Operation of hybrid vehicles

Operation of a hybrid electric vehicle is essentially determined by the operating strategy. Depending on the higher optimization objective (reduced emissions, fuel economy), the operating strategy establishes at every moment the distribution of the requested drive torque to the internal-combustion engine and the electric motor so that the engine operates at the most favorable operating points possible. The operating strategy also controls the generation of electrical energy for charging the traction battery.

Hybrid control

The efficiency which can be achieved with the relevant hybrid drive is dependent not only on the hybrid topology but also crucially on the higher-level hybrid control. Fig. 20 uses the example of a vehicle with a parallel hybrid drive to show the networking of the individual components and control systems in the drivetrain. The higher-level hybrid control coordinates the entire system, the subsystems of which have their own control functions. These control functions are battery management, engine management, management of the electric drive, transmission management and management of the braking system. In addition to pure control of the subsystems, the hybrid control also includes an operating strategy which optimizes the way in which the drivetrain is operated. The operating strategy brings influence to bear on the consumption- and emission-reducing functions of the HEV, i.e., on start-stop operation of the engine, regenerative braking and operating-point optimization. These include the decisions on a driving state such as electric driving or recuperation and distribution of the driver-command torque to the engine and electric motor.

An important integral part of operating-point optimization is the electric-driving function. It is possible through boosting the electric drive to achieve a higher torque and thus a better acceleration capability particularly at low engine speeds. This requires a holistic consideration of design and operating-strategy optimization to exploit the maximum potential.

20 Networking of control systems in the drivetrain

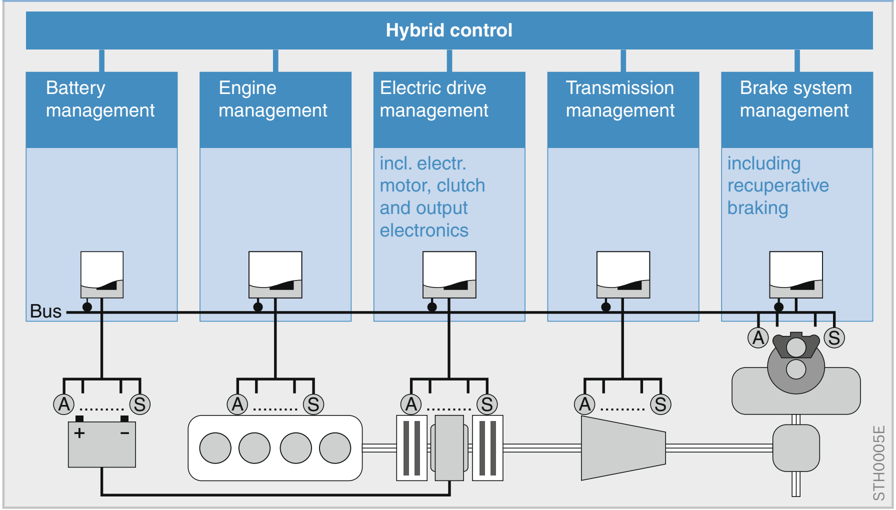


Fig. 20
A Actuator
S Sensor

K. Reif (Ed.), *Fundamentals of Automotive and Engine Technology*,
DOI 10.1007/978-3-658-03972-1_21, © Springer Fachmedien Wiesbaden 2014

Operating strategy here means a driving-situation-dependent distribution of torque between the two drive sources of engine and electric motor.

Operating strategies for hybrid vehicles

Further steps for reducing CO_2 are currently required for all internal-combustion engine concepts. Furthermore, vehicles with diesel engines show a reduction potential with regard to untreated NO_X emissions. Improvements can be achieved here by moving the engine operating points into the ranges of lower emissions.

Operating strategy for reducing NO_X

Vehicles with lean-running internal-combustion engines already achieve relatively low consumption values in part-load operation. At low part load, however, the friction loss increases such that the specific fuel consumption is also high. In addition, low combustion temperatures and a local oxygen deficiency in the low part-load range result in high carbon-monoxide and hydrocarbon emissions.

