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Annex VII: Hybrid Vehicles
Overview Report 2000

Chapter 2: Hybrid drivetrain configurations

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

2 Hybrid drivetrain configurations

2.1 Introduction

When is a vehicle a hybrid vehicle? Defining what a hybrid vehicle is can lead to endless debates. We all have a practical notion of what a hybrid is, but for some applications such a notion does not suffice. Before a vehicle can be sold in large volumes it needs to undergo type-approval testing to see whether it complies with legislative emission and safety standards. Standardized test procedures need to take account of the specific characteristics of hybrid vehicles, and therefore require a self-consistent definition of the distinction between conventional and hybrid vehicles. Policy makers intending to establish fiscal stimulation measures or subsidies for hybrids also need to specify precisely which vehicles they wish to consider as hybrids, in order to avoid that tax-payers' money is wasted on vehicles that do not contribute to the policy goals that are set out. The buyer or owner of a conventional vehicle with a large starter motor, able to electrically propel the vehicle at low speed over a limited distance, should obviously not receive such financial benefits.

In this report the following, somewhat unappealing, definition is used:

A hybrid vehicle has a powertrain in which propulsion energy can be transmitted to the wheels by at least two different energy conversion devices (e.g. ICE, gas turbine, Stirling engine, electric motor, hydraulic motor, fuel cell) drawing energy from at least two different energy storage devices (e.g. fuel tank, battery, flywheel, supercapacitor, pressure tank etc.). At least one of the paths along which energy can flow from an energy storage device to the wheels is reversible, while at least one path is irreversible. In a hybrid-electric vehicle the reversible energy storage device supplies electric energy.

This definition appears in different wording in different documents such as the hybrid vehicle test procedures developed by CEN.

This definition may leave a "grey area" between mild (engine assist) hybrids and pure starter-alternator vehicles, in which the electric machine is not delivering traction power. Whether such vehicles should be considered hybrids in e.g. the definition of fiscal stimulation measures for hybrid vehicles may be a matter of debate, and can be dealt with by including quantitative criteria concerning electric machine power (possibly in relation to thermal engine power) in the definition.

Most hybrid vehicles developed to date are what can be called thermal hybrid-electric vehicles, in which the irreversible energy storage device is a fuel tank from which energy is supplied to a combustion engine delivering mechanical energy. The reversible electric energy storage device in those vehicles generally is a battery, an electromechanical flywheel or a supercapacitor. In theory a multitude of other hybrid vehicle types can be imagined, but in practice only a few other types have actually been developed. The most important examples are mechanical hybrids and hybrid-electric fuel cell vehicles.

Worldwide, hybrid propulsion systems are being developed for a wide range of transport applications ranging from two-wheelers, to small and large passenger cars, vans, trucks and buses. Different applications pose highly different demands on the performance of the hybrid propulsion system, which leads to the development of a wide variety of hybrid drivetrain configurations. Figure 2.1 schematically shows some examples of hybrid configurations in comparison to conventional, battery-electric and fuel-cell electric propulsion systems. In section 2.2 to 2.6 different hybrid powertrain configurations are described. Concrete examples of these configurations are described in chapter 3.

