centers. Also, a large proportion of the emissions associated with charging BEVs would be at night, when sunlight is not present to form ozone and when people are indoors and not exposed.

The greatest air pollution benefits are provided by BEVs and FCEVs when they are powered by hydrogen produced through grid-power electrolysis, or electricity produced from solar, nuclear, wind, or hydroelectric power. Those regions that would benefit most from BEVs include the following:

- California, where most of the electricity comes from tightly-controlled natural gas plants and zero-emitting hydroelectric and nuclear plants,
- France, where most electricity comes from nuclear power,
- Japan, where more than a third of electricity is produced from nuclear power and where fossil fuel-fired plants are tightly-controlled, and
- Sweden and Norway, where most electricity comes from nuclear and hydroelectric sources.

In summary, large reductions in emissions from the use of electric-drive vehicles coul clearly reduce air pollution damage to human health, agriculture and other ecological systems buildings and other landmarks, and visibility. Almost all electric-drive vehicles would be an effective air quality control strategy almost everywhere.

Greenhouse Gas Emissions

Another major environmental benefit of electric-drive vehicles is reduced greenhouse gases As with air pollution, virtually all electric-drive technology options will provide small t large greenhouse gas benefits

In the case of BEVs, the impact depends as before on the source of electricity. As show in Table 3, the use of coal-fired electricity by BEVs would cause a small increase in emissions all greenhouse gases, relative to the use of gasoline (on a per-kilometer basis), taking into account all fuel-related activities from extraction to combustion, including energy used in vehi manufacture But that is a worst case, no country relies exclusively on coal If natural gas were used in the electricity-generating powerplant, there would be a moderate decrease in emissions greenhouse gases, mainly because of the low carbon-to-hydrogen ratio of natural gas. Greenhouse gas emissions are reduced most when powerplants do not use fossil fuels, such as i France and Sweden where most electricity comes from non-fossil energy If nonfossil fuels (nuclear, solar, hydroelectric, or biomass) were used to supply electricity for BEVs, there would be a virtual elimination of greenhouse gas emissions

Table 3: Greenhouse Gas Impacts of Electric-Drive Vehicles Relative to Gasoline-Powere Vehicles

Vehicle Type / Fuel / Feedstock	Percent Change
BEVs, solar and nuclear electricity	-90 to -80
BEVs, natural gas powerplant	-50 to -25
BEVs, new coal-fired powerplant	0 to +10
BEVs, current U S power mix	-20 to 0
FCEVs, hydrogen from solar	-80 to -75
FCEVs, methanol from natural gas	-45 to -35
Gasoline vehicle	--

Source OECD, 1993

Note Based on full fuel cycle analysis Emissions from vehicle and materials manufacturing are assumed to be from the use of fossil fuels

If HEVs operate on gasoline, as do the Toyota Prius and Honda Insight, they would result in fewer GHG emissions The reductions would be determined by their improved fuel economy – in the case of the Prius, about 1/3 less than a comparable ICE vehicle in US driving conditions, and about half as much in slower Japanese driving conditions If other fuels were used, including grid electricity, the reductions would generally be even greater, depending on the fuel and how it is produced, transported and stored Natural gas fuel would be about 10-20% better than gasoline and biofuels anywhere from zero to 100% better.

FCEVs would tend to be at least as efficient as HEVs, and eventually more likely to use non-carbon fuels. If the FCEV were to use methanol, it would be about 35-45% superior to gasoline ICEs, and if using solar hydrogen, even far better (see Table 3)

Petroleum Consumption

Related to air pollution and GHG emissions is fuel use Electric-drive vehicles offer the potential of dramatic reductions in oil use, and therefore decreases in petroleum consumption Oil use is reduced with BEVs because relatively little petroleum is used to generate electricity in most countries -- less than 5 percent in the U.S , and 2 to 3 percent in most Scandinavian and Western European countries (OECD, 1993) With HEVs, fuel economy is improved by 25% to 200% depending on the type of HEV, also leading to oil use reductions, and FCEVs operating on hydrogen or methanol would use virtually no petroleum because these fuels would likely be produced from natural gas or biomass sources Reduced petroleum imports translate into balance of trade benefits, as well as protection against oil supply and price shocks, and reduced risks of oceanic oil spills

Costs of Electric-Drive Vehicles

Will electric-drive vehicles ever be cost competitive with gasoline vehicles? The answer at present appears to be a definitive no, if considering only private costs and initial purchase prices. On a lifecycle basis, however -- calculating costs over the life of the vehicle and discounting them back to the present -- the answer is less certain. As demonstrated later in this chapter, one can generate plausible cost projections in which electric-drive vehicles eventually become cost competitive with gasoline vehicles on a per-kilometer lifecycle basis

In any case, future vehicle costs are the subject of intense debate BEV costs have been carefully analyzed in only a few publicly-available studies, and HEV and FCEV costs have been subject to even less analysis What can be said with confidence is the following the operating costs of electric-drive vehicles (particularly BEVs) should be much lower than those of gasoline cars; vehicle life should be longer, the electric-drive vehicles, minus batteries, should be less expensive, and the non-market benefits are large in some areas (Sperling, 1995, Delucchi, 1992)

BEV Manufacturing Costs

In the appendix (Table A-1), cost estimates of BEVs are provided from a variety of studies conducted between 1994 and 1998 by a variety of government agencies, consultants, and research organizations Most studies suggest that costs of BEVs are expected to remain up to several thousand dollars higher than those of conventional vehicle costs That finding is now the conventional wisdom

Some of the variation found in estimates of BEV manufacturing costs as reported in Table A-1 is due to differing assumptions about vehicle classes, production volumes, and battery types. Other sensitive parameters include assumptions about vehicle performance, cost of the assumed battery type, and costs of accessories and additional equipment needed for the BEV such as battery chargers heating and air conditioning systems and electrical power steering units

The largest single cost component of BEVs is batteries. Even with likely cost and performance improvements – resulting from economies of scale and industrial learning -- battery packs for full-sized BEVs will not be inexpensive in the foreseeable future. The only way to build a cost-competitive electric drive vehicles is to dramatically reduce the size of the battery pack This can be accomplished either by building BEVs for those applications (and consumers) that require less energy and power, by hybridizing the battery with another electricity source, or replacing the battery altogether All are promising strategies They are described below.