Already a relatively weak electric assembly can replace the internal-combustion engine in the low load range. If the required electrical energy can be recovered through regeneration, this simple strategy can deliver a huge benefit with regard to fuel consumption and emissions.

It is to be expected that in future lower emission limits will be increased for nitrogen oxides. By avoiding unfavorable engine operating points, hybridization of a diesel vehicle offers the possibility of significantly influencing exhaust-gas emissions. With low engine emissions the measures for exhaust-gas treatment could be partially reduced.

Fig. 21a shows the ranges in which the internal-combustion engine is primarily operated in the New European Driving Cycle (NEDC). The passenger-car diesel engine is operated both at low part load (i.e., with poor efficiency levels and high HC and CO emissions) and at medium/higher load (i.e., in the range of high NO_X emissions).

21 Shifting of the operating range with strategy for reducing NO_X

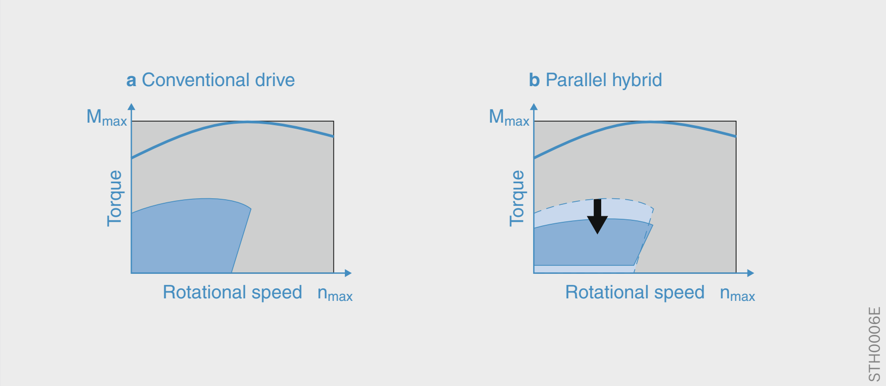


Fig. 21
a Range of operating points in the driving cycle
b Boost: joint operation of engine and electric motor

Fig. 21b shows by way of example the range of operating points for a parallel hybrid which bypasses low internal-combustion engine loads through purely electric driving and/or load-point increase. This on the one hand reduces the fuel consumption, but on the other hand reduces the CO, HC and NO_X emissions – which are high in this range. To achieve a further lowering of NO_X emissions, it is possible to lower load points in the medium load range by simultaneously operating electric motor and engine (boosting).

Operating strategy for reducing CO_2

With vehicles with stoichiometrically running gasoline engines extremely low emission values can be realized on account of the three-way catalytic converter used. In the hybrid vehicle extremely low emissions are also possible with large-capacity internal-combustion engines by means of appropriate warm-up strategies. Under circumstances the demands place on the exhaust-gas treatment system can even be reduced. The objectives for both gasoline hybrid vehicles and diesel hybrid vehicles are thus fuel economy and increased power.

Fig. 22 shows for the different HEV topologies a possible optimization of the operating range of the internal-combustion engine with regard to minimum CO_2 emissions (i.e., reduced consumption).

In the New European Driving Cycle (NEDC) internal-combustion engines in conventional vehicles are operated at low part load and thus at suboptimum efficiency. In vehicles with parallel hybrid drives low engine loads can be avoided by means of purely electric driving (Fig. 22b).

Since the required electrical energy as a rule cannot be recovered exclusively through recuperation, the electric motor is then operated as a generator. This results, when compared with a conventional vehicle, in a shift in engine operation to higher loads and thus better levels of efficiency. In this way more electrical energy can be made available than in the previously described NO_X strategy for diesel, and as a result electric driving is possible to a greater extent. But, here too, on account of the service-life requirements of the traction battery, a compromise must be found between CO_2 emissions and the energy throughput, since a high energy throughput has a negative influence of the service life of the traction battery.

