Diesel Hybrid – The Next Generation of Hybrid Powertrains by Mercedes-Benz

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The next generation of hybrid system by Mercedes-Benz combines a parallel hybrid with a 4-cylinder diesel engine. The newly developed hybrid transmission is based on the 7G-TRONIC PLUS transmission and the vast experience of former hybrid projects within the company.

Most applications of hybrid powertrains are focused on gasoline engines. These hybrid systems achieve a huge reduction in fuel consumption. However the conventional powertrains are also undergoing tremendous efforts to increase fuel efficiency. As a consequence thereof a diesel parallel hybrid system was developed. The combination of the 7G-TRONIC Hybrid and the 4-cylinder diesel engine OM651 a powertrain with highest fuel efficiency, flexibility and modularity has been achieved.

The presentation outlines the specific characteristics of the new hybrid powertrain. Furthermore the functionality is described and the achieved fuel reductions are presented. Finally an insight into the system modularity is rounded up by an outlook on the manifold applications of the system.
1 Introduction

Mercedes-Benz has successfully launched two gasoline hybrid models with its S400 Hybrid and ML450 Hybrid. The first mass-produced hybrid offered by a European manufacturer, the S400 Hybrid climbed to the top of its segment.

Today's marketplace already offers highly efficient diesel engines and gasoline hybrid drives, including in the premium luxury segment. With the introduction of the diesel hybrid system in the E300 BlueTEC HYBRID, Mercedes-Benz achieves a further milestone in advancing automotive design.

The powertrain of the diesel hybrid system is based on the familiar OM651 4-cylinder diesel engine and the 7G-TRONIC PLUS automatic transmission, which was completely redesigned for the hybrid application. The objective of the hybrid development program was to realize an extremely efficient powertrain that consumes very little fuel and does not restrict the installation space of the overall vehicle. Devising a neutral package that can be installed without making substantial changes to the overall vehicle was also the greatest challenge in developing the electric motor, power electronics, and high-voltage battery.

2 System Overview of the P2-20 OM651 Hybrid Powertrain and HV Components

The hybrid system of the diesel hybrid in the E-Class comes from the parallel hybrid module, which serves as the starting point for additional model series and engines coupled with electric motors of graduated output. This P2 arrangement represents the natural further development of the P1 system currently used in the S400h and is characterized by an additional clutch that is integrated between the combustion engine and electric motor. This clutch decouples the engine during pure electric travel while allowing the vehicle to start off using the combustion engine with the performance of a wet start-up clutch. The hybrid transmission is based on the 7-speed automatic transmission, whereby the clutch replaces the torque converter and requires no additional installation space thanks to full integration in the torque converter housing. Figure 1 shows the system configuration of the hybrid drive.

The P2 concept enables the following hybrid functions as a result of the component arrangement:

- Engine start/stop
- Regeneration
- Boosting
- Pure electric travel
The combustion engine is switched off whenever the vehicle is at a standstill as long as this does not interfere with any energy or convenience-related requirements. The vehicle starts off using electricity only. Should the driver request a particularly high amount of drive torque, however, the combustion engine is also used by starting the engine via a 12-volt starter, synchronizing it, and connecting it to the drive system. During periods of heavy acceleration, the electric motor assists the combustion engine and in particular when the vehicle accelerates at low speeds. Braking occurs by way of the electric motor, which harnesses the kinetic energy of the vehicle as the engine is decoupled. The permanently excited synchronous motor is rated to 20 kW and 250 Nm for the above functions. The stator and rotor of the internal-rotor machine are cooled by the transmission fluid.

The electric motor is connected to water-cooled power electronics (Figure 2) that can supply 350 A for brief periods and detects the position of the motor via a rotor position sensor as well as various other component temperatures. Depending on the operating situation, the motor can be controlled within its design limits with respect to speed and torque. For optimum cable length, the power electronics are housed at the lower right of the engine, in the direct vicinity of the motor. A DC/DC converter was also integrated in the power electronics to keep cabling, packaging, and cooling outlay to a minimum. The converter supports the 12-volt on-board power supply with up to 3 kW and can be used to recharge the traction battery via a 12-volt charger.