HEV Manufacturing Costs

Hybridization of the vehicle power system with other electricity storage and production devices is gaining increasing attention from automakers Various strategies are possible, as indicated above Devices with high power densities, such as ultracapacitors and flywheels, that can charge and discharge quickly, could be used to provide surge power for short periods of time (when passing or climbing hills), thus reducing battery needs Or devices that generate electricity onboard, such as fuel cells or small ICEs, could be the principal energy source, with batteries used only for surge power or extended driving These various hybridized designs have the potential to be more energy efficient, lower-emitting, and less expensive than pure battery electrics

Potential manufacturing costs and purchase prices of hybridized vehicles are difficult to assess because there are so many possible design configurations, types of motors, and batteries, and because costs of key electric drive components vary strongly with production volume. Here we focus on more conventional HEVs that combine batteries with combustion engines Few detailed studies have been conducted on the potential manufacturing costs and purchase prices of HEVs, but Energy and Environmental Analysis, Inc (EEA) of Arlington, Virginia has developed some cost estimates for the following types of HEVs

- starter-alternator system HEVs, where the typical starter and alternator are replaced with an integrated motor/generator, and a small battery pack is included to recapture regenerative braking energy.
- motor-assist HEVs, which are similar to starter-alternator HEVs except that the motor and battery are larger (allowing the engine to be downsized and more regenerative braking energy to be captured),
- fully integrated HEVs, which have even larger motors, higher capacity battery packs, and possibly separate generator systems (as in the Toyota Prius), and
- four-wheel drive HEVs, where a motor powers one axle and an engine powers the other axle

EEA's estimates for the incremental manufacturing costs and retail prices of these different HEV types, assuming high volume production, are presented in Table 4 [8]

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[8] In virtually all industries, retail prices the price paid by consumers at retail outlets -- are much higher than the cost of manufacturing the item In the auto industry retail prices are almost twice the manufacturing cost The extra costs incurred downstream of the manufacturer include the cost of transporting the good to the retail store keeping

Table 4: Estimated HEV Incremental Manufacturing Costs and Purchase Prices

HEV Type	Incremental Manufacturing Cost	Incremental Retail Price
Starter-Alternator HEV	$500-700	~$1,000
Motor-Assist HEV	$1,450	~$2,000
Integrated System HEV		
Near Term	~$4,000	$6,000-7,000?
Future (2004+)	~$2,300	~$4,000
Four-Wheel Drive HEV	$2,600	~$4,000

Source Duleep, 1999

As indicated in Table 4, costs and prices of HEVs tend to increase as the size of the motor and battery pack are increased The incremental costs of increasing the size of the electric-drive portion of the drivetrain tend to be greater than the associated savings of downsizing the conventional portion of the drivetrain However, the fuel economy benefits also increase with the relative size of the electric portion of the drivetrain EEA estimates that the starter-alternator, motor-assist, integrated system, and four-wheel drive HEVs have fuel economy benefits on the U.S. EPA city cycle of 22%, 33%, 50-52%, and 28%, respectively, relative to comparable conventional vehicles (Duleep, 1999)

FCEV Manufacturing Costs

As with HEVs, few detailed, publicly-available studies have been conducted on the potential manufacturing costs and purchase prices of FCEVs In one early study, DeLuchi (1992) estimated that a mid-sized, direct-hydrogen FCEV with a 400-kilometer (248-mile) range would have a full retail price (i e., cost of vehicle production, plus manufacturer and dealer markups) of $25,446. Meanwhile, a 250-kilometer (155-mile) range direct-hydrogen FCEV would have a retail price of $23,183 (DeLuchi, 1992) These prices are compared with an estimated retail price of $17,302 for a comparable conventional vehicle

In more recent work, Thomas et al (1998a) of Directed Technologies, Inc (DTI) estimate that a mid-sized, direct-hydrogen FCEV with a 38 1 kW fuel cell system, a 40 3 kW lead-acid battery, and an 82 kW motor/controller system would have an initial production cost (not retail price) of $110,398 and a mass-production cost of $20,179 Meanwhile, the manufacturing costs for a mid-sized "pure" (i e , no batteries) FCEV would range from $136,953 initially to $20,253 in mass production When compared with the manufacturing costs of a comparable conventional vehicle, these high volume FCEV manufacturing costs are estimated to result in incremental

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goods in inventory, and paying sales personnel Note that the goal of e-commerce is to bypass or drastically reduce costs associated with retailing manufacturing costs of $2,179 and $2,253 respectively, for the hybrid and non-hybrid FCEV designs (Thomas et al , 1998a). These manufacturing cost differentials imply retail price differentials of perhaps $4,000 to $5,000 Also, Ogden et al (1999) estimate that the fuel cell system, peak power battery, motor and controller, and compressed hydrogen storage system for a 77.5 kW direct-hydrogen FCEV would cost $3,600 to $7,000 in mass production, but they do not estimate complete vehicle costs.

Table 5 presents the results of a recent analysis of the potential manufacturing costs and retail prices of mid-sized, direct-hydrogen FCEVs, conducted at ITS-Davis The study considered FCEV designs that are hybridized with NiMH batteries, so that the fuel cell system can be downsized and regenerative braking energy can be captured The study considered potential improvements in fuel cell and battery technology, as well as potential reductions in component manufacturing costs with production volume. Two scenarios were considered a low production volume scenario of 10,000 to about 50,000 units per year, and a high production volume scenario of 20,000 to about 270,000 units per year As the table illustrates, estimated purchase costs for FCEVs can be expected to decline sharply due to the combination of technological improvements and higher production volumes, but even in high volume production purchase prices do not reach the estimated $20,155 price of a conventional mid-sized ICE vehicle

Thus, technological improvements and/or cost reductions beyond those forecast in the ITS-Davis study will be required if FCEVs are to reach first-cost parity with conventional vehicles. The DTI and ITS-Davis studies suggest that mid-sized FCEVs in high volume production are likely to have manufacturing costs of perhaps $2,000 to $3,000 higher than those of conventional vehicles, and retail prices that are perhaps $4,000 to $7,000 higher (depending on the pricing strategy used by the automakers) However, future cost reductions beyond those estimated in these studies may well be achieved in time, and manufacturers may choose "forward pricing" strategies to push prices down as fast as possible Furthermore, it is important to note that both the ITS-Davis and DTI studied focused on mid-sized vehicles, but applications of fuel cells to other vehicle types, such as compact vehicles or luxury vehicles, may prove more attractive. Further study is needed to assess the best potential applications of fuel cell technology in motor vehicles, given various vehicle size categories and performance demands. Also, as the following section notes, even if FCEV retail prices do remain above those of conventional vehicles by a few thousand dollars, vehicle lifecycle costs can be comparable or even lower for the FCEVs due to reduced maintenance expenditures, lower fuel costs due to high efficiency operation, and a longer vehicle lifetime

Table 5: Potential Retail Prices of Mid-Sized, Direct Hydrogen FCEVs

Vehicle Generation and Production Volume	**Low Cost Case**	**Mid Cost Case**	**High Cost Case**
Generation 1 (2003-06) 39.2 kW-net fuel cell, 48 5 kW NiMH battery, 82 kW motor			
LPV 10,000-20,000/year	$36,661-$93,589	$48,467-$129 894	$73.321-$176,265
HPV 20,000-59.850/year	$31,750-$91,763	$40,440-$128,078	$59,999-$173,975
Generation 2/3 (2007-14) 23.8 kW-net fuel cell, 51.3 kW NiMH battery, 70 kW motor			
LPV 20,600-28,986/year	$29,178-$30,676	$34.294-$37,574	$46,804-$52,498
HPV 65,460-118,690/year	$26,897-$27,753	$30,115-$32,578	$39,785-$44,403
Generation 4 (2015-26) 20.9 kW-net fuel cell, 48 7 kW NiMH battery, 65 kW motor			
LPV 30,436-52,055/year	$25,803-$26,571	$28,409-$30,246	$37,552-$40,884
HPV 128,500-270,100/year	$24,093-$24,763	$25,910-$27.111	$32,772-$35,354

Source Lipman, 1999b
LPV= low production case
HPV = high production case
Note. The lower purchase price estimates in each range correspond to the higher production volume estimates in each range shown in column one, and the higher purchase price estimates correspond to the lower production volume estimates The retail price estimates are fully-marked up for factory, division, corporate and dealer level costs These are hypothetical estimates - clearly manufacturers would have to subsidize vehicle purchases in early production years

