The Innovative High-Performance Plug-In Hybrid Drivetrain in the New Porsche 918 Spyder

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1 Introduction

With the 918 Spyder, Porsche introduces the world's first Super Sports Car designed as a plug-in hybrid. It represents the next stage in the company's quest to achieve even lower vehicle fuel consumption while at the same time further improving driving dynamics and performance.

The parallel hybrid concept incorporates all of the full-hybrid functionalities familiar from the Cayenne S Hybrid. Like the Panamera S E-Hybrid, the 918 Spyder also features an external charging option and can cover over 30 km using only electric power. This makes it possible to cover short distances with zero emissions and without fuel consumption.

This talk introduces the drivetrain of the new Porsche 918 Spyder. It will include detailed descriptions of the key drive components, most of which have been newly developed. The talk will also cover the complex drive management system which controls the interaction of the drivetrain components. It incorporates five different driving modes which make it possible for the 918 Spyder to achieve optimum performance, whether on the race track or in urban traffic.

2 Requirements for a plug-in Super Sports Car

The conceptual design of this next-generation Super Sports Car needed to take account not only of the requirements to be met by Sports Cars, but also the general requirements that will need to be met by future vehicle concepts.

New vehicle concepts must continue to help reduce fuel consumption and emissions. Further improvements to vehicle efficiency and hence to drivetrain efficiency are required to achieve this goal, and an electric drive combined with a battery which has sufficient energy content and power is an ideal starting point. An emotional design, enhanced driving pleasure and superior driving performance are additional requirements which must be met by Porsche vehicles in the premium segment, and which must continue to be met in a plug-in hybrid Super Sports Car, not only by means of the conventional drive, but also by the electric drive components.

The target values for the 918 Spyder shown in Fig. 1 are based on the demand for top-level efficiency on the one hand and maximum vehicle performance on the other.

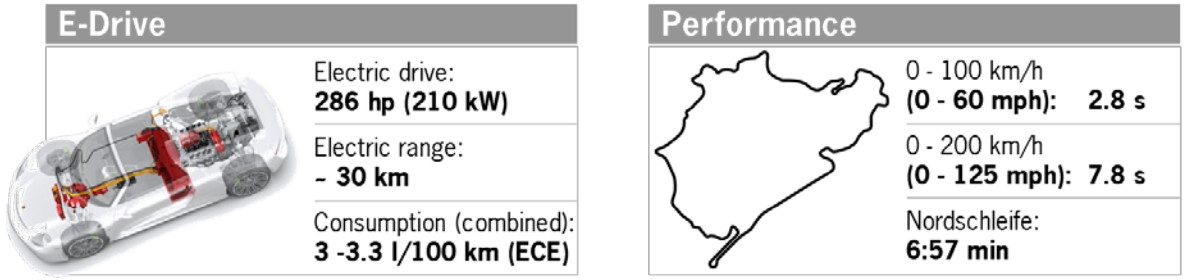


Fig. 1: Target values for the 918 Spyder

3 The drivetrain concept

Fig. 2 provides an overview of the drivetrain and drivetrain components of the 918 Spyder.

