

IEA INTERNATIONAL ENERGY AGENCY



*Annex VII: Hybrid Vehicles
Overview Report 2000*

Executive Summary

*Worldwide developments and activities
in the field of hybrid
road-vehicle technology*

Authors:

Richard T.M. Smokers, Arjan J.J. Dijkhuizen and Rob G. Winkel,
TNO Automotive, the Netherlands

With contributions from:

Robert Kost and Rogelio Sullivan, Department of Energy, USA

Terry Penney, Keith Wipke, and Kenneth Kelly, NREL, USA

Kenji Morita and Nobuo Iwai, JARI, Japan

Peter Coenen and Patrick Debal, VITO, Belgium

Hans G. Pettersson, KFB, Sweden

Markku Ikonen and Sari Nobell, VTT, Finland

François Badin and Bruno Jeanneret, INRETS, France

Erik van den Tillaart, TNO Automotive, the Netherlands

This report

This Overview Report on the status of Hybrid Vehicle Technologies and Programmes is the result of collaborative work carried out in phase I of Annex VII between June 1998 and June 2000. It incorporates the results of both Subtask VII/1 and Subtask VII/2 over this period. The main text is based on the information collected by the participants on the status of hybrid vehicle technology and the R&D and implementation projects and programmes in various countries. As the Topics that have been studied in Subtask VII/2 closely relate to the aspects that are analyzed in the Overview Report resulting from Subtask VII/1, the Topic Reports have been integrated into this report at the appropriate places. Whenever this is the case, authors of the Topic Report are clearly mentioned.

At the end of phase II an updated version of this Overview Report will be published, incorporating the Topic Reports on subjects studied in phase II.

The structure of the report is as follows:

Chapter 2 introduces the various hybrid drivetrain configurations which are being developed and studied by the light duty and heavy duty vehicle manufacturers in the world. Roughly spoken, one can divide hybrid drivetrain configurations using electrical storage devices into series-, parallel and combined hybrids. Furthermore, hybrids making use of a mechanical energy storage device are briefly discussed.

Chapter 3 takes a closer look at some concrete examples of hybrid vehicles that have been developed for different applications (two-wheelers, passenger cars, vans, buses and trucks) and discusses some trends. Different vehicle applications demand different hybrid configurations. On the basis of existing examples the choices made by the R&D community and automotive industry are illustrated.

Subsequently, Chapter 4 deals with the two main components that are specifically developed for hybrid vehicle applications: thermal energy sources and energy storage devices (i.e. batteries, supercapacitors and flywheels). An overview and analysis of the state-of-the-art of these components is presented and some general reflections on the latest developments are given. In a future version of this report more components for hybrid powertrains will be discussed.

Chapter 5 describes large programmes and projects on hybrid vehicles that are being carried out worldwide. These are on the one hand divided into governmental and industrial programmes and on the other hand split up for the three regions Europe, USA and Asia.

Based on the vast amount of data collected in Annex VII Chapter 6 analyses worldwide trends within the field of hybrid vehicle technology in a more statistical manner. Trends in R&D (for instance status of hybrid vehicles, components used within several hybrid vehicle configurations), market introduction and mass production are visualized. Furthermore time paths for the development and introduction of hybrid electric vehicles and fuel cell vehicles are discussed.

Chapter 7 is focused on energy and emission aspects of hybrid vehicles. This chapter is composed of various Topic Reports written by the Annex VII participants. Attention is paid to test methods for HEVs, energy consumption and emissions of hybrids and the perspectives for using alternative motor fuels in hybrid vehicles. As part of the discussion on energy aspects a comparative assessment is presented of different HEV configurations using the simulation tool ADVISOR.

The next chapter (Chapter 8) presents a study of the cost aspects of hybrids, fully based on a Topic Report devoted to this subject.

Chapter 9 concludes the report with some final remarks. A summary of the conclusions from the various chapters of this report can be found in the executive summary.