Figure 1: Mercedes-Benz hybrid system in P2 arrangement
A lithium-ion battery based on the one from the S 400 HYBRID is used to store electrical energy. With 35 cells, it is rated for a nominal voltage of 126 V, a capacity of 0.8 kWh, and a maximum output of 19 kW. Its ultra-compact design allows the HV battery to be installed in the engine compartment and is possible thanks to efficient battery cooling with the aid of the vehicle refrigeration circuit.

To harness the maximum amount of braking energy possible, the vehicle is equipped with a regenerative braking system that translates the braking requirement communicated by the driver into hydraulic and electrical braking while taking all relevant safety aspects into account.

To compensate for times when the combustion engine is not running, the hybrid system also has a high-voltage refrigerant compressor and an electrical power steering system, vacuum pump, and auxiliary transmission oil pump on the 12-V side.
3 The New P2 Hybrid Transmission from Mercedes-Benz

As mentioned, Mercedes-Benz has already launched two hybrid transmissions. The first-generation parallel hybrid transmission has since enjoyed great success in the S 400 Hybrid, and a split-power hybrid transmission was developed in the USA development center for integration in the ML 450 Hybrid.

By leveraging the knowledge gained from these mass-production hybrid applications, the second-generation hybrid transmission was developed based on the 7-G Tronic plus successfully launched in 2010.

3.1 Design

The second-generation hybrid transmission is compact by design and is only slightly longer than the 7G-TRONIC PLUS. It is therefore possible to fit this transmission into the conventional Mercedes-Benz center tunnel (Figure 3). The modular and compact design of the transmission also allows this hybrid powertrain to be used in all model series with rear-wheel-drive or all-wheel-drive.

The new hybrid transmission is based on the familiar seven-speed automatic transmission that is used for inline applications. Unlike the 7G-TRONIC PLUS already available, the hybrid transmission does not have a torque converter. Instead, a wet start-up clutch integrated in the rotor of the electric motor couples the combustion engine, in parallel with the motor, to the 7G-TRONIC PLUS main
transmission (Figure 4). This is necessary to decouple the combustion engine from the rest of the powertrain and minimize drag loss during pure electric travel and regeneration. Two torsion dampers are switched between the engine and hybrid transmission and between the start-up clutch and main transmission for optimum comfort. The elasticity of the dampers counteracts load peaks and effectively dampens engine-induced vibrations to prevent transferal to the rest of the powertrain. This, in turn, eliminates unpleasant resonance and noise, even when driving at low speeds. Both dampers likewise allow the powertrain to be optimally adapted to the respective vehicle via the springs and damping rates.

Figure 4: Traction head of the second-generation hybrid transmission with electric motor, wet start-up clutch, torsion damper, and rotor position sensor

Table 1 lists key technical data of the hybrid transmission.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_{\text{max.}} \text{, transmission input}</td>
<td>600 Nm (first gear), 760 Nm (second to seventh gear)</td>
</tr>
<tr>
<td>Max. T (start, el. motor)</td>
<td>250 Nm</td>
</tr>
<tr>
<td>Max. power, el. motor</td>
<td>20 kW</td>
</tr>
<tr>
<td>Ratio ( \varphi )</td>
<td>6.0</td>
</tr>
<tr>
<td>Starting device</td>
<td>Wet start-up clutch</td>
</tr>
</tbody>
</table>
Control | Shifting plate with integrated shift-by-wire and fully integrated transmission control
---|---
Park by wire | PbW module integrated in EHS
Integr. auxiliary oil pump | For e-travel and stop/start

*Table 1: Technical data of the hybrid transmission*

The second-generation hybrid transmission features two important components that are not found in the 7G-TRONIC PLUS main transmission. The park pawl is embedded as a park-by-wire module in the control plate of the transmission to avoid an outward-facing mechanical connection and further improve the vehicle’s anti-theft properties.