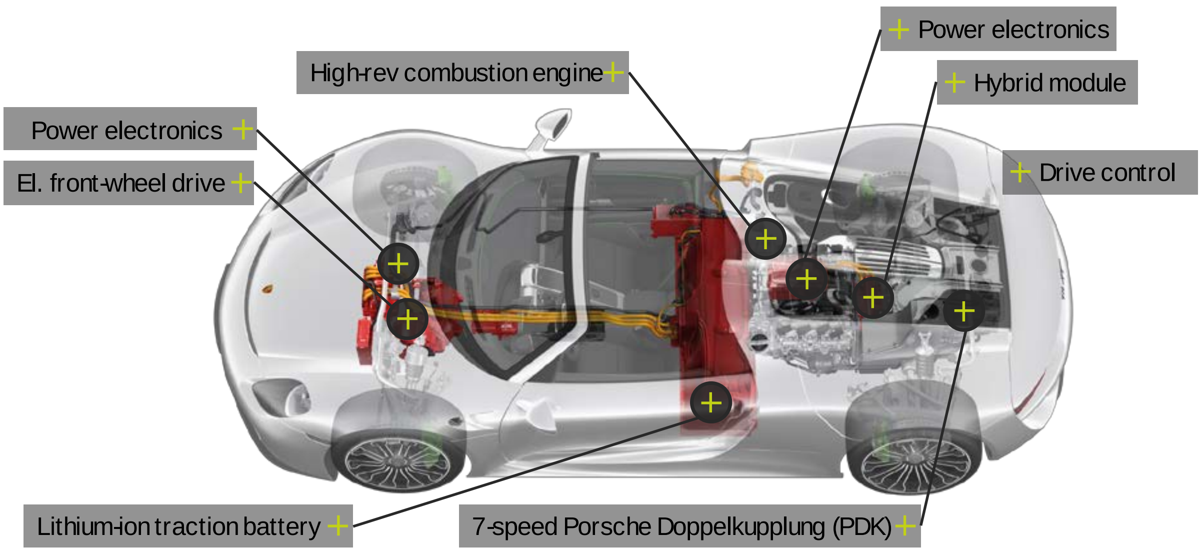


Fig. 2: Overview of the drivetrain of the Porsche 918 Spyder

The rear axle is driven by an eight-cylinder engine in combination with a hybrid module. Power transmission takes place via a 7-speed Porsche Doppelkupplung (PDK). The decoupler in the hybrid module allows the combustion engine to be disengaged when driving under electric power. The combustion engine can also be restarted via the decoupler. This means that the hybrid module, comprising an electric motor on the rear axle and a decoupler, acts as the link between the transmission and the combustion engine.

The electric drive system is also supplemented by an electric motor on the front axle, meaning that the 918 Spyder features electric all-wheel drive. This combination of two electric motors in the drivetrain also provides even greater scope for control of the various operating states via a central drive management system.

The consistent conceptualisation of the 918 Spyder as a plug-in hybrid Super Sports Car with high electric output also entailed the optimum integration of a powerful traction battery with a sufficiently high energy content. This traction battery was then positioned close to the vehicle's centre of gravity. The other drive components were designed to be as compact and low down in the vehicle as possible in order to achieve a compact Super Sports Car with a low centre of gravity (cf. Fig. 3).

Fig. 3: Side view of the Porsche 918 Spyder

The additional weight associated with the plug-in hybrid components had to be compensated by lightweight construction. Firstly, this included the lightweight construction of components such as the carbon monocoque construction of the chassis, and the functional integration of various components in order to achieve further weight reductions. The complete integration of the clean-air shell into the unit carrier is a good example of this.

3.1 The electric drive system

The electric drive system comprises two electric motors and the relevant power electronics. The electric motor on the front axle is designed as an electric final drive. The drive module is shown in Fig. 4.