Finally in Chapter 10 a general overview is given of the information collected on hybrid vehicles (from human powered hybrid two-wheelers up to heavy duty vehicles) which are currently in the R&D or early commercial stage (prototypes, testing vehicles, concept cars). The overview is of course not complete. A selection is made of those vehicles that are attractive or illustrative by virtue of their technical innovation, or that are already in the (pre-) commercial stage. Apart from general vehicle data, some technical information of the driveline configuration is given (whenever available).

Contents

| | | |
|-------|--|----|
| 1 | Executive Summary | 5 |
| 1.1 | What is a hybrid vehicle? | 5 |
| 1.2 | Hybrid drivetrain configurations | 6 |
| 1.3 | Status of hybrid vehicle developments for different applications | 7 |
| 1.3.1 | Passenger cars | 7 |
| 1.3.2 | Heavy-duty applications | 8 |
| 1.3.3 | Other applications | 8 |
| 1.4 | Component development for hybrid vehicles | 8 |
| 1.5 | Worldwide programmes and projects | 9 |
| 1.6 | General development trends | 9 |
| 1.7 | The potential benefits of hybrid vehicles | 11 |
| 1.8 | Costs of hybrid vehicles | 12 |
| 1.9 | Conclusions | 13 |

1 Executive Summary

Hybrid vehicles are well on their way to become a commercially viable, energy efficient and environment-friendly alternative for the conventional, internal combustion engine vehicle. Several hybrid vehicles are already available in both the passenger car and the heavy-duty vehicle markets and all major manufacturers have substantial development programmes running to get this new technology on the road.

For policy makers hybrid vehicles pose three major questions:

- How can hybrid vehicles contribute to policy goals, such as reduction of air pollution and greenhouse gas emissions, reduction of fuel consumption and weakening of the dependence on imported oil?
- What kind of policy support is possible and/or necessary to promote hybrid vehicle technology and other advanced propulsion technologies that contribute to the above-mentioned policy goals?
- What is the time frame in which this technology may become a mature alternative and how does hybrid vehicle technology compare to other alternative propulsion technologies that are under development?

To answer these questions it is first of all necessary to have insight in the potential benefits that hybrid vehicle technology can bring. For a good understanding of these benefits some knowledge is required of hybrid vehicles themselves and of the many powertrain configurations in which this technology manifests itself.

In this report a general introduction of hybrid propulsion technology is presented, introducing the main concepts and terminology. By means of concrete examples of prototypes and commercially available vehicles the state-of-the-art of this technology is discussed. Also an overview is given of research and development programmes that are being undertaken worldwide. In addition a number of policy relevant issues is discussed related to the development and market introduction of hybrid vehicles.

This report is the first publication produced by Annex VII “Hybrid Vehicles”. This is a project carried out in the context of the IEA Implementing Agreement for Hybrid and Electric Vehicle Technologies and Programmes, an international cooperation programme facilitated by the International Energy Agency. The Implementing Agreement was started in 1993 and was continued into a second phase in 1999. At present 13 countries are participating. In the context of this programme institutes from the participating countries carry out a range of projects. Initially, projects in the Implementing Agreement focused on various aspects of battery-electric vehicles. In June of 1998 Annex VII on “Hybrid Vehicles” was started to create an overview of hybrid vehicle technology and programmes in the world and to assess policy relevant aspects. Scientists and government representatives of seven participating countries have contributed to this Overview Report: Japan (represented by JARI), the USA (represented by NREL and DoE), Sweden (represented by KFB), Finland (represented by VTT), the Netherlands (represented by TNO), Belgium (represented by VITO) and France (represented by INRETS) have joined the project. TNO, the Netherlands Organization for Applied Scientific Research, has been appointed as Operating Agent (O.A. = project leader) of Annex VII.

The main results and conclusions of the work performed in Annex VII are summarized below:

1.1 What is a hybrid vehicle?

This question is more easily asked than answered. The nature and especially the complexity of the answer will generally depend on the purpose for which this question is asked. Some examples of the purposes, for which a definition of the term “hybrid vehicle” is necessary, are:

- general communication, including news items and political or public discussions
- emission regulations and test procedures
- tax regulations
- marketing
- etcetera.