The integrated auxiliary oil pump was also fully integrated in the main transmission so that no interference contours are encountered on the exterior. This greatly contributes to favorable packaging of the transmission in the vehicle tunnel. Figure 5 provides an exploded view of the transmission to illustrate the most important changes with respect to the conventional automatic transmission.

*Figure 5: Exploded view of hybrid transmission*
3.2 Hybrid Functions of Transmission

A Mercedes-Benz vehicle with the new second-generation hybrid transmission is now also capable of traveling on electricity only. The new diesel hybrid can therefore quietly and immediately start off after stopping at traffic lights without having to use the combustion engine. During e-travel, the start-up clutch is opened and the deactivated engine decoupled from the powertrain.

When considerable power is required, the combustion engine is started and coupled via the hydraulic start-up clutch to provide better propulsion. Since the engine has a separate electric starter, it does not need to be tow-started by the kinetic energy of the vehicle. Full electrical power can then be used at all times.

As soon as the vehicle starts traveling at a constant speed, the combustion engine can be switched off, at which point the start-up clutch is opened and the engine is decoupled from the powertrain. This allows the deceleration torque to be freely set via the regeneration energy used. Figure 6 illustrates the functions of the second-generation hybrid transmission.

Figure 6: Hybrid transmission functions with power delivery via the traction head
4 The Diesel Hybrid Engine

The OM651.924 hybrid engine is based on the conventional OM651 engine, which incorporates a second-generation common rail direct injection (CDI) system, two Lanchester balancer shafts, fuel injectors with piezo technology, two exhaust-gas turbochargers connected in series with self-regulating compressor bypass, an exhaust-gas recirculation facility with precooling system integrated in the cooling circuit and an exhaust-gas recirculation cooler with switchable bypass channel and advanced thermal management with actively regulated coolant pump and oil-injection nozzles.

![Figure 7: Hybridized OM651 combustion engine](image)

The high-voltage components of the OM651 hybrid engine are particularly noteworthy in relation to the conventional drive. The compact hybrid system was realized by integrating the high-voltage power electronics with DC/DC torque converter where the alternator is otherwise installed. Vibration is dampened by stop-shock elements that reliably connect the high-voltage power electronics to the combustion engine. Cooling via the primary cooling circuit and heat shields safeguard operation even under high load and thermal conditions.

The electric refrigerant compressor, which is used to cool the interior and battery, could also be connected directly to the engine. An electric vacuum pump ensures that the required brake pressure is provided in all driving situations. Electrifying the
refrigerant compressor and brake vacuum pump made it possible to simplify the belt drive and, thus, reduce loss torque.

Arrangement of the high-voltage components directly next to the combustion engine facilitated very compact and weight-optimized HV wiring in the engine compartment.

5 Function Topology and System Partitioning

The components of the P2 hybrid system and the output and information flows are depicted in the following graphic, whereby the hybrid state control and high-voltage energy management functions form the central hybrid control unit. Both functions are integrated as part of engine management, which controls all powertrain components and coordinates output flows. Individual components locally control the respective actuators automatically.

Engine management encompasses conventional control measures such as those pertaining to fuel quantity, air path, ignition, exhaust gas recirculation, and exhaust aftertreatment as well as thermal management, monitoring, diagnostic functions, and torque coordination of the entire powertrain in addition to hybrid state control and HV energy management.
Transmission control encompasses the familiar aspects of gear change sequence control, the gearshift program, thermal management, and the recently developed hybrid coordinator and actuation of the integrated start-off and separating element.

On-board power electronics convert the electrical energy from the direct-current voltage source into 3-phase alternating current and back, set the operating point of the electric motor, control heat build-up, and even assume subfunctions for actively dampening the powertrain.