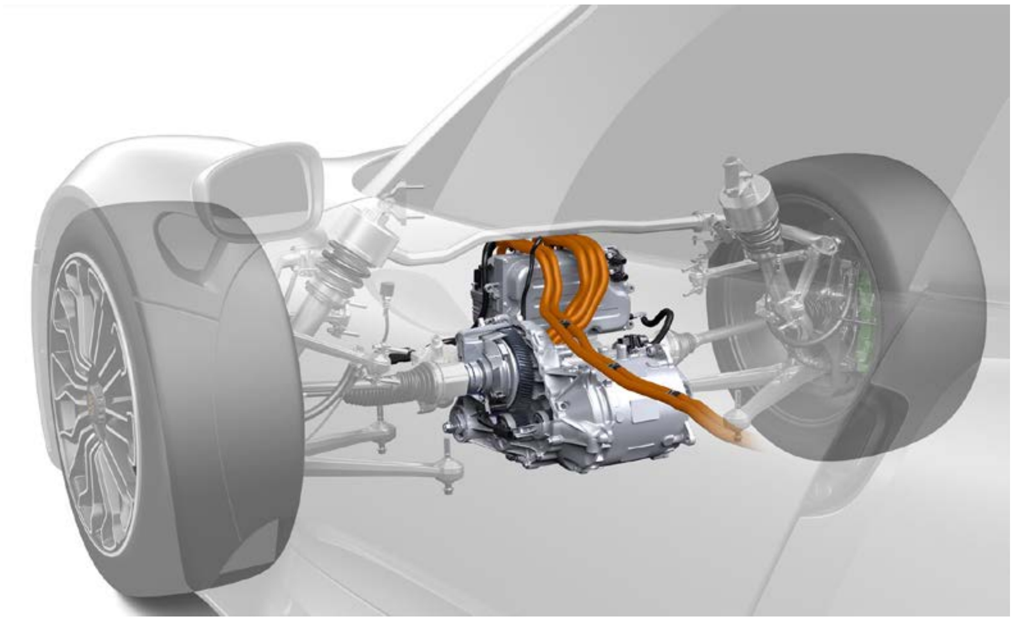


Fig. 4: Electric drive on the front axle of the 918 Spyder

The electric motor is connected to the front axle via a 3-shaft transmission with an overall ratio of 7.5. This gear ratio and the maximum electric motor torque of 210 Nm mean that high dynamic torques can be achieved on the front axle at typical urban traffic speeds. The maximum permitted electric motor speed of 14,000 rpm means that the motor is disengaged at a speed of 235 km/h, via a claw coupling which is integrated into the drive module on the front axle. The installation position of this module was also selected with a view to achieving the lowest possible centre of gravity.

Consistent lightweight construction meant that an overall module weight of 48 kg could be achieved, including the water jacket and the unit mount. This powerful module is therefore a further key feature of drive electrification. It has a maximum power output of 95 kW at a rated voltage of 390 V, and a maximum torque of 210 Nm at a current of 420 A.

The high-performance hybrid module operates on the rear axle between the combustion engine and the transmission. Fig. 5 shows a design view of this module. A consistent focus on maximum power and efficiency made it possible to achieve peak power of 115 kW at a voltage of 380 V, within an axial length of 180 mm including the torsional vibration damper. The maximum torque of 375 Nm is available over an engine speed range from 0 to 2,000 rpm. In combination with the electric motor on the front axle, the driving dynamics are on a par with those of powerful purely electric vehicles.

Fig. 5: View of the high-performance hybrid module

From the design stage onwards, priority was given to ensuring that the full electric output of the system was available as frequently and for as long as possible. In order to avoid any restrictions on performance caused by overheating of the electric drives at full load, attention was also paid to achieving a high level of efficiency and good heat dissipation when developing the electric drives. Since the electric motor in the high-performance hybrid module is subject to higher levels of thermal stress due to its location between the combustion engine and the Porsche Doppelkupplung (PDK), the water cooling of the rotor was supplemented by additional air cooling, achieved firstly by means of a fan wheel on the electric motor. In addition, the ram air at the supply air housing more than doubles the available cooling air flow at high speeds, depending on the operating point. The cooling air can then be routed directly past the main sources of rotor heat, with optimum dissipation of the heat produced. This allowed significant improvements to be made in terms of the heat transfer between the rotor and the cooling medium.

As soon as the combustion engine is activated, the maximum available power from the three drive sources can be drawn upon in boost mode. The combination of a combustion engine and an electric motor provides the vehicle with extraordinarily high flexibility and dynamics in this operating state; for example, acceleration from 80 km/h to 120 km/h is achieved in under 1.5 s.

3.2 The high-rev combustion engine

Fig. 6 shows a design view of the combustion engine used in the 918 Spyder, which is a redesign of a V8 cylinder engine with a 4.6-litre displacement and four valves per cylinder. In terms of design, the combustion engine is based largely on the concept of the V8 racing engine from the Porsche RS Spyder, adapted to the specific requirements of a plug-in hybrid.

