Annex VII: Hybrid Vehicles
Overview Report 2000

Chapter 1: Introduction

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

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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 Introduction

This report gives an overview of the state-of-the art of hybrid-electric propulsion technology for road vehicle applications, development trends, and of the worldwide activities concerning the development and implementation of this new technology. Various policy relevant aspects are discussed, such as the benefits of hybrid-electric vehicles for the reduction of emissions and fuel consumption, vehicle production and operation costs, and the relation with other new propulsion technologies. This Overview Report is the product of a project called Annex VII "Hybrid Vehicles", which is part of an international collaboration programme on electric and hybrid vehicles, facilitated by the International Energy Agency (IEA).

This reports concentrates mainly on the developments in hybrid electric vehicles (HEVs) using internal combustion engines. Fuel cell vehicles (FCEVs) are discussed to some extent, as their powertrains are electric and often hybrid-electric. The state-of-the-art of fuel cell vehicles, however, is not described in this report. Non-electric hybrid vehicles, such as mechanical hybrids with a flywheel, are only briefly discussed.

1.1 Why hybrids?

Five years ago battery-electric vehicles (BEVs) were "hot". Various manufacturers started small series production, and it was claimed that electric propulsion would bring us emission-free cars for daily use, as soon as improved battery technology would enable a sufficient driving range at affordable costs. But battery developments where slower than hoped for, vehicles remained expensive and consumer demands remained minimal. In 2000 the general consensus, among developers, manufacturers and policy makers, is that BEVs may only have a future in specific niche application, but will never replace the general-purpose passenger car. In the mean time developers have been able to combine benefits of electric propulsion with those of the combustion engine in what is called hybrid-electric vehicles (HEVs). Some manufacturers have started manufacturing and selling these vehicles at a volume that has never been reached by battery-electric vehicles. By virtue of their concept, hybrid-electric vehicles possess a number of specific qualities that can offer significant benefits compared to 'conventional vehicles' in areas such as environmental impacts, energy consumption and (to a lesser extent) vehicle design, performance and applicability.

1.1.1 Environment

Over the last three decades a tremendous effort has been made to reduce the environmentally harmful exhaust gas emissions of road vehicles. Governments have been setting emission limits and the industry has responded with continuous impressive improvements of engine and exhaust aftertreatment technology. Especially California has always been one of the key pioneers in setting new and strict emission limits. Having a legal status to set such limits independently of the rest of the USA, California has been the initiator for USA legislative standards such as ULEV (ultra low emission vehicles), SULEV (super ultra low emission vehicles) and ZEV (zero emission vehicles). In Europe, legislative standards on exhaust gas emissions have been set more strictly over the last decades as well, resulting in several generations of so-called Euro regulations (Euro 3 since the year 2000, Euro 4 in 2005, etcetera). For Japan, a similar trend as in the USA and Europe can be distinguished: setting emission limits for several years now, and making them stricter periodically. It is worth noting that the regulations in the USA, Europe and Japan differ from each other, due to specific, region dependent, emphasis on reducing certain emission components and different traffic conditions in these regions. Traffic conditions are e.g. reflected in the different legislative driving cycles, which are used for homologation testing of vehicle emissions in the USA, Europe and Japan.

One of the ways to meet the ever more stringent emission limits is the use of hybrid-electric vehicles. Apart from meeting the exhaust gas emission limits in a laboratory test on the standardized driving cycle, hybrid propulsion may above all offer specific environmental benefits compared to conventionally propelled vehicles in specific practical application areas. The possible emission benefits of HEVs can be summarized as follows:

- reducing the emissions of regulated components (i.e. CO, NO_x, HC, Particle Matter) and unregulated components under real-life driving conditions;
- reducing the tailpipe emissions of greenhouse gasses (CO_2, CH_4 and other) under real-life driving conditions
- the possibility of driving in pure electric, zero emission mode (e.g. in residential or inner city areas);
- reducing the noise emissions of vehicles

The extent to which these possibilities are realized generally depends on the powertrain configuration, the selected components (e.g. gasoline versus diesel engines), the sophistication of the powertrain control algorithm and the application in which a vehicle is used.

Energy use

The general technical principles of HEVs and layout of various hybrid drivetrain configurations are described in chapter 2. A general characteristic of hybrid vehicles is that the power requirement on the primary energy source (in most cases an internal combustion engine) is to a smaller or a larger extent uncoupled from the road load. In this way it can be avoided that the engine is operated in less favorable, i.e. energy inefficient and/or polluting, areas of the engine map. Because the engine is largely or completely uncoupled from the road load in some HEV-configurations it also becomes possible to use other primary power sources (also called: auxiliary power units or APUs) than combustion engines, such as gas turbines, Stirling engines or fuel cells, in combination with a wide range of alternative fuels.