The HV battery control unit (BMS) calculates the state of charge (SOC) of the HV battery, controls individual cell voltages, and monitors the current and voltage limits of the battery. The BMS also assumes important tasks for HV system monitoring and diagnostics for interlock generation and monitoring of insulation resistance.

Integration of the fully regenerative braking system means that the brake control system realizes the deceleration torque required by balancing electrical energy recovery with application of the conventional wheel brakes.

The transition between the different operating states of

- pure electric travel,
- driving with the combustion engine (with/without elect. boost),
- and vehicle deceleration (with/without regeneration)

is initiated and coordinated by engine management based on driver input.

6 Consumption Development

Reducing consumption was of prime importance in developing the diesel hybrid system. Success was achieved in the form of 109 grams of CO\textsubscript{2}, a level that establishes a new benchmark in the premium luxury segment and considerably undershoots the entire playing field of conventional diesel powertrains and all other hybrid drive systems that use a gasoline engine.

Overall consumption is based on the conventional E250 CDI, which emits 129 grams of CO\textsubscript{2}, an already good figure that was reduced by an additional 16 percent. This, in turn, shows that the potential to be tapped with intelligent hybridization is significant, even in conjunction with very efficient diesel engines and despite the added weight of the hybrid components, improved system performance, and better agility made possible by the boost characteristics of the electric motor.
Comparing the sedans offered in the premium luxury segment highlights the relative significance of the savings possible with the hybrid variant (see Figure 10) in relation to the base engine of identical displacement, whereby consistent integration of consumption-reducing measures has the potential to lower the CO$_2$ emissions of diesel hybrid drives to an extent that is consistent with gasoline hybrids. Some hybrid drives from other manufacturers, however, consume almost as much as their conventional equivalents and only increase system output. This is worth mentioning because the competition offers electric motors that are rated to much higher outputs and the savings potential for hybrid drives with a gasoline engine is frequently communicated as being greater.
6.1 Consumption-Optimized Driving Strategy

The focus of the new operating strategy was on optimizing consumption in all driving situations. Levers for achieving this include:

1. Maximizing the potential of regenerative braking
2. Deciding whether to drive using the combustion engine or the electric motor only
3. Recharging and discharging the HV battery via load-point displacement of the combustion engine

Unlike hybrid vehicles that use a gasoline engine, the diesel engine is highly efficient in the partial-load range as well, which means that the potential gains in efficiency through load-point displacement are considerably lower with respect to the overall efficiency of all components.

A consumption-optimized e-travel strategy must therefore always be implemented in line with:

- The source of the electrical energy, i.e. via regenerative braking or recharging by way of the combustion engine
- The load point set for the combustion engine
6.1.1 Regeneration

The best way of reducing consumption for hybrid drives is to maximize energy recovery when the vehicle is coasting or being braked. As soon as the brake pedal is pressed down, deceleration torque is applied by the electric motor instead of the friction brake. The combustion engine is also switched off during periods of coasting and its drag torque is then used for regenerative purposes by the electric motor. When the brake pedal is not pressed down, however, no further deceleration torque is applied to recharge the battery and the vehicle "sails". Additional charging against the driver's wishes would merely lead to increased battery cycling and reduce overall efficiency due to converter losses in the powertrain.

The energy balance of the HV battery as tested under NEDC conditions is graphed in Figure 11 to evaluate the influence of regenerative braking. As you can see, the regenerative share of all energy provided (300 Wh) is 6:1 with respect to the recharging energy provided by the engine. Around one-third of the driving resistance energy associated with NEDC testing (approx. 1 kWh) can thus be realized by regeneration.

The decisive criterion for maximizing regenerative energy is consistent deactivation of the combustion engine at all times when the vehicle coasts so that friction loss can be replaced by charging torque of the electric motor. If one compares the energy recovered to a driving strategy in which the engine is not deactivated (similar to a P1 system), this energy, in conjunction with the current strategy, can be increased by 43 percent (from 210 to 300 Wh) under NEDC conditions.