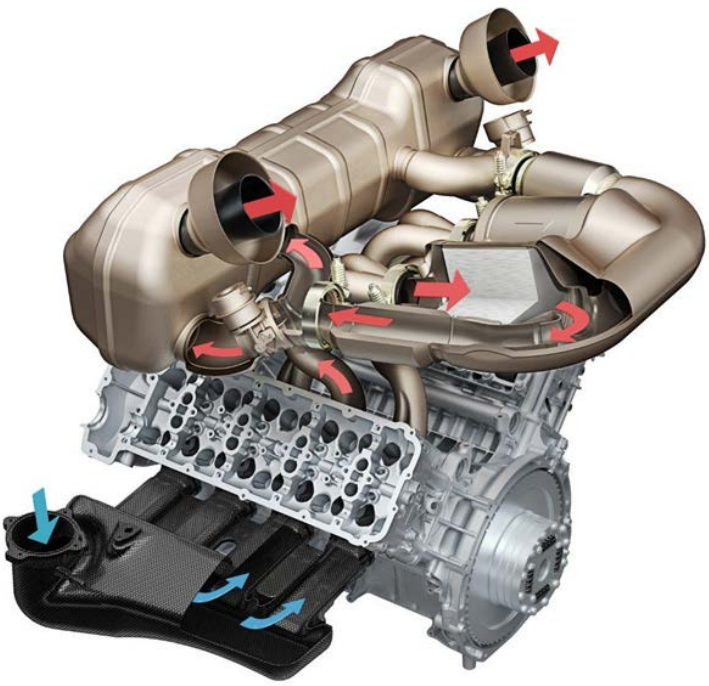


Fig. 6: Design view of the high-rev combustion engine

This includes dry-sump lubrication and direct fuel injection with a central injector location. Together with an enhanced combustion process, this central injector location allows extremely efficient combustion engine operation.

The exhaust manifolds are located in the "inner V" of the combustion engine. In combination with the exhaust system and the "top pipes" (exhaust tailpipes located directly above the combustion engine), this meant that an extremely compact exhaust system with minimal losses could be achieved. The combustion engine has a specific power of 132 hp per litre of displacement, which is the highest in the world for a naturally aspirated engine in a standard-production vehicle. The rated output of 608 hp is achieved at an engine speed of 8,700 rpm and the maximum torque of 540 Nm at 6,700 rpm.

With a gross weight of 137 kg, this compact and powerful combustion engine offers an ideal basis for the drive of the 918 Spyder.

Fig. 3 also shows that the high-voltage battery was positioned immediately in front of the combustion engine, close to the vehicle's centre of gravity. The exhaust flow in the inner-V was designed to avoid the routing of hot exhaust gases past the battery. This protects the high-voltage battery against unnecessary heating and makes it possible for the electric drive system to deliver its peak power for even longer.

3.3 The 7-speed Porsche Doppelkupplung (PDK)

Power is transmitted from the combustion engine and the electric motor on the rear axle via a 7-speed Porsche Doppelkupplung (PDK) with injection lubrication.

In order to achieve the lowest possible centre of gravity for the transmission, the Porsche Doppelkupplung (PDK) from the 911 Turbo was rotated by 180° (cf. Fig. 7.) and mounted "upside down". This lowered the position of the engine-transmission flange, resulting in a correspondingly lower centre of gravity. Rotating the transmission meant that the control hydraulics were now located above the gear wheel set, making possible a very flat lower oil pan. This then allowed the use of a diffusor sloping noticeably upwards from the rear axle.

The gear wheel set had to be adapted to a much higher maximum engine speed and a higher top speed, and so gears 5 to 7 were redesigned and the final-drive ratio redesigned.

The installation position and crash requirements necessitated a new transmission housing.

The output flanges were redesigned to use tripod joints, a technique which has become particularly popular in motor sports and which offers advantages over conventional bolted flanges in terms of weight and efficiency.

Fig. 7: View of the 7-speed Porsche Doppelkupplung (PDK)

The hydraulically regulated rear differential lock which features in the current 991 model line is integrated into the Porsche Doppelkupplung (PDK). This means that it can be activated via the PDK hydraulics, with significant advantages in terms of weight and space. This functionality had already been expanded in the GT3 in order to meet the demands of the GT vehicles, and was then adapted to meet those of the 918 Spyder. The regulated rear differential lock thus makes a key contribution to the handling and traction of the 918 Spyder.

The overhead positioning of the hydraulics places high demands on their ventilation and the effectiveness of the oil supply from the lower oil sump. This problem was solved using targeted hardware measures and redeveloped software functions to ensure consistently rapid gearshifts, particularly at high engine speeds. The Porsche Doppelkupplung (PDK) had to meet a further specific requirement resulting from the hybridisation of the 918 Spyder and the fact that it can also be driven in front-axle mode using purely electric power. Hydraulic pressure is not available to the transmission in either the stationary stop mode or while driving on the electric front axle, because the rear electric motor is not running. A combination of hardware measures and enhancements to the conventional Start-Stop functions meant that an auxiliary pump could be dispensed with, however. At the same time, the rear axle can be rapidly and easily reconnected out of the passive state as soon as required.