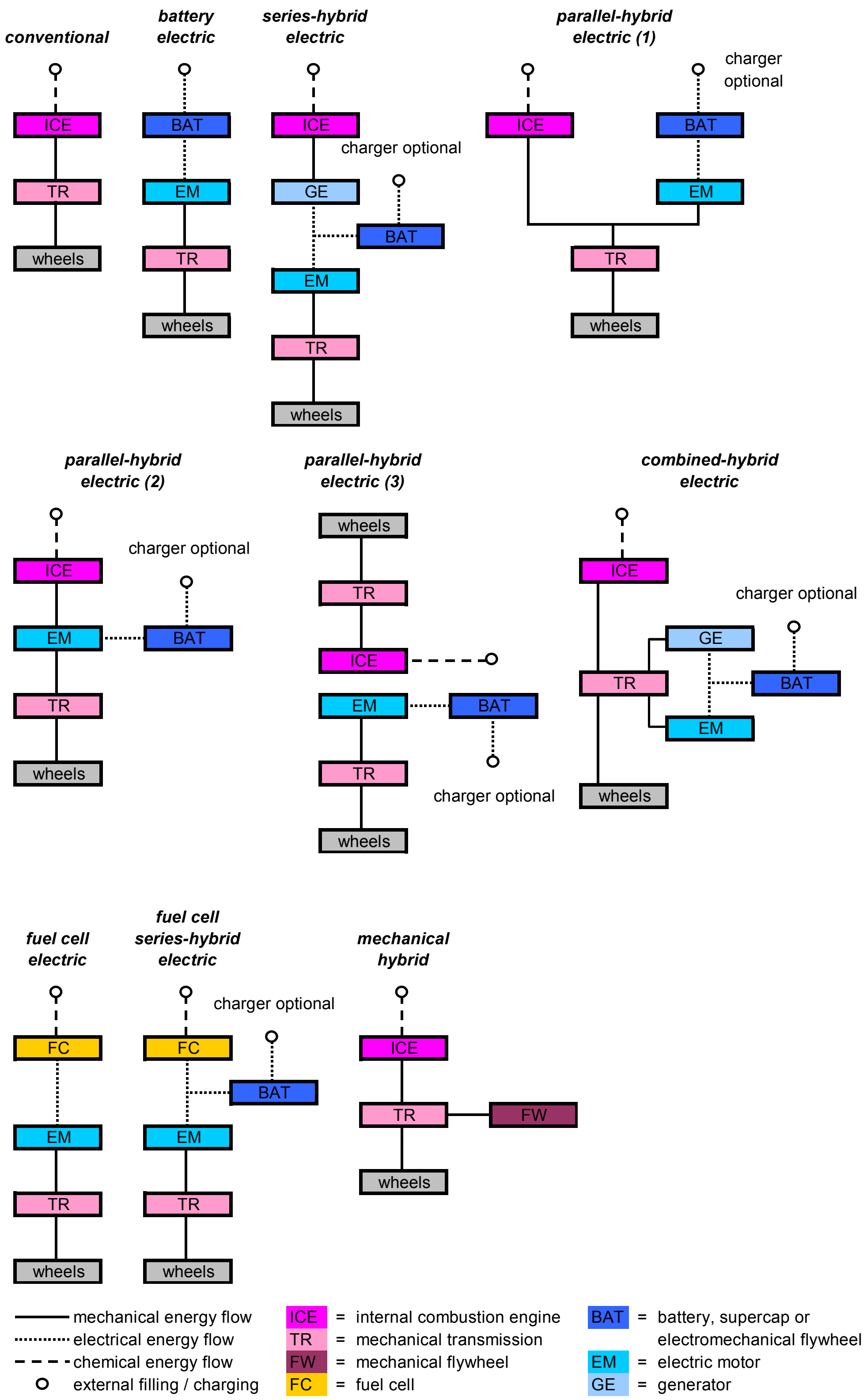
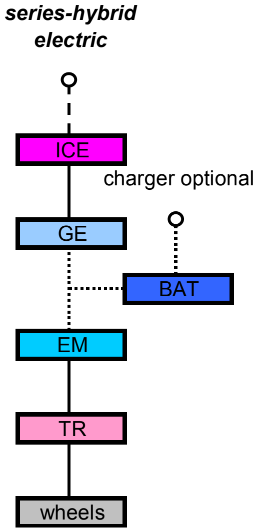


Figure 2.1 Schematic representation of various electric and hybrid propulsion system configurations

2.2 Series hybrid-electric vehicles



In a series-hybrid electric vehicle the electric motor that drives the wheels derives its electricity from either a battery or an engine-generator set, or from both simultaneously. The engine-generator set generally supplies the average demanded power, while an energy storage device (mostly a battery but also supercapacitors or electromechanical flywheels are applied) supplies peak power. Under low load conditions and during (regenerative) braking the battery is recharged. In general series-hybrids are charge sustaining and do not require charging from the grid. This is not true for so-called range extender vehicles, which are basically battery-electric vehicles with a small on-board thermal energy source to increase driving range.