Lifecycle Costs

Some argue that electric-drive vehicles could become cost competitive with gasoline vehicles on a per-kilometer lifecycle basis in the foreseeable future, though the major automakers are publicly skeptical In Table 6, the lifecycle costs of a mid-sized conventional ICE vehicles are compared to BEVs and FCEVs In this case, the FCEV is a direct-hydrogen design that stores hydrogen onboard the vehicle in compressed gas cylinders, and incorporates a nickel metal hydride battery pack to allow for a smaller fuel cell system The BEV and FCEV designs incorporate forecasts for improvements in key technologies, but they do not assume any radical breakthroughs in battery or fuel cell technology High-volume production is assumed for battery, fuel cell system, and hydrogen storage cylinders

Table 6: Lifecycle Cost Breakdowns for High Production Volume, Mid-Sized Vehicles (1997$/km)

Lifecycle cost category	Gasoline ICEV	BEV	FCEV
Purchased electricity ($0.065/kWh)	0.000	0.017	0.000
Vehicle (excluding battery, fuel cell, and hydrogen storage)	0.109	0.091	0.088
Battery, tray, and aux (including recharger for BEV)	0.000	0.068	0.017
Fuel, excluding excise taxes[a]	0.034	inc. in elect.	0.019
Fuel storage system	inc. in vehicle	0.00	0.008
Fuel cell system	0.000	0.000	0.018
Insurance[b]	0.042	0.049	0.049
Maintenance and repairs (excluding oil and inspection)	0.030	0.023	0.026
Oil	0.001	0.000	0.000
Replacement tires[c]	0.003	0.003	0.002
Parking, tolls, and fines	0.007	0.007	0.007
Registration fees[d]	0.003	0.003	0.003
Vehicle safety and emissions inspection fees	0.004	0.001	0.001
Federal, state, and local fuel excise taxes[e]	0.011	0.011	0.011
Accessories	0.002	0.002	0.002
Total lifecycle cost	0.246 $/km	0.274 $/km	0.249 $/km

Source: Lipman, 1999b. Analysis based on model described in Delucchi et al., 1999. See Lipman, 1999b, for higher and lower cost scenarios.

Notes

[a] Based on fuel costs of $1.20/gallon for gasoline and $9.47/MMBTU for hydrogen.

[b] Calculated with a complex formula that estimates physical damage and liability insurance premiums as a function of VMT and vehicle value. Insurance premiums related to theft and damage costs are estimated to be proportional to vehicle value, while premiums for personal injury related costs are assumed to be independent of vehicle value.

[c] Calculated as a function of VMT and vehicle mass. Tire wear is estimated to be proportional to vehicle mass, and a linear function of VMT. If a scheduled tire replacement falls near the vehicle scrappage date (i.e., if the owner would get 20% or less of the full life of the last set of tires) then no final tire replacement occurs and the last set of tires is worn past the usual point of replacement.

[d] Calculated as a linear function of vehicle mass, with a fee of $50 per year for the baseline ICEV (based on the fact that most states charge vehicle mass-based registration fees with a range of fees of $20 to $100 per year).

[e] Fuel taxes are assumed to be proportional to VMT, such that all vehicles have the same per-mile fuel tax.

As shown in Table 6, the lifecycle costs of electric-drive vehicles (particularly FCEVs) can be comparable to those of conventional vehicles, even though the purchase prices for the electric-drive vehicles are considerably higher (in this case an estimated $25,990 for the BEV and $25,910 for the FCEV, compared with $20,150 for the gasoline ICE). Reduced maintenance and fuel expenses, plus the fact that EVs of all types are expected to last somewhat longer, nearly makes up for the difference in initial purchase price over the lifetime of the vehicles. Of course there are many uncertainties associated with the lifecycle costs of future vehicles types, and only one set of plausible values is shown in the table (see Lipman, 1999b, for higher and lower cost cases).[9]

Markets and Marketing of Electric-Drive Vehicles

In the very early years of the automotive industry, when production was measured in thousands of vehicles per year rather than tens of millions, electric vehicles competed head-to-head with gasoline cars They soon faded from the marketplace, however, because electricity recharging infrastructure was too sparse (including at homes), batteries were far inferior to those now available, and the technology did not match well with the contemporary market (Schiffer, 1994) After batteries were made somewhat more reliable around 1907, including Thomas Edison's nickel-iron battery, BEVs made a brief resurgence. But limited-range cars had little appeal to households owning only one vehicle, especially because vehicles at that time were used disproportionately for "touring " Many people appreciated the BEVs' quietness, cleanliness, and ease of driving -- especially women (including Henry Ford's wife) -- but they were a shrinking minority.

In the 1990s, BEVs gained renewed attention – in large part due to California's ZEV requirement -- but also because their quiet and zero emission attributes were attractive for European city centers, and because of advances in battery technology Indeed, battery technology was advancing at a rapid pace By the mid 1990s, new high-performing rechargeable battery technologies were sweeping aside older technologies and making possible booming markets in a variety of consumer products, from portable computers to camcorders As it has turned out, however, the new nickel-metal hydride and lithium technologies have not been easily upscaled for use in vehicles, and have remained far too expensive for normal vehicle applications. Aspirations exceeded reality, and BEV commercialization has been slower than BEV proponents expected Nonetheless, the BEV phenomena of the 1990s played an important role in the evolution of electric-drive vehicles, and demonstrated the attractions of electric-drive vehicles

Commercialization Activities

In general, commercialization of full-sized BEVs appears to be in stasis or contracting, with two of the market leaders, GM and Honda, having put production on hold Meanwhile, several companies are marketing small BEVs with limited success, tentative commitments are being made to HEV products, and enthusiasm for FCEVs is expanding quickly

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[9] The large cost uncertainties swamp any cost differences that might exist between Sweden and other countries Thus we do not estimate costs specifically for Sweden

Conventional BEVs

The limited introduction of BEVs to date has not been especially successful. In the U.S., where California has been the focus of BEV marketing efforts, less than 3,000 vehicl were leased between 1997 and 1999, including hundreds of each of the following -- GM EV1, Toyota RAV4, Ford Ranger pick-up, GM S10 pickup, and Honda EV Plus. In addition, smalle numbers of Nissan Altra, Chrysler EPIC minivan, and Solectria Force conversion vehicle were sold or leased there and elsewhere in the US. Virtually of these vehicles were supplied in response to memoranda of understanding agreed to by the State of California and major automakers (as part of requirments of the state's ZEV mandate) In Europe somewhat larger quantities of production BEVs have been sold by Renault, Peugeot, Citroen, and Elcat (vans). Many others are sold elsewhere in the world in small quantities. In mid 1999, 580 BEVs were operating in Sweden, one of the greatest concentrations of BEVs anywhere in the world on a pe capita basis

No company has announced plans for major expansion of conventional-sized BEV production As indicated above, both Honda and GM have ceased production. Renault and som others have indicated plans for limited production, but only for fleet sales It remains unclear ho manufacturers will respond to the California ZEV mandate requirements in 2003 (which allows some flexibility in vehicle technology but still requires 4% of vehicles sold to be true ZEVs) Most major suppliers, if not all, are hoping that the 4% rule is rescinded