Another distinctive feature of hybrids is the possibility to store energy, recovered during braking (so-called regenerative braking), for re-use during accelerations or driving in electric mode. Because in HEVs electric power is available at high voltage levels it becomes favorable to replace relatively inefficient belt-driven auxiliaries (pumps, air conditioning, etcetera) by efficient electrically driven ones.

When made use of in a cleaver way, these qualities lead to lower fuel consumption and thus a more efficient use of scarce oil supplies. For hybrids in which the battery is (partly) recharged with electricity from the grid, the use of efficiently produced electricity may also offer an environmental benefit and reduce primary energy consumption.

1.1.2 Vehicle design and application

Hybrid-electric vehicle configurations are generally more complex in design compared to vehicles with conventional drivetrains. They contain various extra components and the interaction and energy flows between components, as well as their management is more complex. On the other hand, however, in hybrids some of the components, which in a conventional necessarily have to be connected mechanically to the engine, can be replaced with electrically powered components (e.g. pumps for power braking and steering) or can be done without all together (e.g. the starter, belt driven alternator). In the extreme case of a series-hybrid (see chapter 2) the engine-generator set is electrically connected to the electric machines that drive the wheels. All this offers certain design flexibilities as powertrain components and auxiliaries can now be placed in different parts of the vehicle wherever needed or practical, without mechanical connections placing demands on the overall vehicle layout. This offers the possibility to further optimize vehicle design to the needs of specific applications. In a passenger car batteries and electric devices can for instance be placed in the trunk or under the seats. In case of a bus, the engine and power electronics may be placed on the roof. In combination with the use of in-wheel electric motors this offers the possibility to increase the low floor area.

1.1.3 Challenges

Along with the above described advantages the development and introduction of hybrid vehicles also brings along challenges and problems which have not been solved completely yet. Knowing that 'conventional' vehicles have been optimized for over one century now, it is of course not surprising that the introduction of a largely different drivetrain technology is confronted with some hurdles to be taken. Without a solution, the following problems may turn out to become disadvantages:

- *Weight:* Hybrid electric vehicles often comprise more components than their conventional opponents do and this tends to increase the weight of the vehicle. Especially the battery can give rise to a significant weight increase. In general, more weight means more energy required propelling a vehicle, reducing the potential energy benefits of hybrids (even if a part of this energy may be recovered during braking).

- *Complexity:* The already mentioned complexity of hybrid propulsion systems is partly due to the use of new technology and partly due to integration aspects concerning the energy flows and communication between the various components, governed by the powertrain control algorithm. In first instance this could have consequences for the reliability and durability, for which extremely high standards have been set by conventional combustion engine technology.

- *Price:* Containing more and relatively high-tech components, a hybrid-electric vehicle is probably more expensive to produce than conventional vehicles. Especially in the early introduction phase, where production volumes are small, the market price of hybrids will be higher. Tax incentives and other financial stimulation measures may overcome this. In the long run hybrids can only be successful if the commercial price without these financial measures comes down to a reasonable level, where in the lifetime costs a slightly higher purchase price may be cancelled by savings due to a lower fuel consumption.

Furthermore, aspects such as the necessity of battery charging infrastructure or consumer acceptance are of utmost importance when trying to introduce hybrids.

Safety is an important issue both in objective and in subjective terms. Vehicles have to meet stringent legislative safety standards. Introducing new powertrain components in the vehicle will therefore pose new demands on crash-safety design. The use of e.g. batteries, flywheels or fuel cells in combination with hydrogen as a fuel brings along intrinsic safety issues associated with the specific component technologies. Even when the objective safety demands are met, the introduction of new technology and propulsion configurations in a relatively short period of time could cause some buying reservation among consumers. Careful marketing of such vehicles is therefore of crucial importance. Pointing out the user benefits explicitly and making the potential buyers have a positive feeling about hybrids will make these vehicles more easy to sell.

In the current economic and political climate it can be stated that selling hybrid vehicles solely on the basis of improved fuel economy and their benefits for the environment will not be easy. The chances for success will be significantly bigger if the introduction of a hybrid propulsion system offers other unique selling points, such as improved driving comfort or the availability of high voltage connections for driving new accessories or to plug in household appliances.