The engine of a series hybrid is to a large extent uncoupled from the road load and runs either in a fixed operating point or a restricted range of operating points. The engine can be an internal combustion engine or another engine that is not well suited for directly driving the wheels. The engine-generator set as a whole can also be a fuel cell. In terms of emissions and efficiency the engine can be optimized without compromising demands for driveability. Series-hybrid vehicles on gasoline, LPG or natural gas can have extremely low emissions. Series hybrids with a diesel engine on the other hand can be more fuel efficient and offer the advantage that exhaust aftertreatment systems such as deNOx can be kept simple as a result of the more or less stationary load.

The required ratio between installed average power from the generator set and peak power from the battery is determined by the characteristics of the application, in particular the driving pattern. This is at the same time the advantage and the disadvantage of a series-hybrid. On the one hand the system can be optimized to yield minimum fuel consumption and emissions for a given application, while on the other hand designing a series-hybrid for e.g. an all-purpose passenger car tends to require overpowered systems with sub-optimal efficiency in average driving. In general it can be stated that series-hybrid drives are best suited for vehicles of which the mission is well known, such as urban distribution trucks or urban buses. For those vehicles series-hybrid drives also offer design flexibility. All components are connected electrically, and therefore the designer has a large amount of freedom to place the various powertrain components at suitable positions in the vehicle. In a series-hybrid bus e.g. mounting the engine on the roof and driving the wheels with in-wheel electric motors provides the opportunity to increase the low-floor area all the way to the back of the bus.

Electric transmissions

Without a battery or other electric storage device the series hybrid-electric configuration is reduced to a so-called electric transmission. These are widely used in applications such as trains and buses. The most common configuration is the diesel-electric drive in which a full size diesel engine drives a generator, which in turn provides electric power to the electric motor(s) that drive(s) the wheels. Recently some bus manufacturers have developed diesel-electric buses to gain experience with electric drives. In future developments a battery will be added, turning the vehicles into series HEVs.

2.3 Parallel hybrid-electric vehicles

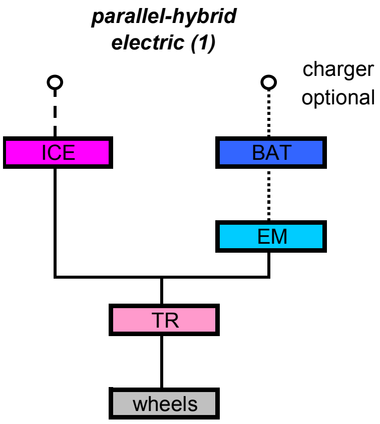
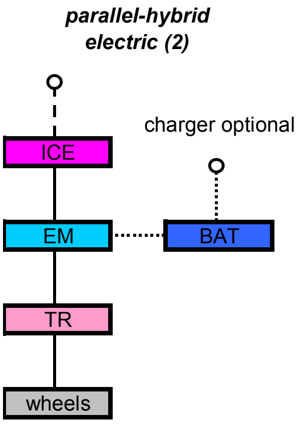
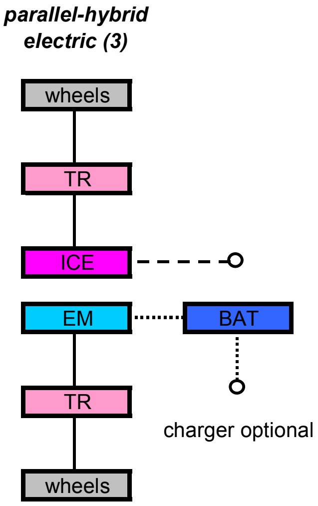


Figure 2.1 shows three different parallel hybrid configurations. Configuration (1) is the classical parallel hybrid containing a conventional and a battery-electric drivetrain which are coupled at the level of the transmission or at the wheels. Such vehicles are generally able to run either in an ICE-mode, a hybrid mode or in a pure-electric mode with the engine switched off. The required electric energy is largely obtained by charging from the grid. During ICE-driving the electric drivetrain provides the option for regenerative braking. During hybrid driving, the IC engine can also charge the battery. The electric mode is generally used for city driving. This avoids cold start emissions taking place in urban areas and avoids the use of the ICE in unfavorable areas of its engine map. In rural and highway driving the ICE runs nearer to its optimal point yielding acceptable fuel consumption and emissions.