For general communication it suffices to define a hybrid vehicle as a vehicle in which the energy required for propelling the vehicle can be drawn from two (or more) different energy sources. One of these energy sources has to be reversible, implying the possibility of energy storage. In most cases this reversible source is an electric energy source in the form of a battery that supplies its energy to an electric motor propelling the wheels. In this case one speaks of a hybrid-electric vehicle (HEV). When the energy storage and its coupling to the wheels are of a mechanical nature (e.g. a flywheel) one speaks of a mechanical hybrid. The non-reversible energy source in a hybrid vehicle most often is a combustion engine, but it can also be a fuel cell.

However, a definition of hybrid vehicles for e.g. test procedures, emission regulations and tax regulations requires a higher degree of exactness. General definitions can not be given here. E.g. for tax incentives the exact definition will depend on the policy goals that are set out, and the risks one can afford to take to unintentionally promote powertrain configurations that do not possess the qualifications necessary to contribute to the policy goals set out. Some hybrids are cleaner and/or more energy efficient than others are, and under the wrong definition also a conventional vehicle with a large starter motor could be considered a hybrid. An example of such a policy-oriented definition is used in California, where hybrid vehicles that fulfil a specific set of requirements can be allowed so-called partial ZEV-credits, meaning that they can be partially considered as a zero-emission vehicles. Many, from a more general perspective, promising hybrid configurations, however, do not meet this set of requirements.

For test procedures (e.g. homologation testing in the context of emission regulations) one has to look at the specific aspects of hybrid propulsion technology that prohibit the application of conventional test procedures to hybrid vehicles and therefore require specific procedures. Examples of such specific properties are the possibility of energy recovery during braking (regenerative braking), the fact that the battery charge may change during a test (meaning that the net energy production by the combustion engine during the test may be significantly more or less than the energy supplied to the wheels), and the high sensitivity of hybrid powertrain control systems to small variations in the driving cycle. It starts to be recognized, however, that many of these aspects are also found in some way or another in advanced conventional vehicles (e.g. with storage catalysts causing a time delay between the road load dynamics and the instantaneous emissions from the tailpipe). This means that for the purpose of homologation testing it may in the end not be useful to define hybrid as a separate category. Instead, the definition of test procedures should be adapted in such a way that a wide variety of advanced propulsion systems can be tested in a consistent and comparable way, under more realistic test conditions than currently applied.