The 918 Spyder is the first Porsche vehicle to combine the Porsche Doppelkupplung (PDK) from the 911 Turbo with a high-speed engine. It is larger than the Porsche Doppelkupplung (PDK) used in the 911 GT3, and can transmit up to 1,000 Nm for short periods. The longer response times necessarily entailed by the larger Porsche Doppelkupplung (PDK) were compensated by software functions specially enhanced for the 918 Spyder to achieve total response and shift times of significantly less than 200 ms, or in other words on a par with the 911 GT3. Particular attention was paid to the overrun downshifts, which have to be performed as overlap gearshifts even during maximum recuperation and need to take place instantly and with no changes to wheel torque, even in the case of tip shifting.

In order to ensure the outstanding performance of the 918 Spyder during sporty driving and on the race track as well as during fuel consumption-optimised fully electric operation, optimum interaction between the Porsche Doppelkupplung (PDK) and the various drive sources was required. For this purpose, the interface between the transmission control unit and the drive management system was completely redesigned and the transmission control was expanded to encompass hybrid-specific features. These included significant enhancements to the intelligent shift programme (ISP) of the Porsche Doppelkupplung (PDK) in order to coordinate the many different operating states of the plug-in hybrid vehicle and the 5 driving modes (E-Power, hybrid, sporty, race and hot-lap) with the appropriate gearshift strategy. The priority for every driving state - whether electric or hybrid, economical or sporty, braking or accelerating - was the ability to select the optimum gear and to pre-select the appropriate shadow gear most likely to follow it.

This made it possible to integrate the Porsche Doppelkupplung (PDK) into the drivetrain of a standard-production plug-in hybrid vehicle with 2 separately driven axles and 3 independent drive sources - a world first. The ambitious goals and requirements set in respect of weight, centre of gravity, aerodynamics, fuel consumption and performance, as well as in terms of the drivability and spontaneity expected of a Super Sports Car, could also be met.

4 Drive management system

The drive management system is the central control mechanism of the Porsche 918 Spyder. The drive management system (digital engine electronics - DME) integrates control of the combustion engine, the Porsche Traction Management (PTM), the Porsche Recuperation Management (PRM) and the entire hybrid coordinator with the state control system. Features necessary to achieve these functionalities included communication with the two electric motors and the two sets of power electronics as well as with the battery management system, the transmission and the stability management (PSM and ESP). The hybrid coordinator thus determines the vehicle system state depending on the driving programme selected and driver input.

Thanks to its drive topology, the 918 Spyder can theoretically operate in any of the drive states shown in Fig. 8 . When operated purely under electric power, the vehicle can be driven by one or both axles. When the vehicle is in hybrid mode, serial operation can be selected by the hybrid coordinator in addition to all-wheel drive and rear axle only mode. A vehicle in this state is driven by the front axle while the rear electric motor serves as a generator.