22 Shifting of the operating range with strategy for reducing CO_2

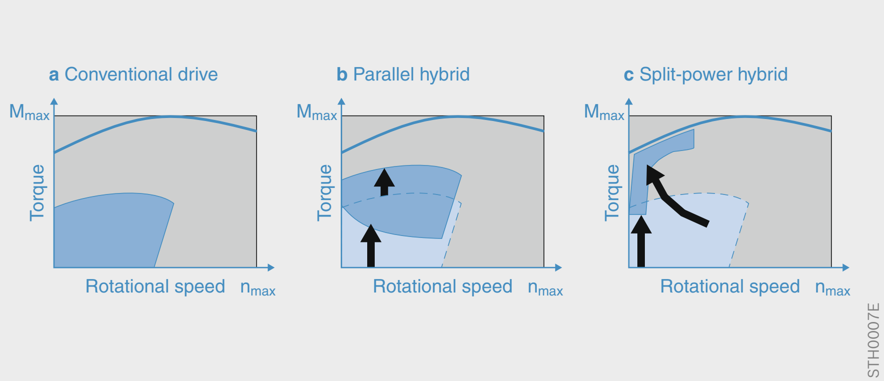


Fig. 22

a Range of operating points in the driving cycle

b Avoidance of lower engine loads through purely electric driving with subsequent charging

c eCVT effect: movement of operating points to the optimum energy range of the drivetrain

In the case of the power-branching hybrid vehicle (Fig. 22 c), the operating range of the internal-combustion engine is subject to greater limitations than the parallel hybrid vehicle. As a rule it is operated as a function of engine speed at the load at which the entire drivetrain operates under optimum energy conditions. Here, too, it is possible, because of the series operating mode, on the electrical path (simultaneous operation of the two electric motors as generators and motors) to keep energy throughput and cycling of the traction battery lower than in a parallel hybrid.

Operating-point optimization

Distribution of drive torque

Different configurations of hybrid vehicle control or operating-strategy optimization have significant effects on fuel consumption, emissions, available torque, and the layout of the components (e.g., operating range of the electric motor and of the engine, energy throughput and cyclization of the electrical accumulator), since their operating points are directly dependent on the operating strategy. It has already become clear that cross-system hybrid control is of crucial importance. There is a multitude of possibilities and degrees of freedom for optimizing operation.

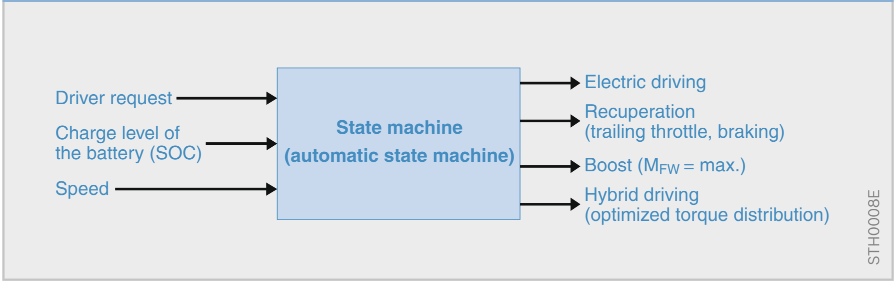
To exploit the fuel-economy potential, in particular distributing the requested drive torque to the drive source of engine and electric motor is hugely important.

Determination in the automatic state machine

Torque distribution is however not necessary in all driving states. Fig. 23 shows the different driving states of a hybrid vehicle which a determined in an automatic state machine by the driver command, the state of the electrical accumulator and the vehicle speed.

In the case of purely electric driving and recuperation the internal-combustion engine is shut down and in boost mode the maximum available torque is requested from both drive sources. Purely electric driving is limited to low vehicle speeds and low accelerations. Recuperation occurs only when the vehicle is decelerating. Boost mode is then used above all when maximum propulsion is requested by the driver (kickdown).

23 Driving states of hybrid vehicles



Distribution by operating strategy

The wide range of hybrid driving in which distribution of the drive torque is to be specified lies between the operating states which are determined by the automatic state machine. On account of the many degrees of freedom and dependencies an optimization is required which can be realized most effectively with the aid of model-based procedures.

Fig. 24 shows the dependencies of the operating strategy. The hybrid control distributes the desired drive torque to the drive sources of engine and electric motor, including in so doing among others the vehicle speed and the state of the electrical accumulator. In addition the operating strategy still requires an equivalence value of the stored electrical energy, which contains how much fuel has been consumed in order to generate this electrical energy.