Neighborhood BEVs

In addition to full-sized BEVs, commercialization efforts are also underway to produce small "neighborhood" electric vehicles (NEVs). Perhaps the most prominent of these efforts is the recent opening of the new Th!nk Nordic production plant in Aurskog, Norway This plant ca produce up to 5.000 of the two-seat Th!nk vehicles annually Th!nk Nordic AS is now primarily owned by the Ford Motor Company, which purchased a controlling interest in the company from Pivco AS in 1999. The commercialization of the vehicle was given a boost recently when the Norwegian telecommunications provider, Telenord, agreed to purchase about 700 of the vehicles over the next several years for use in its fleet The vehicle will sell for about $25,000, considerably more than the cost of comparable ICE vehicles The principal market initially will be in government and company fleets in Europe. although the vehicle will also be available to the public

Several other manufacturers also have NEVs in production or pre-production prototypes A Canadian company, Bombardier, has been producing the two-seat, lead-acid battery powered NV vehicle since 1997 The $6,200 (base price) vehicle is being sold through about 50 dealers in the U S , primarily in California, Florida, and Arizona (Bombardier, 2000) A more recent entr in the NEV market is Global Electric MotorCars of Fargo. North Dakota (Global Electric MotorCars, 2000) This company is now producing both two-seat and four-seat NEV models, along with utility vehicles Another NEV that is commercially available is the $13.900 Corbin Motors Sparrow, a one-seat vehicle that is produced in Hollister, California The Sparrow is equipped with lead-acid batteries and a brush DC motor that provide it with a top speed of 110 km/hour (70 mph) and a range of 50-100 km (30-60 miles) (Corbin Motors, 2000)

Toyota has developed the e-com concept vehicle, a small two-seater with a nickel-metal hydride battery pack that provides a range of about 100 km (60 miles) and a top speed of about 100 km/hour (62 mph) Toyota has been showing the e-com in North America and Europe, and testing up to 100 vehicles in Japan, but is not yet marketing the vehicle. Also, Nissan has designed the "Hyper-mini" EV, which has a rear-mounted motor and a small lithium battery pack (Miyamoto, 1999). This is also a concept vehicle, with production possible in the near future. In addition, there are two small NEV models that have been produced in Denmark. the two-seat Kewet El-Jet and the one-seat Citycom City, both sold in Europe and the U.S About 50 small BEVs are operating in Sweden, mostly Kewets

Off-Road BEVs

The most successful electric-drive vehicles to date have been off-road BEVs. As indicated in Table 7, about 1.5 million BEVs were sold in 1999 for about $7 billion. Of this total, conventional-sized on-road BEVs accounted for perhaps $60 million; they are included in the "other" category of Table 7. The authors of the survey, with extensive experience in industry, found that market growth of the overall BEV market is about 25% per year and a large share of the companies are already profitable (79% of those providing services and 46% of those with manufacturing operations) Only 7% of car, bus, and taxi BEV operations were reported to be profitable; in contrast, fully 93% of manufacturers of vehicles for disabled, 85% of manufacturers of industrial and commercial BEVs, 57% of leisure BEVs, and 50% of component and subsystem suppliers reported being profitable in 1998. In addition, 95% of BEV maintenance operations were also profitable

Table 7: Worldwide BEV Sales, 1999

Market Segments	Number	$million
Fork lifts and related	250,000	$5,100
Golf carts and related	250,000	800
Bicycles and scooters	500,000	400
Wheelchairs and other vehicles for disabled	250,000	300
Other	250,000	400

Source Harrop and Harrop, 1999

Hybrid EVs

Toyota, Honda. and Renault are the first automakers to produce and market large numbers of HEVs As indicated earlier, Toyota began selling its Prius in Japan in late 1997 and will begin selling in Europe and the US in 2000, Honda will begin selling its Insight in the US in early 2000 and Europe shortly thereafter, and Renault will sell its Kangoo hybrid in 2000, probably just in France

The Honda Insight is an innovative two-seat model that will be priced under $20,000 It is composed primarily of aluminum and molded plastic The use of these lightweight materials allows for a remarkably low vehicle curb weight of just 840 kg The Insight also has a teardrop shape that results in a drag coefficient of 0 25 Honda has incorporated more than 300 patents into the vehicle design, which combines a 1-liter, 3-cylinder VTEC engine, a 144-volt nickel-metal hydride battery pack, and a 3-phase BPM motor/generator. The vehicle achieves an estimated 26 km/liter (61 mpg) city and 30 km/liter (70 mpg) highway, as well as ULEV emission levels (Knight, 1999). Honda expects to sell about 4,000 Insights in the first year in the U S., along with another 4,000 in Japan. Production is expected to rise in 2001 due to increased production capacity and the introduction of the vehicle into the European market (Cogan, 1999a)

Meanwhile, Toyota sold 27,000 Prius vehicles in Japan in the two years after its December 1997 launch (Hermance, 1999). The Prius combines a high expansion ratio, Atkinson-cycle engine with a BPM motor and a nickel-metal hydride battery pack (which operates at 288 volts, double the 144 volts of the Honda Insight battery pack) Other innovative features include a planetary gear transmission and a separate BPM generator (in addition to the motor) that allows extra power from the engine to supply electricity to the motor. Over the U S combined test cycle, the Prius has achieved about 23 km/liter (55 mpg) (Hermance, 1999)

A few other companies are nearing commercialization of HEVs Renault plans to introduce a version of its light truck, the Kangoo, as a BEV and HEV in 2000. The hybrid version will have a parallel design intended to be used in ZEV mode most of the time with a small engine available as a range extender. Nissan has developed the Tino HEV, which is a small station wagon A demonstration project with about 20 of the vehicles is currently underway in Japan, and the vehicle may be sold in Japan as soon as 2000 (the project appears to be targeted at the Japanese market at present) The vehicle uses a 1 8-liter, 4-cyclinder engine, coupled with a permanent magnet motor and a lithium-ion battery pack The Tino is reported to have approximately double the fuel economy of similar conventional models (Katoh, 1999). Also, General Motors has produced a prototype HEV, called simply the "advanced technology vehicle," with an extraordinarily low drag coefficient of 0 16 (lower than the EV1) The vehicle combines a rear-mounted 1 3-liter diesel engine with a BPM motor and a nickel metal hydride or lithium polymer battery pack The fuel economy figures for the vehicle have not yet been released, pending EPA testing, but it is considered possible that the vehicle will come close to the 80 mpg (3 liters/100 km) goal of the PNGV partnership (McCosh, 2000)

Fuel Cell EVs

Rapid developments in fuel cell component, stack, and system performance and design have made near-term introduction of FCFVs possible Recently, a partnership was forged between DaimlerChrysler, Ford, and Ballard Power Systems of Canada (the world leader in developing PEM fuel cell system technology) [10] One of the first products of this partnership was the new Th!nk FC5 FCEV prototype by the Ford subsidiary This is the first vehicle to incorporate the newest Ballard Power Systems fuel cell system, known as the Mark 900 The

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[10] They formed three new companies -- Xcellsis (formerly know as Dbb Fuel Cell Engines), Electric Drive Company (ECO), and Ballard Automotive -- with the goal of commercializing fuel cell systems for transportation (Dircks, 1998) They have targeted 2004 as the date by which to introduce FCEVs Within the alliance Ballard Power Systems is held 20% by DaimlerChrysler, 15 1% by Ford, with the remainder traded on the NASDAQ and Toronto exchanges Xcellsis, which receives fuel cell stacks from Ballard Power Systems and produces complete fuel cell "engines," is held 51% by DaimlerChrysler, 27% by Ballard, and 22% by Ford ECO, which produces electric motors and controllers, is held 62% by Ford, 17% by DaimlerChrysler, and 21% by Ballard Ballard Automotive is the marketing company for the alliance

Th!nk FC5 is a four-door family sedan that is fueled with methanol (converted to hydrogen onboard the vehicle). Production of the Th!nk FC5 is slated for 2004, and the vehicle will be road tested in California in the summer of 2000 under the California Fuel Cell Partnership.