![Figure 11: Comparison of regenerative energy, under NEDC conditions, with the engine on/off during coasting](image)
To safeguard maximum consumption potential, including in customer driving cycles, special emphasis was placed on consistently deactivating the engine at speeds of up to 160 km/h. Additional, key levers for optimizing regenerative energy were a braking system that allows for all regenerative braking down to low travel speeds and maximum battery recharging performance via fast and intelligent active control that observes battery limitations. Additional potential could be tapped via coordinated application of the gearshift program to simultaneously reduce drag loss in the transmission as well as motor and inverter loss.

6.1.2 E-Travel Strategy

The objective of a consumption-optimized e-travel strategy is to use electricity as much as possible, especially in driving situations in which the combustion engine is inefficient. The most favorable time for using electricity is during standstill periods, when “silent starting” occurs and the vehicle accelerates from a stop using electric power in the exhaust test, for example, unlike with gasoline hybrid vehicles.

The operating strategy also dictates whether the combustion engine is switched on or off with regard to current performance requirements, the source of the energy used (regeneration or charging), ambient parameters, ancillary consumer power requirements, the driving style and agility of the driver, and the preceding events of the driving cycle.

![Figure 12: Driving profiles in NEDC, propulsion via el. motor and combustion engine with charging status of HV battery](image)
Figure 12 shows a corresponding driving strategy for the NEDC. Note that the combustion engine is used to improve efficiency during acceleration or extended periods of travel at higher speeds while the vehicle is propelled using electricity at low or constant speeds during city driving. In total, the engine is switched off 63.5 percent of the time.

Figure 13 shows the energy balance of the HV battery in the NEDC. The objective of the e-travel strategy was to use the energy provided through charging as efficiently as possible and to minimize loss at this time. This was achieved by optimizing gear shifts to minimize converter loss for the electric motor as well as friction in the transmission and consumption of the electric components of the engine (glow plugs, pumps) and transmission (operating pressure level control). The concept of using electric power to provide propulsion under low engine loads in particular can also be recognized in relation to the energy consumed when traveling at constant speeds and during acceleration. With the exception of the low-speed range, it is more efficient to use electrical energy for travel at constant speeds. This principle is also applied very prevalently in all driving situations.

6.1.3 Load-Point Displacement

Figure 14 plots the NEDC load points of the combustion engine in the fuel consumption map, whereby blue represents the loads for the conventional powertrain
and red for the diesel hybrid. Even during e-travel under low-load conditions, a significant share of the load points characterized by particularly poor efficiency is reduced. With load-point displacement, these points can be moved for more favorable consumption. The flat efficiency curve of the diesel engine, however, means that this measure is only beneficial in conjunction with the e-travel strategy for particularly low loads. Such shifts are very dependent on the driving cycle. In the NEDC, this share is particularly low.

![Figure 14: Comparison of load points, E300BTH (red) and E250CDI (blue)](image)

### 6.2 Evaluation of Consumption Measures

If one compares the consumption results of a strategy based on regeneration and stop/starts, only 55 percent of reducible consumption can be realized. When the increased regenerative capacity available during coasting is also regarded in this manner, however, 82 percent of consumption can be reduced via regeneration and 18 percent via optimized load-point displacement for the combustion engine.
By carrying out many calculations, simulations, and test bench tests, it was possible to develop an operating strategy that allows the diesel hybrid system to return a consumption figure that is approximately 16 percent lower than that of an already efficient diesel powertrain.

Although the consumption benefits of a P2 diesel hybrid as compared to those of a P2 gasoline hybrid translate to the diesel hybrid system having lower hybrid-specific potential, combining the P2 system with the efficient OM651 diesel engine in the E-Class returns the best consumption figure in this segment, with only 4.2 liters of fuel consumed per 100 km and only 109 grams of CO$_2$ emitted per km during NEDC testing.