The different types of electrical energy generation (recuperation and combustion-engine charging) in order to assign to the battery's energy content an equivalence value of the optimization variable (e.g., fuel consumption). This equivalence value provides the basis for deciding which energy is used.

Determining the equivalence value

Determining and optimizing this equivalence value can be done in different ways. The optimum can only be found when the entire driving cycle is known, which amounts to a look into the future (a priori knowledge). However, this look into the future is only possible during specified driving cycles or during simulation. In real driving operation only present and past driving states can be used to determine the equivalence value (a posteriori knowledge). The different optimization horizon for the equivalence value is shown in Fig. 25.

The diagram shows by way of example the speed characteristic of the NEDC driving cycle. Time t = 625 s is taken as the present. Without knowing the full distance, the last long braking from 120 km/h to a stop, which contains a large recuperation potential, cannot be used to optimize the equivalence value.

24 Operating strategy

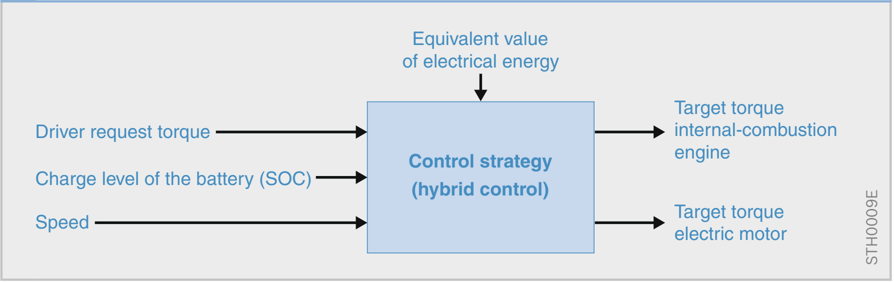
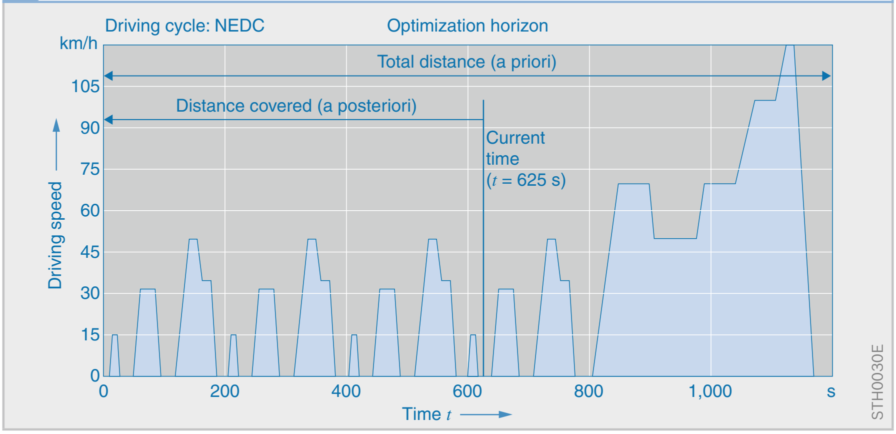


Fig. 26 uses the cumulative fuel consumption to show the different optimization horizons. The consumption of a comparable conventional vehicle is also shown. It can be recognized that an a priori optimization exploits additional potential, since it can among other things utilize the recuperation phase at the end of the cycle.

If the operating-strategy optimization is networked with driver-assistance systems, e.g., with a navigation system, the future driving profile (especially the speed profile) can be estimated down to a certain level.