Meanwhile, Toyota and GM are apparently developing fuel cell technology "in-house," although various GM subsidiaries have purchased Ballard fuel cell stacks in the past Toyota has demonstrated two FCEVs, one running on direct hydrogen stored in hydride tanks, and another running on liquid methanol reformed onboard into hydrogen Toyota has announced that it plans to reach market with a "mass-produced" FCEV in 2003, one year before DaimlerChrysler and Ford (Sacramento Bee, 1999)

Smaller automakers have also announced their intent to produce fuel cell vehicles. Honda is planning to produce 300 fuel cell vehicles in 2003, using the EV Plus as a base vehicle and probably running on reformed methanol (Fuel Cells 2000, 1999) Also, Nissan and Volkswagen have recently unveiled prototype vehicles that use Ballard stacks, and Mazda and Renault have produced concept vehicles (Dircks, 1998).

These various efforts are indicative of the level of research and development attention that the world's automakers are applying to FCEV introduction Many technical achievements have been made in recent years through these efforts, and the remaining technical hurdles to FCEV introduction primarily involve those associated with fuel choice and system optimization and integration issues Increasingly, it seems that manufacturing cost and fuel infrastructure issues, rather than technical feasibility, are the major barriers to FCEV introduction.

Demonstration Projects

A variety of countries have created programs to accelerate the development and commercialization of electric-drive vehicles, especially battery-powered EVs The programs are almost all in countries with major automotive manufacturing industries. Each program is distinct, largely because they were designed with different goals in mind (Karlberg, 1999, Zwaneveld et al, 1999, Zwaneveld et al, 2000).

A variety of organizations in Sweden have undertaken programs to introduce electric-drive vehicles, dating back to 1992 when the Swedish National Board for Industrial an Technical Development (NUTEK) issued a procurement Through various mechanisms and with funding from various sources, and often in cooperation with government buyers elsewhere in Europe, Sweden has imported over 500 BEVs

The two most active supporters of BEVs in Europe have been Switzerland and France Motivated by the availability of abundant off-peak electricity (from nuclear powerplants), air pollution problems in Paris, and a strong automotive industry, France has promoted BEVs in a number of ways Various French ministries contribute to a variety of projects, including the $5 million Praxitele car sharing demonstration project outside of Paris that closed in 1999, and a citywide program in La Rochelle In addition, EDF (Electricite de France), the electric utility, has provided substantial subsidies to BEV buyers and has purchased over 2000 BEVs for its own fleets. EDF does not plan to expand its BEV fleet much in the foreseeable future and vehicle subsidies for new cars and batteries have been eliminated, a byproduct of the ongoing privatization of EU (and US) electric utilities The Praxitele car sharing project used 50 small Renault BEVs It did not prove commercially viable as implemented but new car sharing projects using BEVs are planned for elsewhere in France (Massot et al, 1999)

Switzerland has actively supported BEVs for many years, motivated mostly by environmental and energy concerns. The national government has provided several million dollars to various electric-drive vehicle R&D projects, including hybrid and fuel cell research, but mostly for lightweight vehicles. The Tour de Sol race initiated in the 1980s was an early focal point for those interested in lightweight BEVs The centerpiece of these activities in recent years is the small city of Mendrisio Almost 200 small EVs are now reportedly used in the small city, with the goal of achieving 8% overall market penetration.

Germany's efforts on behalf of BEVs have been less enthusiastic. The Environment Ministry is actively critical of BEVs, mostly because Germany's electrical supply system is largely based on coal The most significant effort was the $30+ million (DM 60 million) demonstration project on Rugen Island in former East Germany (Voy, 1996.) From 1992-96, 60 vehicles were driven under everyday conditions by 100 users, covering 1.3 million km. Vehicles included German-made cars, minibuses, and buses, and were powered mostly by NiCad and sodium nickel chloride ("Zebra") batteries, plus three by sodium sulfur and another three by lead-acid When the subsidized demonstration ended, the project came to a complete halt Since then, the national government has had no BEV program The lack of enthusiasm for follow-up was apparently due to the many problems with the retrofitted vehicles and the realization that BEVs are not an attractive GHG strategy in Germany due to the high use of coal in generating electricity

In the U S , several EV demonstration projects have been conducted These include the California and Arizona BEV lease programs by General Motors and Honda, in which GM EV1s and Honda EV Pluses were leased to private consumers and government and industry fleets, with data collected on vehicle use and recharging behavior Toyota conducted various demonstrations of the Prius HEV in several U.S cities in 1999-2000, in preparation for the commercial launch in the summer of 2000

FCEVs have also been tested in neighborhood vehicles in Palm Desert, California, where a larger effort to introduce neighborhood electric vehicles as been in place for over five years Perhaps the most notable FCEV demonstration effort is the California Fuel Cell Partnership, initiated in 1999 In this program, DaimlerChrysler, Ford, Honda, Volkswagen, the California Air Resources Board, and several energy companies have committed to testing a few dozen fuel cell cars and buses in California from 2000-2003

Market Demand

Automakers face a large range of possibilities in designing and building electric-drive vehicles These vehicles can, from a consumer's perspective, be nearly identical to today's internal combustion engine vehicles – examples include FCEVs or HEVs operating exclusively on gasoline (or a gasoline-like fuel) Or, at the other extreme, they can be BEVs with limited driving range per charge Moreover, automakers can make minor modifications in electric-drive vehicles to render them more like today's vehicles – for instance by altering the regenerative braking to make the vehicle "feel" more like today's ICE vehicles

Automakers thus confront a broad array of electric-drive technology options, with very different attributes, and they must decide which technologies and attributes to build into the vehicles They will make that decision based primarily on what consumers are willing to pay for, and secondarily in response to government rules Here we review those attributes that differ significantly from today's ICEVs, and examine likely consumer responses to those differing attributes. Some attributes are superior, some inferior, and some just different.