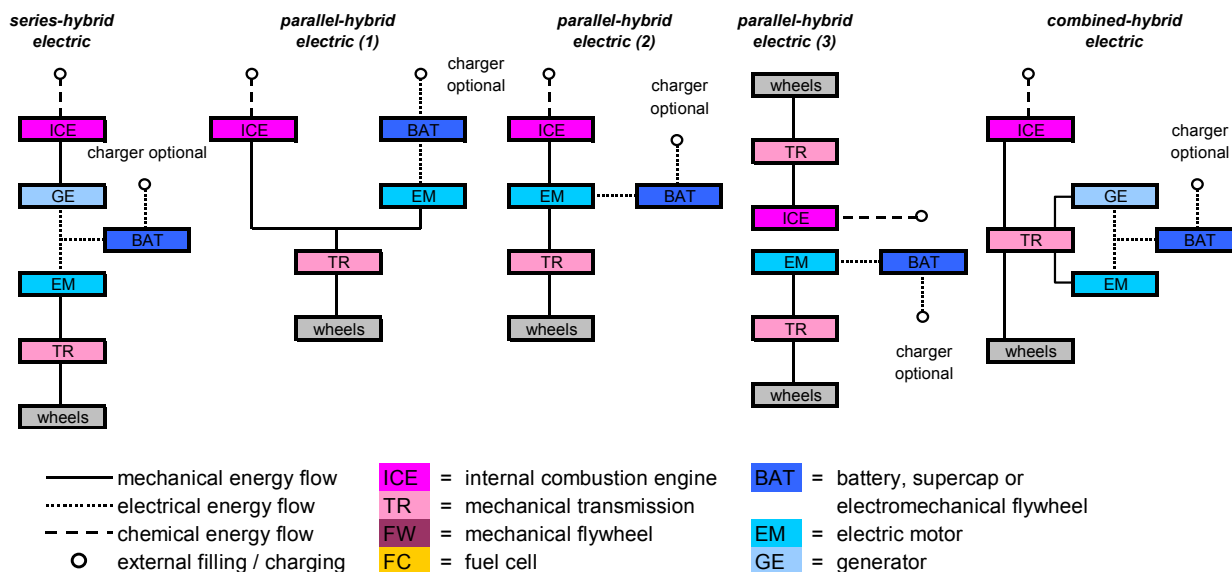
1.2 Hybrid drivetrain configurations

This report concentrates on hybrid-electric vehicles, for which three main drivetrain configurations can be discerned:

- a series hybrid configuration
- a parallel hybrid configuration
- a combined hybrid configuration

In a series hybrid-electric vehicle all energy supplied by the non-reversible source (combustion engine

or fuel cell) is converted into electricity. The wheels are always driven by the electric motor that derives its energy from the battery and/or from the combustion engine (or fuel cell). Series-hybrid powertrains are most often applied in urban buses.



In a parallel hybrid-electric vehicle most of the mechanical energy supplied by the combustion engine is transferred to the wheels by a mechanical transmission. In addition or alternatively (depending on the exact configuration) the wheels are also driven by the electric motor that derives its energy from a battery. Depending on the way the combustion engine and the electric powertrain interact different types of parallel hybrid powertrains are distinguished. Examples of parallel hybrids are the Audi DUO and the Honda Insight.

A combined hybrid combines characteristics of the two configurations described above. A well-known example is the Toyota Prius.

1.3 Status of hybrid vehicle developments for different applications

1.3.1 Passenger cars

Worldwide only two hybrid-electric passenger cars are commercially available, the Toyota Prius and the Honda Insight. At the end of 2000 since its introduction in 1997 Toyota has sold some 50,000 Priuses. All major car manufacturers, however, have large R&D programmes in the field of hybrid technology. Many of them have revealed prototypes and have announced plans for commercialization in the next five years. Most hybrids under development have a parallel configuration. Momentarily large research efforts are concentrated on the so-called engine-assist or starter-alternator type of hybrid in which a small electric motor is mounted on the internal combustion engine at the location of the engine's flywheel. This electric motor provides peak power as well as limited regenerative braking capability and furthermore enhances the vehicle's driveability. Examples of vehicles with such a configuration are the Honda Insight, the Xsara Dynalto developed by Citroën, and the prototypes developed in the US by Ford, DaimlerChrysler and GM under the PNGV-programme.

So far only Japanese manufacturers have dared to take the step towards large-scale manufacturing and marketing of hybrids. European and US manufacturers seem to await more stringent demands for clean or fuel-efficient vehicles that may emerge from future legislation or covenants between governments and industry, e.g. to reduce fleet average fuel consumption or CO₂-emissions.

Ford, DaimlerChrysler and GM all have announced plans to introduce hybrid sport-utility vehicles by the year 2003. Although generally used as passenger cars these vehicles are officially categorized as trucks.

1.3.2 Heavy-duty applications

Especially for urban buses the potential benefits of hybrid propulsion are significant. Many manufacturers have produced prototypes or are able to produce small series of hybrid vehicles, which are so far mainly used in government-sponsored demonstration projects. Developments can therefore be categorized as being in a demonstration to pre-commercial stage. Costs and, related to that, battery-life are important issues in this market. Cost benefits can e.g. be caused by reduced brake wear as a result of regenerative braking.

Hybrid vehicle development for trucks mainly concentrates on distribution vehicles operated in urban areas. Some examples of prototypes of larger trucks have also been developed. Developments are all in the prototype and demonstration phase.

1.3.3 Other applications

Other applications of hybrid propulsion technology can be found in military vehicles and in racing. In the military hybrid vehicle technology can not only improve the autonomy of vehicles but may also help to improve "stealth" properties (e.g. reduced heat signature).