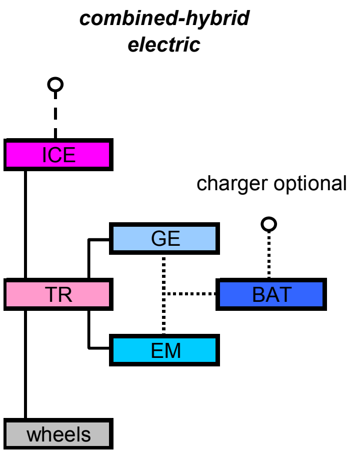
Configuration (2) is another type of parallel hybrid, sometimes called “mild hybrid” or “engine assist”. In this case, a small electric machine is mounted on the location of the flywheel of the ICE. It drives the vehicle at low speeds in zero-emission mode, operates as a starter for the ICE, provides extra torque to the ICE at low rpm’s and supplies additional peak power whenever needed. During braking and during ICE-driving the electric machine acts as a generator and charges the battery. This parallel-hybrid can be charge sustaining so that it does not require external charging. This system helps to reduce fuel consumption and emissions and also offers improved driveability and engine response. As the number of drivetrain components is reduced and the size of the electric components (electric machine and battery) is limited, this system also offers cost advantages. It has to be mentioned however, that this configuration does not enable full electric mode. Examples of this system are the ISAD (Integrated Starter Alternator Damper) as demonstrated in the Citroën Xsara Dynalto and the IMA (Integrated Motor Assist) as applied in the Honda Insight. A more elaborate description of this type of hybrids and the mentioned vehicles can be found in section 3.2.4.





Configuration (3) is one that has been used in some of the earlier hybrid prototypes. It actually consists of two separate powertrains of which one drives the front wheels and one the rear wheels. In a more recent prototype, the GM Precept, this configuration is used again in a slightly different form, with a mild hybrid powertrain driving the rear wheels and a separate electric motor driving the front wheels This configuration allows the designers to optimize regenerative braking as well as driving characteristics.

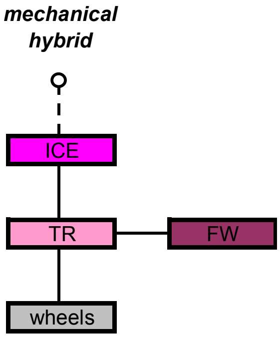
2.4 Combined hybrid-electric vehicles



It is ironical in a way that the first series-produced and commercially available hybrid vehicle, the Toyota Prius, has the most complex drivetrain configuration of the options displayed in Figure 2.1. The Prius is a so-called combined-hybrid electric vehicle. Its drivetrain partially operates as a series hybrid and partially as a parallel hybrid. This requires two electric machines, a relatively complex transmission and an intelligent control system. Through a high level of system integration, however, Toyota has been able to maximize the advantages of this configuration in a cost-effective way. For a more detailed description of the Toyota Prius the reader is referred to section 3.2.5.

2.5 Mechanical hybrids

Besides hybrids that combine mechanical and electrical components also completely mechanical hybrids are being developed. Figure 2.1 shows the example of a mechanical hybrid in which a mechanical flywheel connected to the transmission supplies peak power when required and takes up power during driving and regenerative braking. The transmission generally is of the CVT-type. In this configuration the ICE is again (partially) uncoupled from the road load leading to increased efficiency and reduced emissions.



2.6 Other hybrids: human powered vehicles

Finally, a hybrid-like configuration is presented, which contains certain aspects of the aforementioned hybrids, but deserves being treated in a separate category: the electric-assist human powered vehicle. In general such vehicles are small and lightweight in construction, being either bicycles or covered bicycle- or tricycle-like vehicles. The driver supplies a large part of the propulsion energy for these vehicles. A small electric machine, powered by a battery, augments the driver’s muscle power. A torque and velocity sensor measures the human effort in terms of supplied pedal torque and the vehicle’s speed, and a control system determines the amount of electric torque that is added to increase the power output to the wheel(s).

The human-electric hybrid therefore formally falls into the category of parallel hybrids, and is moreover charge depleting. The battery has to be charged externally. In this application it would not make sense to charge the battery with energy supplied by the driver.

The electric motor can be small (for instance in the range of 0.1 - 1 kW) and is therefore relatively cheap. Although this form of transport is rather low-tech in comparison to e.g. hybrid passenger cars, it can be considered as having a big market potential. Examples are discussed in chapter 10.