Positive attributes of electric-drive vehicles, from a buyer's perspective, include the following:

- quieter than ICE vehicles;
- smell, toxicity, and combustion dangers of gasoline can be eliminated;
- fewer air pollutant and greenhouse gas emissions (no direct emissions with some technologies),
- better driving "feel";
- can easily be pre-cooled, heated or defrosted,
- electrical appliances can be plugged in and operated when the vehicle is not being used (for instance at recreational areas),
- high power electrical appliances can be utilized in the vehicle (such as coffee pots and microwave ovens),
- BEV recharging can take place where the vehicles are parked, including home, work and shopping, eliminating trips to refueling stations

Meanwhile, the negatives for electric-drive vehicles are

- higher purchase cost,
- shorter driving range and longer recharging time for BEVs,
- high battery replacement cost

Other attributes that are different from those of today's vehicles, but not clearly superior or inferior, are listed below Most are not understood well enough to be characterized as positive or negative and vary greatly depending on the electric-drive technology employed In this list are different braking characteristics, different cost and maintenance schedules, and costs that may be equivalent on a lifecycle basis but are borne more as fixed or operating costs

Various studies have been conducted attempting to predict consumer responses to these various attributes (see Bunch et al, 1993, Garling and Thogersen, 2000, Kurani et al, 1994, 1996) The most sophisticated that are publicly available have focussed on BEV attributes and technologies None have specifically addressed hybrid and fuel cell vehicles The various studies have many weaknesses, in part because of questionable assumptions about vehicle technologies, but more so because they are investigating consumer responses to unfamiliar attributes The problem is that consumers are ill prepared to state their preferences and intentions As Bob Lutz, then vice chairman of Chrysler, noted in a 13 January 1997 Fortune magazine interview:

> [T]he customer, in this business...is usually, at best, just a rearview mirror. He can tell you what he likes among the choices that are already out there But when it comes to the future, why...should we expect the customer to be the expert in clairvoyance or in certainty?

Based on the state of knowledge, including 15 years of personal involvement in market research for alternative fuel vehicles, we conclude – setting aside cost considerations for now – that electric-drive vehicles appear to be a superior option for consumers We are confident in making this assertion, though we note that the underlying research is spotty and limited. The fundamental and underlying premises for this conclusion are listed above, especially the opportunities presented by the high-power electric infrastructure within the vehicle, the driving feel, and the pollution and energy advantages

BEVs have all the above positive attributes, plus two other strong consumer attractions. BEVs allow home recharging, which many users apparently strongly prefer,[11] and BEVs have no combustion engine In this second case, it is not just that BEVs are zero emitting, but that they represent in consumer eyes an unequivocal break from today's "unsustainable" ICEVs To many people, BEVs represent a clean, healthy, quiet alternative [12] In contrast, HEVs and non-hydrogen FCEVs have small combustion devices, and as a result are not seen as unambiguously "green" by consumers [13]

An important qualification must be offered here regarding environmental attributes. Market research is virtually unanimous in showing that consumers give little or no weight to environmental benefits in determining whether to purchase a particular vehicle (Kurani et al, 1996, Golob et al. 1996) This finding does *not* mean that environmental benefits are irrelevant to consumers, or will be in the future Just as safety played little role in vehicle purchase decisions until very recently, it is possible that environmental impact will play a role in the future.

Moreover, environment *does* play a role, but in search behavior, not purchase behavior That is, many consumers use environment impact as a criterion in focussing their search The current car buyer is confronted with hundreds of available models of new cars and light truck, but typically will actively consider not more than six vehicles and actually shop to compare only three (David Power, cited in Kurani et al, 1996) When aware of vehicles that are clearly superior environmentally, many consumers, those with strong environmental concerns, are inclined to put that vehicle on their short list of 3 or so to be seriously investigated This role in search behavior

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[11] These include elderly people and others concerned about security at fuel stations, parents concerned about children's exposure to gasoline fumes and dangers of moving vehicles at fuel stations, well-dressed people who must fuel themselves when full service is not available, and women who are often reluctant to deal with the typically young males working at fuel stations Indeed, research in the USA suggests that a significant portion of consumers would pay several thousand dollars extra for home recharging [Kurani et al, 1996]

[12] FCEVs, operating on hydrogen may also be seen this way, what is unknown is whether users will be troubled by hydrogen fueling and large on-board storage tanks

[13] In market studies comparing natural gas and battery electric vehicles, consumers indicated that BEVs were greatly preferred over natural gas vehicles as an environmental and lifestyle choice, if costs and other attributes were equivalent (Turrentine et al , 1992) Based on our interpretation of those earlier studies and our own anecdotal observations over 15 years of market research with alternative fuel vehicles, we expect that consumers will also greatly prefer pure electrics over vehicles with combustion engines, all else being equal

can be a huge attraction for automakers, who spend billions of dollars trying to distinguish their products in a crowded marketplace (automakers spend over $5 billion per year for advertising in the U.S.).

Cost is the most powerful determinant of consumer preferences. Batteries are inherently expensive and are expected to remain so into the foreseeable future. As indicated above, battery costs are not likely to drop low enough in the foreseeable future for conventional sized vehicles to be competitive with gasoline vehicles This is a perception widely held in the automotive industry. As a result, the future of conventional sized BEVs is bleak, certainly into the foreseeable future.

Automakers are most excited about the prospects for fuel cell vehicles, and secondarily for hybrid electrics They are enthusiastic about FCEVs because they have the potential to be cost competitive with gasoline ICEVs (they do not require large battery packs); from a consumer perspective, they are, apart from cost, at least as attractive to consumers as gasoline ICEVs (being fuelled similar to today's ICEVs with a chemical fuel, perhaps even a gasoline-like fuel and having similar driving ranges per tank of fuel)

Hybrid EVs are also attractive, for the same reasons, but do not generate the same enthusiasm as FCEVs because they tend to require larger (more expensive) battery packs, may have more complex drive systems because they are integrating a combustion engine system, and suffer the various maintenance, pollution, and noise disadvantages of conventional ICEVs (though to a lesser extent since the combustion engine is operated in a steadier more calm fashion).

This assessment of automaker attitudes toward alternative technologies and fuels is illustrated by their pricing strategies. Consider the most advanced BEVs available in the marketplace General Motors, Honda, and Toyota all set the retail price for their respective vehicles at $30,000 and up That price is far higher than the price of comparable gasoline ICEVs In contrast, at the same time Honda and Toyota priced their hybrid electrics in Japan and the USA under $20,000, and DaimlerChrysler publicly announced their intention in 1999 to sell their future fuel cell vehicle also under $20,000 This apparent irrationality is explained by strategic considerations.

Automakers have a longstanding history of incorporating strategic considerations into their pricing practices For instance, small vehicles are priced closer to cost than large vehicles because automakers hope to lure new buyers in at the bottom of the market with the expectation that the buyers will remain loyal and move up to larger cars that are more lucrative (And in the US, they also price small cars near cost as a means of inducing more sales of those vehicles in order to meet Corporate Average fuel Economy standards.) In another well known case, General Motors built the entirely new Saturn car division in the 1980s to test and integrate new manufacturing processes, management practices, retail distribution methods, and labor relations They priced the vehicles to be competitive, but in doing so, they were strategically deciding that they would defer recovery of R&D and many other initial costs (perhaps forever)

In the case of BEVs, automakers set prices high because they never expected those vehicles to be successful mass-market products, they were treating the vehicles as high-priced prototypes.[14] In contrast, automakers priced HEVs and FCEVs very competitively because they believe that hybrid and fuel cell electrics could be successful mass-market vehicles They take quite seriously the prospect of being a market leader with HEVs and especially FCEVs.