Some attention in the report is paid to human-powered vehicles. In general these are two-wheelers where an electric powertrain augments the muscle power supplied by the driver. It can be debated whether these vehicles should be discussed in the same context as hybrid passenger cars or trucks, but given the high market potential of this electric drive technology, both in developed and in developing countries, it is considered useful to bring it under the readers attention.

1.4 Component development for hybrid vehicles

Although hybrid vehicles use many components also found in conventional vehicles and in battery-electric vehicles, most of these components can be optimized for use in a hybrid configuration. This is especially true for the combustion engine and for the battery.

Combustion engines in hybrid vehicles are used in a limited range of their engine map and in a less dynamic way than is the case in conventional vehicles. The engine and its exhaust aftertreatment can therefore be optimized for energy efficiency and emissions without compromising driveability. In general the engine can be smaller than engines in conventional vehicles. Also various types of engines can be applied that are not suitable for driving the wheels directly. Examples of these are gas turbines and Stirling engines. The ambitious goals set out in the US PNGV-programme (3 l/100 km for a US-type mid-size family sedan) have caused the American manufacturers to reconsider their attitude towards diesel engines, and direct-injection (or CIDI) engines are used in all three prototypes revealed in 2000.

Battery development for battery-electric vehicles concentrates on maximizing the energy content (kWh/kg) of the battery in order to reduce vehicle weight and increase driving range. Clever hybrids use the battery mainly for supplying peak power or storing energy during regenerative braking and will tend to minimize the energy flow through the battery. This means that batteries for hybrids need to be optimized for specific power (kW/kg). Various well-known cell types (e.g. lead-acid, NiMH and

Li-polymer) allow this kind of optimization.

1.5 Worldwide programmes and projects

In the USA, Europe and Japan different “models” are used for setting up government sponsored programmes. The “Partnership for a New Generation of Vehicles” (PNGV-programme) in the USA is characterized by a strong programmatic coordination and intensive cooperation between automobile manufacturers, component suppliers, the US government and governmental research centers. The US Department of Energy coordinates the programme. The goal is to develop commercially viable passenger cars that are a factor 3 more energy efficient than today’s vehicles. Along similar lines the “21st Century Truck Program” is currently being set up, which will aim at a factor 2x increase in energy efficiency for trucks.

In Japan the New Energy and Industrial Technology Development Organisation (NEDO) coordinates the so-called Advanced Clean Energy Vehicle Project (NEDO-ACE). Within this programme various manufacturers develop prototype vehicles and components for a range of applications.

There are no really large, European Union or partly European Union sponsored programmes which are entirely focused on the development of advanced vehicles, let alone hybrid vehicles specifically. Instead the EU sponsors and coordinates so-called Framework Programmes, which focus on research, development and demonstration projects in the field of innovative energy technologies in general. Various themes within these programmes cover (H)EV development activities and projects. The project consortiums generally set development goals with limited influence by the EU. There is very little cooperation or coordination between the various development projects. Projects in which various manufacturers cooperate are generally initiated by EUCAR.

All large automotive manufacturers in the world have their own hybrid vehicle R&D programmes. Information on their R&D activities can only be obtained from publications, press releases, internet sites and presentations of prototypes at auto shows. From these sources it is difficult to deduce a coherent picture of the R&D strategies of the various manufacturers. Unfortunately their willingness to participate in a questionnaire to create an overview of industrial activities was very limited. The report does contain a brief overview based on publicly available information, but a more in depth analysis of industrial programmes and HEV development strategies could not be made.

1.6 General development trends

The participants in the project have collected information on vehicle and component development activities worldwide. From the collected data a number of conclusions can be drawn.

In the passenger car segment many prototype vehicles have been presented but so far only two vehicles (the Toyota Prius and the Honda Insight) have the stage of commercial availability. In the market of heavy-duty vehicles and vans the commercial availability of hybrid vehicles seems slightly better, but in those markets the distinction between the prototype and the commercial stage is less clear. Markets are generally smaller and accordingly manufacturing technologies are less capital intensive. Also vehicles are used and maintained in a professional context, which makes it easier to handle the peculiarities of not completely matured technologies. For example, various bus manufacturers have sold small series of hybrid buses to public transport authorities for use in a demonstration programmes.