25 Horizon of different equivalence values



26 Cumulative fuel consumption with different operating strategies

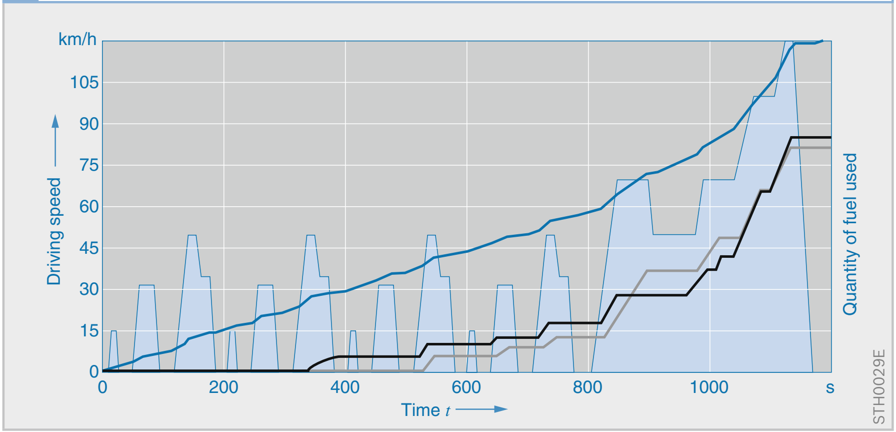


Fig. 26
— Conventional vehicle
— HEV: a priori strategy
— HEV: a posteriori strategy

Strategy of electrical energy generation

In the hybrid vehicle electrical energy can be generated by means of battery charging with the engine and by means of recuperation (recovery of braking energy). Whereas energy is recovered without additional fuel expenditure during recuperation, fuel must be expended to charge the battery with the engine. Here the efficiency of this charging process is dependent on the engine's current operating point.

Because for the most part not enough energy can be generated from recuperation alone and furthermore the storage capability of the battery is limited, charging with the engine cannot be avoided. To keep the amount of fuel to be expended for this purpose as low as possible, this type of power generation is performed then if possible when the engine is operated in operating ranges with poor efficiency and as large an efficiency increase as possible can be achieved by means of the additional load (Fig. 27). Optimum utilization of efficiency improvement when charging with the engine is the function of the operating strategy in that this also involves a distribution of torque between the engine and the electric motor.

27 Shifting of the operating point

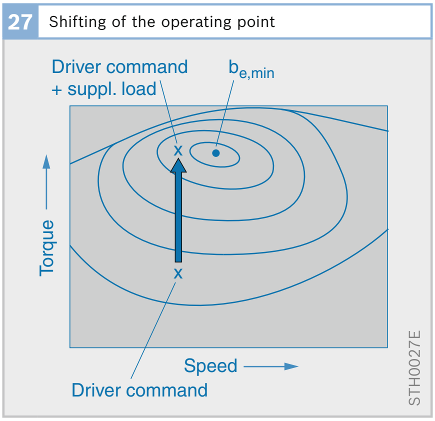


Fig. 27
$b_{e,min}$: minimum effective fuel consumption

Design of the internal-combustion engine

Use of suitable internal-combustion engines

It is basically possible to use any internal-combustion engine from vehicles with conventional drivetrains in a hybrid vehicle. Gasoline, natural-gas and diesel engines can be combined with an electric drive, but with different optimization objectives (see sections *Operating strategy for diesel hybrid vehicles / for gasoline hybrid vehicles*).

Thanks to the additional possibilities provided by the HEV interconnection for example with regard to operating-point shifting, it is also possible if necessary to pursue for hybrid vehicles internal-combustion engine concepts which are different from those for conventionally driven vehicles. Because of the reduced size of the operating range, the necessary efficiency optimization can be limited to this range and high costs for additional components can be avoided. For example, the second turbocharger in modern twin turbocharging concepts can be dispensed with, since its functions (providing for a fast response and for a higher torque at low engine speeds) are covered by the electric motor.

If sufficient power is made available by the electrical accumulator, the electric drive can compensate for torque deficits and a slower response by certain engine concepts.

Dynamic demands placed on the drivetrain are implemented by the combination of an electric drive and an internal-combustion engine. The engine can be relieved of load during dynamic processes thanks to the favorable torque characteristic above all at low engine speeds and the fast response of the electric drive. Load peaks on the engine can therefore be avoided.

Atkinson cycle

The previously described altered requirements with regard to maximum power and dynamic response make it possible to use the Atkinson cycle, which cannot be used with a conventional drive because of the lower specific power (due to poor full-load charge) and weakness in dynamic processes. The Atkinson cycle (Fig. 28) necessitates a different stroke/bore ratio of compression and expansion strokes, which geometrically can only be realized with difficulty, but can be represented with the aid of variable valve timing. It offers a better utilization of the expansion phase and thereby increased efficiency.