Summary of International Assessment

The automotive industry and the world at large is entering a difficult transition period – moving from a long-established technology to a new promising set of electric-drive technologies Such transitions are inherently disruptive, and naturally slowed by vested interests and conservative personal and organizational behaviors During these transition periods, especially in this case where large market externalities are involved, governments can play a particularly influential role Indeed, in the case of certain technologies, such as many hybrid vehicle options, one can imagine a modest set of government regulations and incentives resulting in large market penetration

In any case, it seems certain that electric drive technology will eventually supplant internal combustion engines -- perhaps not quickly, uniformly, nor entirely -- but almost inevitably The question is when and in what form. Based on the cost, environmental, and market analyses presented in this report, we believe that the following can be stated with some confidence

- BEVs are unlikely to replace many conventional-sized private vehicles in the foreseeable future,
- the most attractive applications of pure battery EVs in the foreseeable future appear to be as off-road vehicles and small, limited-performance urban and neighborhood vehicles, with the potential for significant market penetration in some locations,
- FCEVs are the first choice of automakers as the vehicle technology of the future,
- HEVs are seen by automakers as a fallback choice for the consumer vehicle market if FCEV costs do not drop to competitive levels or other problems are encountered with FCEV commercialization,
- HEV and FCEV technology may emerge as attractive options for various medium and heavy-duty vehicle applications.

There can be many reasons and many ways to participate in the advancement of electric-drive vehicles, and to benefit from that technology While air quality is currently the strongest motivation in most countries for promoting advanced environmental vehicles, that need not be the case in Sweden

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[14] Other companies such as Renault and PSA, priced their BEVs somewhat more competitively They did so largely because the vehicles were really converted gasoline vehicles and therefore not costly to develop or manufacture Converted vehicles tend to have reduced reliability and performance

Candidate Technologies for Sweden

Given the above assessment, with the understanding that Sweden is a small country with an economic and environmental interest in advanced technologies, what initiatives seem most compelling? We answer in two stages Here, in this section, we identify and examine two sets of technologies that we judge most relevant to Sweden's interests and circumstances. In the recommendations section that follows, we suggest specific actions Sweden might consider in pursuing those two sets of technologies

Small BEVs: An Environmental Policy Initiative

As indicated throughout this report, the only type of BEVs that might prove attractive in the foreseeable future are small and limited performance off-road BEVs. Sweden does not have the industrial or research base to launch a BEV industry, but there are two other factors that make BEVs an attractive option to pursue a very clean electricity supply system, and a strong environmental ethic

Small BEVs include various off-road vehicles, and range from very small golf cart-like vehicles with top speeds of about 35 km/h up to highway-capable vehicles with top speeds of about 100 km/h and ranges (per charge) of about 160 km Here we limit ourselves to an examination of the prospects for on-road vehicles[15] The largest of the small passenger BEVs, which we consider here, include the Toyota e-com, Nissan Hypermini, Ford Th!nk, and Honda City Pal prototypes (all similar in size to the DCX Smart). There are others as well, as noted earlier in the text.

Much was learned in the 1990s about the market for BEVs It was learned that the demand is potentially significant – that BEVs do indeed have some strong consumer attractions -- but that the market is likely to evolve only under certain conditions and only with considerable marketing effort. This assessment is especially applicable to small BEVs. Generally, it was learned that customers are conservative, slow to embrace new vehicle attributes, must be exposed to intensive informational and education campaigns before they accept new attributes; are highly sensitive to purchase prices; strongly influenced in their search behavior by environmental attributes but not in their purchase behavior; often value home recharging and the superior driving feel of electric-drive vehicles, and retail outlets for new fuels must be widespread even for early adopters In the case of small BEVs, all of the above lessons apply (though the vehicles will require fewer retail recharging outlets since they will be used only for local trips and therefore more likely to be charged at home)

Generally, though, it will be a slow and arduous process building a market for BEVs, and even more so for small BEVs, though easier in some markets and locations than others It will be especially slow and arduous in affluent OECD market regions since customers have little experience with small vehicles, government safety and traffic rules often limit the use of small vehicles, and few or no incentives exist for their use (Kurani et al, 1995, Lipman et al, 1994; Stein et al, 1994) Nonetheless, it is our judgement that the large economic, environmental and land use benefits of small BEVs justify strong public support, and that the provision of modest

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[15] As indicated elsewhere in this report, the off-road market for these vehicles is large and growing but analysis of this market is sparse and we are unable to assess the specific opportunities in Sweden

incentives, such as preferred parking, could greatly increase the attractiveness of such vehicles to consumers.

Several key factors influence the demand for small BEVs in Sweden. On the one hand, the relative lack of traffic congestion and parking difficulties in Sweden may undermine demand for small BEVs. On the other hand, high levels of affluence, high car ownership rates, and high environmental awareness suggest that small BEVs could find a market as a second car.

Car ownership continues to grow As of 1998, 27% of households in Sweden had no cars, 55% had one, 16% had two, and 2% had three or more (SIKA, 1999, Table 3 10) Small BEVs could be of interest to each of these groups – as a convenient low cost means of mobility that either supplements or replaces current vehicles, or as the principal means of travel for households in city centers.

Moreover, most vehicles are not used intensively and most car trips are short In Sweden, about 40% of trips are less than 2 5 km and 50% less than 5 km, half of which are by car (SIKA, 1998)

Even though most trips are not long and most vehicles are not used intensively, it is well known that individuals purchase cars that can satisfy some "marker" need (such as, as indicated ealier, a once-per-year family trip to visit Grandmother, an occasional need to dispose of large amounts of trash or, in the case of BEVs, the ability to travel from work to home to get a sick child and bring her to a hospital without recharging)

Thus, for a small BEV to be accepted, most owners would need to have easy access to larger, longer range vehicles for occasional travel needs This need could be filled by a second household vehicle, easy access to rental cars, or easy access to "shared cars" (Whitelegg, 1999, Shaheen et al, 1998)

As car ownership increases, the opportunities to introduce a more specialized vehicle, such as a small limited range BEV, increase Indeed, the proliferation of cars creates a favorable situation for small BEVs The small BEVs become more attractive because car owners no longer require all vehicles to serve all purposes, and can substitute a lower-cost vehicle for larger more expensive all-purpose vehicles And small BEVs are more attractive to society because use of the vehicles leads to sharp reductions in energy use, pollution, and space needs

Electric-Drive Trucks and Buses: An Industrial and Environmental Policy Initiative

Sweden is home to a major truck and bus manufacturing industry As noted earlier, Volvo Bus and Truck and Scania are ranked third and sixth in the world, respectively, in production of heavy vehicles (over 16 tonnes) Almost all heavy buses and trucks everywhere in the world are powered by diesel engines and fuels This pattern is unlikely to change in the case of trucks. Diesel fuel has a very high energy density, diesel engines are energy efficient and long-lasting, and large trucks are often used for long distance transport Thus, it is likely that most heavy trucks will remain powered by diesel engines and diesel fuel into the foreseeable future Certainly, heavy trucks are likely to lag other vehicles in being switched to electric-drive technologies and alternative fuels

The same can not be said for buses, though Indeed, it is likely that the transformation of buses to electric drive will be faster than for any other vehicle type In the US, about 1/3 of new bus orders in the late 1990s were for natural gas, and a growing number are for hybrid electric powertrains As indicated above, 12 HEV buses have been purchased for use and testing in Sweden (plus Volvo is designing and testing two hybrid heavy duty trucks and two hybrid buses)

Companies involved in heavy duty electric-drive vehicle technology development in Sweden include Volvo, Scania, Ericsson Communication System, ABB, Höganäs, and Ni-Mc Hydrid AB.