The vast majority of hybrid vehicle prototypes developed so far use spark or compression ignited

internal combustion engines. Only in a few projects other engine types such as Stirling engines or gas turbines have been used. Similarly most vehicles use batteries for energy storage, although, especially in heavy duty applications, examples of vehicles with flywheels are known. For main stream markets such as passenger cars “exotic” configurations do not seem to bring substantial advantages.

The general trend at least in the US market seems to be towards charge-sustaining hybrids, vehicles that do not require charging from the grid. The two mass-produced commercial hybrid vehicles on the market (Toyota Prius and Honda Insight) are both also of the charge-sustaining type. In Europe both charge depleting and charge sustaining vehicles have been demonstrated. The rising interest in starter-alternator or engine assist hybrids, however, also may indicate a trend towards charge sustaining vehicles. In general, vehicle manufacturers want to be in control of the recharging strategy of the batteries to avoid possible warranty costs originating from incorrect charging of the batteries by the customer. From their viewpoint, the charge-sustaining option fulfills this desire better. On the other hand, utility companies in many countries want to find new markets to sell electricity. Especially in France, who has a large share of nuclear power in its generation mix, this has led to a strong interest in charge-depleting vehicles. The extent to which the zero-emission driving possibilities of charge depleting vehicles are appreciated generally depends on the emissions of a country's electricity generation system and on national and local environmental policy.

Of course, hybrid propulsion is not the only candidate propulsion system for the car of the future. While hybrid vehicles are just becoming commercially available various manufacturers have already announced that they will start small series production of fuel cell powered vehicles by the year 2003. The interaction between these two technologies is viewed in different scenarios. If indeed fuel cell vehicles can be built in a cost-effective way around the year 2005 then they could become a serious competitor of the hybrid vehicle. If the fuel cell vehicle is not ready by that time, then hybrid propulsion technology will very probably reach a significant market share. This may have different consequences for the fuel cell vehicle. On the one hand large investments in producing and marketing hybrid vehicles may cause manufacturers to postpone the introduction of fuel cell vehicles for several decades. On the other hand a successful introduction of hybrid vehicles also leads to cost reduction of electric propulsion system components such as electric machines, power electronics and batteries, and to an increased acceptance of electric propulsion by the customer. Both these developments may benefit the introduction of fuel cell vehicles. Fuel cell vehicles may also have hybrid configurations, when an additional battery is used. In this way the development of hybrid vehicles may in the end also stimulate the development and introduction of fuel cell vehicles. The benefits of using a hybrid configuration for fuel cell vehicles depend on the amount of fuel cell power that is replaced by battery power. In first instance the use of a battery may reduce costs and power train volume and may help to overcome the long start-up time of fuel cell systems. Possible energy benefits depend on the developments in battery efficiency and fuel cell system efficiency. Given the rapid developments especially the latter is difficult to predict.

In the long run, when depleting oil resources force a drastic redesign of the energy system, fuel cell vehicles do seem the logical option. In the 2005 – 2010 timeframe, however, fuel cell vehicles will have to overcome some serious technical and non-technical problems. One such problem is that they are much cleaner than what is required by most emission regulations foreseen for that period. At the same time their overall fuel efficiency will not be better than that of CIDI conventional vehicles or hybrid vehicles. Fuel cell vehicles running on hydrogen are very efficient at the vehicle level but the production of hydrogen will in the short and mid term be based on fossil fuels and will involve serious energy losses. Fuel cell vehicles running on methanol or other carbon based fuels will be less efficient on the vehicle level and will also require fuel supply chains with significant losses. Unless conventional fuels are used, the availability of fuels for fuel cell vehicles will in first instance be limited. Furthermore, in the 2005 – 2010 timeframe fuel cell vehicles will obviously be more expensive than conventional or hybrid alternatives. It seems unlikely that customers are willing to buy a car that is cleaner than required and at the same time more expensive to drive.