This concept is implemented, for example, in the Toyota Prius. In addition, the maximum rotational speed is limited here in order to reduce the basic friction of the overall engine through a weaker design of the valve gear. The required maximum rotational speed of the generator can be kept small here.

Downsizing

In addition to using simple or cost-effective internal-combustion engines, specific optimization of the internal-combustion engine in combination with an electric drive delivers advantages. One possibility for improvement is offered by downsizing, which anticipates reducing engine displacement while retaining the power output with the aid of turbocharging. Here,

28 Atkinson cycle

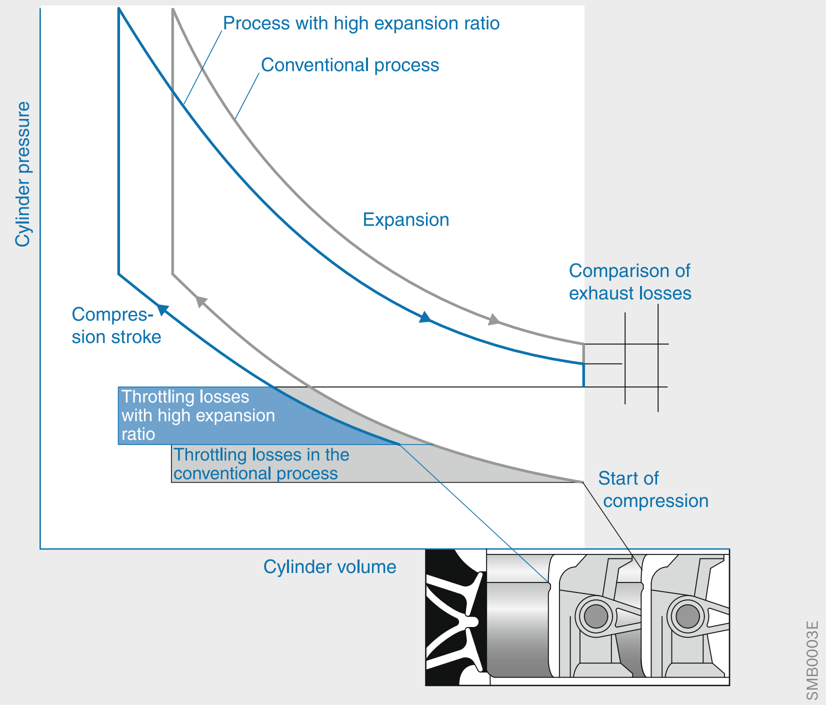


Fig. 28
Source: Toyota

through the use of the electric motor's drive power, unfavorable operating ranges can be avoided and dynamic torque weaknesses compensated for.

In the case of the hybrid vehicle, however, it is also possible with downsizing to tolerate a reduction in engine power, since this can be compensated for with the aid of the electric drive. The overall drive power remains the same here. However, in this case, the maximum power is only available for a limited time (necessitated by the battery charge), which gives rise to a reduced sustained vehicle top speed.

Optimization with regard to emissions and fuel consumption

To achieve the objectives of reduced emissions and consumption, it is possible to exploit degrees of freedom for engine operation which are dependent on the topology of the drivetrain.

An important strategy is to avoid operating points at which the engine demonstrates unfavorable efficiency or high emissions. The underlying operating strategy must be optimized with regard to the improvement objective (e.g., reduced consumption or reduced CO_2 or NO_X). The changed operating conditions can be utilized to optimize the engine concept and exhaust-gas treatment. From the changed requirements there follow changes in functions and in the application of engine management, which are not considered further here.

Friction optimization of the internal-combustion engine

Some primary energy is saved in a hybrid vehicle through the recovery of braking energy (recuperation). This can be performed during both active braking and overrunning, e.g., when driving downhill. To exploit the savings potential as fully as possible, the internal-combustion engine must be shut down in these operating ranges. If this is not possible, the engine must be under coupled motion and its drag friction limits the recuperation potential. In this case, friction optimization of the engine represents an important requirement of the engine.