Buses are an early target market for several reasons: their pollution causes a disproportionate health effect because emissions tend to be in areas with high outdoor populations, diesel particulates are arguably the most serious health threat from vehicular pollution, and buses are usually government owned and managed and therefore more responsive to public policy. The bus market, though not nearly as large as the heavy-duty truck market, is important because the engines and drivetrains are the same as used in heavy duty trucks. Thus, early penetration of the bus market leads naturally to later penetration of the larger truck market

Policy Suggestions for Sweden

Below we provide a list of policy and investment suggestions that might be pursued in support of the two initiatives proposed above -- to accelerate the use of small BEVs, and to develop and commercialize heavy duty electric-drive vehicles This list is meant to be suggestive, not comprehensive nor definitive

Incentives for the purchase and use of small BEVs To accelerate the introduction of small BEVs as efficiently as possible, a necessary pre-condition is the adoption of incentives These incentives might be both monetary and non-monetary, ranging from lower vehicle purchase taxes and registration fees to preferred parking in downtown areas These incentives ideally would be adopted in a form that reflects the social benefits of these vehicles Some effort should also be devoted to creating incentives for electricity recharging infrastructure at homes and for public stations, but the small energy requirements of these vehicles suggest that recharging infrastructure costs should be small

Demonstrations of small BEVs These vehicles are unfamiliar to vehicle operators and travelers, traffic enforcement officials, infrastracture managers and operators, and business owners. For small BEVs to be introduced as passenger vehicles, changes should and in some cases must be made in various rules and practices, so that travelers feel and indeed *are* safe It will take much time and effort, and partnerships will need to be formed with a variety of organizations. Demonstration projects can be costly and not very useful but, if conducted wisely and with clear goals, can also play a critical learning and educational role The goal here is to learn what changes in the transport system are necessary to accommodate the vehicles, and to increase their exposure to potential buyers and users Related demonstrations might focus on deliveries of e-commerce goods to neighborhoods, or integration of small BEVs into car sharing programs

Create "EV" standard for clean urban cars Sweden is not alone in considering the use of electric-drive vehicles in polluted and noisy city centers Many other cities are exploring and enacting rules that prohibit vehicles with combustion engines on certain days and in certain areas Sweden might want to coordinate with other cities and countries, or even take a leadership role, in developing a standard for "clean" urban cars Such a standard could be used to enact traffic rules, adopt incentives and create the framework for liability determinations Adoption of this standard could be pivotal in the introduction of small BEVs

R&D funds for innovative, leading-edge technologies. Careful strategic thinking should go into this program, since government funds are limited, government is not omniscient, and the resources of large industrial companies dwarf what might be made available by government. In this case, we suggest the highest priority be given to hybrid and fuel cell technologies for heavy duty vehicles, and that funds be directed at small entrepreneurial companies and major companies with relevant expertise but not traditionally involved in vehicle manufacturing.

Demonstration of hybrid and fuel cell buses. The role of the national government in this case is mostly to facilitate the testing of buses in actual operation. The intent is to help the vehicle suppliers learn about bus operator and customer acceptance issues and problems. These tests can be rather limited.

Fuel cell research. We purposefully refrained from recommending a fuel cell strategy, given the apparent lack of investment in fuel cells in Sweden.[16] We suggest, however, that Swedish businesses and government seriously ponder this issue. It appears plausible that fuel cell technology will play a major role in powering a vast range of future products, from small consumer devices to home energy use, cars, and stationary electricity generating powerplants. Can Sweden afford to ignore such an important development?

These suggested initiatives and actions reflect our assessment of the state of knowledge, and our interpretation of what might be most advantageous for Sweden. We are not omniscient, however. Circumstances change. Surprises happen. To provide insight into our thinking, and therefore to aid those confronted with the difficult decisions of how to proceed, we provide some discussion of our general understandings and beliefs.

First, we suggest that actions taken by Sweden for the social good can create a halo effect for the entire country. That is, the country and its products will be seen more favorably and treated better in world dealings. Also, it could lead to more tourism.

Second, we are skeptical of a large government role in funding R&D, especially in a small country such as Sweden, but do believe that strategic support of research will have large payoffs. The greatest payoffs are likely to result from research funds directed at small innovative companies, universities that train the next generation of scientists and engineers, and long term research in general. We note that large industrial companies have R&D budgets that dwarf the resources of government; R&D investments in those companies should be pursued with prudence. It is important, though, that major vehicle suppliers be involved to provide strategic insight.

Finally, Sweden needs to look to other partners and models. In the case of small BEVs, where Sweden would be a technology receiver, the critical partnerships are with other countries and regions also interested in deploying those vehicles. In the case of heavy-duty vehicle technologies, Sweden would be a technology supplier and, since no single company is likely to supply entire systems, companies need to form alliances and partnerships with other component

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[16] A Swedish business magazine, *Affarsvarlden*, carried a feature story on fuel cells in its 26 January 2000 issue. It claimed that only one Swedish company listed on a stock exchange is connected to the fuel cell industry, and it is a small company that manufactures compressors for fuel cells.

and subsystem suppliers, thus the critical partnerships in this case are with other technology suppliers.

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Table A-1: Summary of BEV Purchase Cost Estimates from Various Studies

Cost Study	Purchase Cost Estimate			
ITS-Davis – Delucchi, et al (1999) Mid-sized vehicle, lead-acid battery, high volume production	Driving range 65 miles $23,669	Driving range 80 miles $25,146	Driving range 110 miles $28,527	Driving range 125 miles $30,615
Mid-sized vehicle, NiMH battery, high volume production	70 miles $23,884	100 miles $25,785	160 miles $32,450	190 miles $35 292
Argonne Nat'l Lab – Vyas et al (1999) Subcompact BEV	2000 (<10K/yr) $18,500 - 41,400	2005 (10-40K/yr) $18,300 - 35,900	2010 (>40K) $17,800 - 32,900	2020 (>40K/yr) $17,700 - 30,300
Minivan BEV	$27,300 - 63,500	$27,100 - 53,900	$26,300 - 49,400	$26,000-44,100
Booz-Allen & Hamilton (1995) Compact BEV	1998 40,000/yr $28,173	2000 41,000/yr $25,606	2002 107,00/yr $20,060	2004 243,000/yr $18,290
U.S DOE (1995) Minivan BEV	1998 $25,409-30,739		2005 $20,318-22,254	
U S GAO (1994) Compact BEV	Handbuilt $42,700	1000/yr $28,700	10 000/yr $27,000	100,000/yr $18,300
NAVC – Moomaw et al (1994) Purpose-Built BEV	1995 (prototype) $60,515		1998 (20 000/yr) $22,915	
Cost Study	**Incremental Cost Estimates** (compared to comparable gasoline ICE vehicle)			
Office of Technology Assessment (1995) Incremental Cost (Retail)	Subcompact 2005 (24,000/yr) $8 090 - $56,600	Mid-size 2005 (24,000/yr) $10,920 - $74,100	Subcompact 2015 (24 000/yr) $2,260 - $25,560	Mid-size 2015 (24 000/yr) $3,175 - $33,090
Sierra Research (1994) Small Passenger BEV Incremental Cost	1998 $10,000 - 27,143	2002 $7.000 - 17,254	2006 $4,250 - 20,280	2010 $10,000 - 22,726
Rand Institute (1996) Compact BEV Incremental Cost	1998-2002 $3,320-$15 000			

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