1.7 The potential benefits of hybrid vehicles

Although hybrid vehicles are currently being introduced on the market, there are no specific emission regulations and associated homologation test procedures available for hybrid vehicles. Both the Toyota Prius and the Honda Insight are charge-sustaining vehicles, that need and can not be charged from the grid, and both have relatively small batteries. These characteristics allow the application of existing test procedures for conventional vehicles with acceptable accuracy. This will, however, not be the case for vehicles with larger batteries or battery charging from the grid.

Due to their technical complexity hybrid-electric vehicles in general pose tremendous challenges for the definition of measurement methods and test procedures. A crucial characteristic of hybrid vehicles is the fact that the instantaneous fuel consumption and emissions are uncoupled from the instantaneous road load. The energy supplied by the battery during an acceleration, for instance, has been generated by the engine and generator some time before the acceleration occurs. In general, the state-of-charge (SOC) of the battery at the end of the test will not be the same as the SOC at the beginning of the test. For an accurate determination of energy consumption this Δ SOC needs to be measured and compensated for. All in all the complex and sometimes discrete nature of the powertrain control strategy leads to a highly non-linear response of the energy consumption and emissions of hybrid vehicles to changes in the test circumstances, as specified by e.g. the vehicle conditioning (battery state-of-charge, soaking temperature, etc.), the dynamics and length of the driving cycle and the accuracy with which the cycle is followed. Test procedures for hybrid vehicles will need to deal with these issues in an appropriate way.

It needs to be stressed that the implementation of appropriate homologation procedures is mandatory for a successful large-scale market introduction of hybrid vehicles. The exact definition of regulations and test procedures, in combination with the associated legislative emission limits, is critical as this definition in itself influences the relative performance of different technologies subjected to a test procedure. This fact is already known from homologation testing of conventional vehicles. The goal of homologation testing and emission regulations is to lower the environmental impacts of vehicles on the road. However, wrong definitions of the structure of the procedure and the laboratory test conditions may induce the marketing of sub-optimal technical solutions. Technologies that score well on a laboratory test do not necessarily perform better than their alternatives when used in actual traffic

The development of hybrid vehicles is to a large extent motivated by the need to decrease fuel consumption and exhaust emissions. However, other benefits are also being recognized, and these may in the end be of greater importance to the actual user of the vehicle. Hybrid propulsion may e.g. significantly improve the vehicle's driveability, may reduce internal and external noise levels and also fits very well to the increasing demand for on-board electric power. Concerning the latter, the present interest in starter-alternator systems is strongly related to the trend towards a 42 V board net.

The emission benefits of hybrid propulsion can be easily understood in a qualitative sense, but are difficult to quantify at the present stage. Emission data of state-of-the-art hybrids are scarce. Computer simulations are powerful tools to evaluate the performance and energy consumption of future vehicles, but fail to predict emissions in a reliable way. Therefore no quantitative statements are given in this report on hybrid vehicle emissions. As more emission data will become available in the next few years we hope to be able to fill this gap in the 2002 update of this report.

Concerning energy benefits of hybrids the picture is clearer. Commercially available vehicles and prototypes prove significant fuel savings and computer simulations give clear insight in how these savings relate to powertrains configurations, control strategies, and other improvements in the vehicles.

The Toyota Prius has a rather conventional vehicle body so that most of the achieved energy savings can be attributed to the hybrid powertrain. Over various driving cycles fuel savings of 30 to 40% have been measured. For the Honda Insight, as well as for the prototypes developed under the PNGV programme (the Ford Prodigy, the Dodge ESX3 and the GM Precept), it can be stated that a large share of the fuel savings is to be attributed to other energy saving features such as light-weight construction and improved air drag and rolling resistance. Nevertheless all these vehicles show that hybrid propulsion plays a vital role in attaining the goal of 3 liter per 100 kilometer, which, depending on the reference vehicle, is an efficiency improvement of a factor of 2 to 3.