In analyzing the chances for a successful introduction of hybrid vehicles it is important to have a clear view of the development potential of 'conventional' vehicles. ICE developments of the last decades have shown considerable improvements in fuel economy and emissions, thanks to the application of new engine concepts, enhanced motor management systems, improved fuel injection systems and enhanced catalysts. These developments are still in progress and it is to be expected that ICE developments will be able to lower the fuel consumption and emissions of conventional engines considerably with respect to the current levels. In order to be a viable solution the fuel economy and emission levels of hybrid vehicles should not only be better than those of current ICE vehicles, but should also outclass those of future ICE vehicles. Exhaust gas emission legislation will become stricter in the next five years, and if vehicle manufacturers manage to cope with such limits by only improving already existing technologies, their solutions could be cheaper and less risky than developing and introducing new hybrid technology.

The same observation, by the way, can be made with respect to other new propulsion technologies that are being developed. They have to compete with the improved conventional technology of the future and with each other. Fuel cell technology is developing rapidly. Small-series pilot production is expected for 2004. Hybrid vehicles may serve as an intermediate technology, introducing electric propulsion into the powertrain, and thus paving the way for fuel cells. Fuel cells, when introduced sufficiently rapid could even render the introduction of hybrids obsolete. The other way around a successful introduction of hybrids in the next years could postpone the necessity for fuel cell vehicles.

The year 2000 has witnessed the market introduction of two hybrid vehicles, the Toyota Prius and the Honda Insight, in the USA and Europe. Since December 1997 the Toyota Prius has been available in Japan. The worldwide sales exceeded 50,000 vehicles by the end of 2000. This number is higher than the total number of battery-electric vehicles (BEVs) ever sold worldwide. Sufficient reason therefore to set up an international collaboration to monitor the developments and to study the potential benefits and drawbacks of this new technology.

1.2 The IEA Implementing Agreement for Hybrid and Electric Vehicle Technologies and Programmes

The IEA Implementing Agreement for Hybrid and Electric Vehicle Technologies and Programmes is 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. These projects are called "Annex" as they are described in annexes to the legal document that formally establishes the cooperation between countries in the Implementing Agreement.

For more information on the International Energy Agency and the Implementing Agreement for Hybrid and Electric Vehicle Technologies and Programmes please visit the following web-sites:
http://www.iea.org
http://www.iea.org/impagr/imporg/iadesc/hev.htm
http://www.ieahev.org/

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. This report is the first publication of Annex VII. Based on the initial studies carried out in Annex VII new projects may be generated to study various aspects of hybrid vehicles in more detail.

1.3 Annex VII on hybrid vehicles

TNO, the Netherlands Organization for Applied Scientific Research, has been appointed as Operating Agent (O.A.) of Annex VII. Apart from the Netherlands also Japan (represented by JARI), the USA (represented by NREL and DoE), Sweden (represented by KFB), Finland (represented by VTT), Belgium (represented by VITO) and France (represented by INRETS) have joined the project. Experts involved in Annex VII are experienced scientists and engineers from government, research institutes and universities, working in hybrid vehicle programme management, R&D and/or demonstration and test projects.

As mentioned Annex VII started in June 1998 for a first phase of two years. Starting June 2000 the project will be continued in a second phase running until June 2002.

Work in Annex VII is organized in two subtasks:

a) Subtask VII/1 *Overview of Existing Programmes on and State-of-the-Art of Hybrid Road Vehicles in Europe, North America and Asia*
b) Subtask VII/2 *Analysis and Discussion of Important Topics in the Field of Hybrid Vehicle Technologies*

1.3.1 Subtask VII/1

Subtask VII/1 concerns the production of an overview of what is happening worldwide in the field of hybrid vehicle development. All participants have supplied information on the hybrid vehicle activities in their countries. Besides this, the Operating Agent has collected information from non-participating countries. Based on this input the various chapters of this report have been written.

In Subtask VII/1 an overview has been created of existing programmes and projects in the field of hybrid vehicles and of the state-of-the-art of this technology in terms of existing prototypes, demonstrators and more or less commercially available vehicles. Also an analysis of development trends in hybrid technology has been performed. This overview also serves as a basis for further work in Annex VII.

The Operating Agent has developed a database in which all information related to vehicles, components, projects and programmes, as supplied by the participants, is stored in a systematic way. This database is available to the project participants. The Appendix of this report contains an abstract of the information on hybrid vehicles that is available in the database, which is available for the Annex VII participants.