### Table: Consumption Delta

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Regeneration strategy</th>
<th>Consumption</th>
<th>Delta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>0</td>
<td>129 g</td>
<td></td>
</tr>
<tr>
<td>Vehicle measures</td>
<td>130.5 g</td>
<td>+1 %</td>
<td></td>
</tr>
<tr>
<td>Start/stop only</td>
<td>210 Wh</td>
<td>118 g</td>
<td>-9.5 %</td>
</tr>
<tr>
<td>Incl. e-travel</td>
<td>300 Wh</td>
<td>109</td>
<td>-8 %</td>
</tr>
</tbody>
</table>

#### 7 Vehicle Integration, E300 BlueTEC HYBRID

The P2 system proved to be the best system for the E-Class taking the systems available in the Mercedes-Benz hybrid portfolio and bodyshell and production/vehicle integration requirements into account.

The high-voltage battery, electric vacuum pump, high-voltage refrigerant compressor, electrical power steering system, and fuse box were fully integrated in the engine compartment. A requirement for this was to connect the specially designed power electronics, with DC/DC converter, directly to the engine for use in the P2 hybrid. A decoupling element designed specifically for this application prevents diesel engine vibrations from being transferred to the power electronics. It is this measure that enables the space-saving arrangement in the engine compartment. The transmission with electric motor is installed in such a way that they fit in the vehicle without having to make any changes to the bodyshell structure.

To this end, standardized installation space was identified in the E300 BTH for the relevant hybrid motors and components, including the transmission, HV battery, power electronics with DC/DC torque converter, and electric refrigerant compressor. The power electronics are connected to the hybrid systems via an adapter plate, since this facilitates further adaptation with other E-Class powerplants, such as the 6-cylinder gasoline engine.
The compact design of the hybrid system becomes very evident when considering the packaging of the E 300 BlueTEC HYBRID.

The electrified ancillary components ensure safe operation and the desired level of comfort when the engine is switched off and the vehicle is driven using electric power only. The intelligent packaging also does not restrict interior space for the customer, and the overall concept provides for scalability and compatibility with other vehicles and engines, such as the E-Class station wagon. A regenerative braking system also forms part of the component modular system and is capable of recovering the maximum amount of braking energy possible in conjunction with the electric motor. This does not come at the expense of braking performance, however, which remains unchanged.

Increasing the extent by which electricity is used in the powertrain also heightens requirements for cell and battery technology. The battery used in the S400 Hybrid was systematically advanced for the E300 BlueTEC HYBRID.

In addition, a great deal of attention was paid to ensuring safety. Challenges to overcome in this regard include complying with all global and internal requirements as they pertain to crash tests as well as providing the highest possible level of safety for all electrical components.
This encompasses production, active use (e.g. by the customer or workshop employee during maintenance service), and intervention by emergency personnel who are required to rescue people inside a vehicle that has crashed. Overall, the vehicle and hybrid system meet the highest safety requirements.

8 Summary & Outlook

The new diesel hybrid system from Mercedes-Benz raises the bar when it comes to consumption in the premium luxury segment. The system impresses with its efficiency and modularity and enables hybridized driving at the premium level with excellent consumption and no restrictions in vehicle configuration.

The question of whether it should be a diesel or hybrid powertrain in the premium luxury segment is now best answered with a drive concept that combines both technologies.

The second-generation Mercedes-Benz hybrid system can be easily adapted to other engines (e.g. the 6-cylinder gasoline engine in the E400 Hybrid) by varying the turbine torsion damper, and application in other vehicles is very conceivable due to the compact design. Finally, the degree of hybridization can be altered to realize consumption-oriented full hybrids through to performance-optimized plug-in hybrids by varying the length of the electric motor and reconfiguring the power electronics and battery cells while maintaining the system architecture.

The authors would now like to take this opportunity to thank everyone involved for their successful collaboration in the project. Special thanks also go to those colleagues who played a key role in writing this document.

9 Bibliography