The project participants have carried out computer simulations using the ADVISOR simulation tool. In these simulations various hybrid passenger cars are compared to conventional vehicles with similar size, body weight and resistance factors. All compared vehicles meet the same programme of demands and therefore have comparable performance. Calculations show that under urban driving conditions hybrid passenger cars can be over 50 % more energy efficient than conventional cars. The benefits are relatively small under simulated highway driving conditions. Under average driving conditions (a mix of urban, rural and highway driving) hybrids can reduce fuel consumption by 30 to 40%. In general the benefits are larger for heavier cars. Parallel hybrids are generally more fuel-efficient than series hybrid configurations in this application. Calculations on heavy-duty vehicles are currently being conducted and results will be presented in the 2002 update of this report.

In this project an analysis has been made of the possible interactions between the introduction of hybrids and the use of alternative fuels. The analysis indicates that the advent of hybrid vehicles will not increase the attractiveness of alternative fuels, but may in fact lower their ranking with respect to gasoline. Hybrid vehicles cannot be expected to pull alternative fuels into the marketplace at a faster rate than would occur otherwise. Thus, it appears that plans for the introduction of alternative fuels need not be adjusted in any major way if hybrid vehicles start replacing conventional vehicles.

1.8 Costs of hybrid vehicles

When first introduced to the market new technologies are generally more expensive than conventional alternatives. With increasing production volumes economies of scale and learning effects will reduce production costs. For a new technology to be successful it must either be cheaper than its conventional alternatives or it must bring added value at an acceptable price. Unless stringent emission legislation or energy policy simply requires the application of new technologies, car manufacturers are faced with a chicken-and-egg problem when introducing new clean and efficient vehicles. Without cost reduction no significant sales can be achieved, while cost reduction is only possible when production volumes increase. Government policy may help overcome this problem. To find out which policy instruments may be successful, an analysis has been made of vehicle production costs and sales prices in different regions of the world.

The apparent similarities and differences between Asia, Europe and the US relative to the production and sale of hybrid vehicles include:

- Similar vehicle production costs in Europe and the US.
- Hybrid powertrain cost requirement of less than 2,600 EUR to compete on cost with conventional powertrains in Europe and the US.
- Hybrid vehicles must be priced less than 20,000 EUR to compete with the top selling conventional vehicles.
- Sales tax and fuel taxes are higher in Europe than in the US.
- All regions show similar reasoning in buying vehicles: fuel economy, fuel price and low emissions are not primary decision factors in a vehicle purchase. However, efficiency is a more inherent characteristic in Asian and European lifestyles (and might not be seen as a key differentiator).

Global opportunities to influence manufacturers to build hybrid vehicles include:

- Direct subsidies of the sales price.
- Indirect subsidies to support hybrid powertrain cost reduction.

Global opportunities to influence consumers to buy hybrid vehicles include:

- Direct subsidies of the purchase price.
- Tax credits/exemptions for purchasing a hybrid vehicle. Sales tax exemption in some EU countries could reduce the purchase price substantially (66% in Denmark).
- Guaranteed lower ownership cost to ease the anxiety associated with adopting new technology (e.g., subsidized repair and maintenance insurance).

A specific opportunity in the US is import duty exemption for a imported hybrid trucks.

1.9 Conclusions

Hybrid propulsion technology manifests itself in a wide range of powertrain configurations using different types of energy conversion and storage components. Different configurations can be applied in different vehicle applications. Currently most R&D and market introduction efforts are aimed at hybrid-electric systems in which the prime energy converter is an internal combustion engine running on gasoline or diesel, which is optimized for application in a hybrid powertrain. Besides the well-known parallel and series hybrid concepts, an interesting newcomer is the starter-alternator or engine-assist configuration. This mild hybrid offers the possibility to introduce hybrid technology as an incremental improvement to conventional powertrains.

Almost all passenger car manufacturers and many heavy-duty vehicle manufacturers have R&D programmes to develop hybrid vehicles. A few have recently taken the step to actually market hybrid vehicles.

The energy benefits of hybrids are well established and recognized. Hybrid-electric propulsion may also bring user benefits such as improved driveability and comfort and the possibility to efficiently apply a wider range of electric auxiliaries.

A successful large-scale market introduction of hybrid vehicles requires significant cost reductions. Attaining the necessary production volumes can be stimulated by various policy measures including direct subsidies and tax incentives.