1.3.2 Subtask VII/2

The goal of Subtask VII/2 is to study and discuss a wide range of relevant questions in the field of hybrid vehicle development and implementation. In short, the way of working in Subtask VII/2 is the following:

- A number of relevant topics in the field of hybrid vehicles has been selected for analysis and discussion among the participants;
- For every topic one participant (or a few participants in collaboration) has prepared a Discussion Paper which serves as a basis for group discussions at Experts Meetings. A Discussion Paper contains analyses of problems and aspects related to the selected topic and incorporates items for discussion at the Experts Meeting;
- The Experts Meetings have a workshop-like character. On the basis of the Discussion Papers

topics have been discussed and conclusions drawn;
- Following the discussions at the Expert Meetings, sometimes collaborative assessment and analysis activities have been carried out by the participants in order to improve the insight in certain topics and to come up with relevant conclusions and recommendations;
- Based upon the conclusions from the above-described process concise Topic Reports have been prepared.

In the first phase of Annex VII the following Topics have been studied and discussed:
- *Definition of hybrid vehicles:* Collection and comparison of different existing definitions of hybrid propulsion systems in relation to different applications for these definitions.
- *Comparative assessment of different HEV configurations using ADVISOR:* Comparison of conventional reference vehicles and different HEV configurations for typical vehicle classes in Japan, the USA and Europe using the ADVISOR simulation tool.
- *Alternative motor fuels and hybrid vehicles:* Analysis of the relation between fuel choice and powertrain hybridization. Assessment of the possible benefits of using alternative fuels in hybrid vehicles or vice versa of the opportunities that hybrid vehicles offer for the introduction of alternative motor fuels.
- *Test methods and procedures for hybrid vehicles:* Evaluation of present activities concerning the development of test methods and procedures in Europe, Japan and the USA, and assessment of the needs for harmonization as well as for separate test procedures for type approval purposes and technology evaluation purposes.
- *Energy consumption and emissions of hybrid vehicles:* Analysis of available information on energy consumption and emissions of hybrid vehicles, both from measurements on existing vehicles and from simulations. Creating insight and pointing out the need for reliable emission factors for scenario studies and policy evaluations.
- *Costs of hybrid vehicles:* Analysis of present and foreseen future costs of hybrid vehicles and their components.
- *Trend from charge depleting to charge sustaining hybrids:* Analysis of a perceived trend away from using electricity as an input energy carrier for hybrid vehicles.

For most of the above Topics final or intermediate reports have been produced that have been incorporated into this Overview Report (see “This report” on page 2).

Some Topics to be studied in phase II are:
- *Benchmarking HEVs coming to the market worldwide:* collection and analysis of test results on hybrid-electric vehicles
- *Emissions of hybrids:* Analysis of the concrete emission benefits of hybrid-electric vehicles
- *Analysis of the role of hybrid propulsion in achieving 80 mpg:* Increased powertrain efficiency compared to the contributions of other energy saving technologies in the vehicle.
- *Assessment of the energy consumption of hybrid trucks using ADVISOR:* Analysis of possible fuel economy improvements resulting from using different HEV configurations in typical classes of trucks.
- *Assessment of the energy consumption of buses using ADVISOR:* Analysis of possible fuel economy improvements resulting from using different HEV configurations in typical bus applications.
- *Market introduction scenarios for HEVs:* Descriptions of the various ways in which large-scale introduction of HEVs can be envisaged.
- *Hybrid versus non-hybrid configurations for fuel cell electric vehicles:* Analysis of role of hybrid powertrain configurations in fuel cell vehicles.
- *HEVs and regulations:* Assessment of how present and foreseen regulations (e.g. concerning emissions) influence the development and market introduction of hybrid vehicles.

1.3.3 The goals of Annex VII

The primary goal of the above described work process is:

- To provide policy relevant information on hybrid vehicle technology to the governments of the participating countries. Communication with these governments takes place through the national representatives that have been delegated by the participating countries as members of the Executive Committee. This Executive Committee manages the Implementing Agreement. In first instance Annex VII directly reports to these Executive Committee members. When approved the deliverables of Annex VII are distributed more widely within the participating countries, and – when appropriate – also to relevant stakeholders in non-participating countries.

In general, work in projects of the IEA Implementing Agreements also serves the following additional goals:

- To provide a platform for exchange of information and opinions between researchers and other stakeholders from different countries and different regions of the world. Experience within the various projects of the Implementing Agreement has shown that the potential of a technology may be viewed upon quite differently in different countries as a result of different political, industrial, social, energy-economic and fiscal circumstances in these countries. A discussion on objective technical information is of limited relevance if these non-technical aspects are not recognized. The mutual understanding created in projects of the Implementing Agreement may help to facilitate a more globally harmonized strategy towards achieving sustainable energy production and use in the future.
- To promote the creation of international networks of researchers and policy makers. International collaboration inside and outside the context of the Implementing Agreement will strongly benefit both the development and the market introduction of environmentally friendly and economically attractive energy technologies.