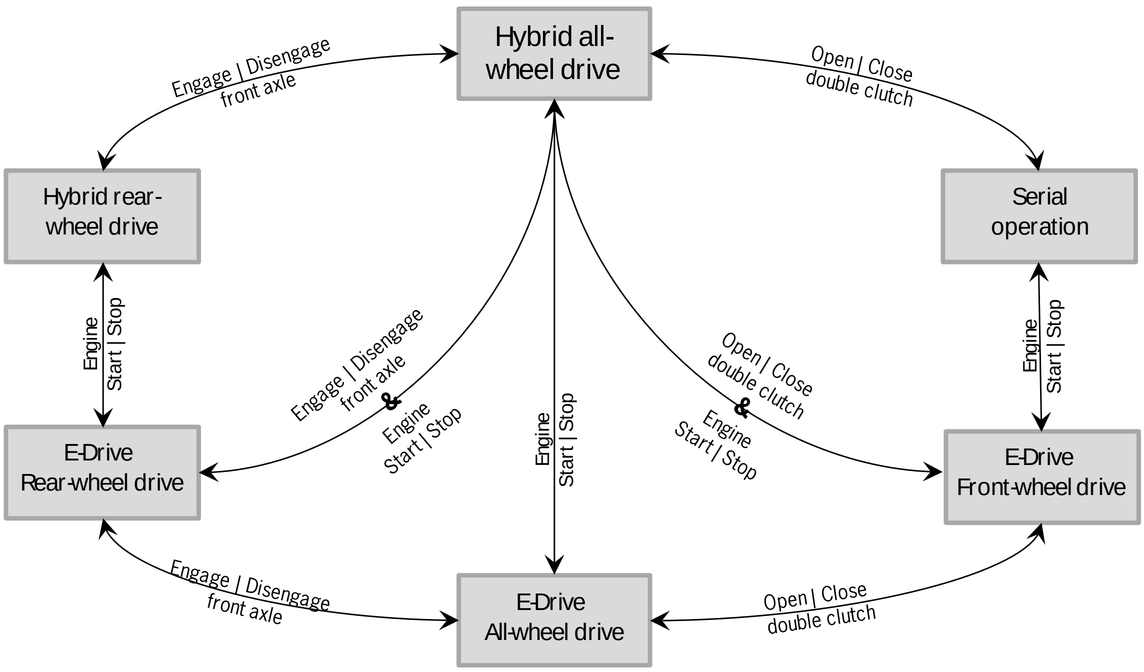
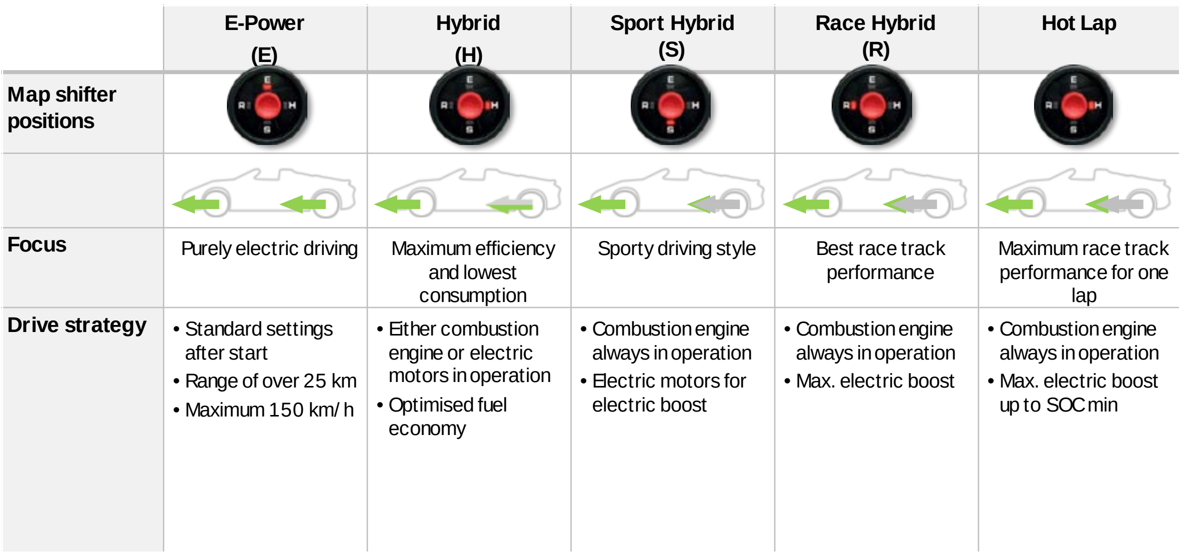


Fig. 8: Diagram of the state machine in the hybrid coordinator

The greatest challenge in this respect was coordinating the drive torques of the three drive sources in the drive states shown in Fig. 8 with the transitions between the states in order to guarantee the constant availability of the required drive power. In addition, the hybrid coordinator needs to be able to identify when a switch to a different drive state is necessary or expedient. Switching between these drive states may be necessitated due to a wide variety of conditions. One of the goals in this respect was to ensure the constant availability of sufficient electrical energy and power for the current driver request, e.g. during manoeuvres requiring all-wheel intervention. This electrical energy is then made available to the electric all-wheel control. When designing the operating modes, particular attention was therefore paid to the availability of sufficient electric power.

5 The operating modes

Fig. 9 provides an overview of the five operating modes that can be selected by the driver. The driver can switch to whichever operating mode he requires using the map switch on the steering wheel.



	E-Power (E)	Hybrid (H)	Sport Hybrid (S)	Race Hybrid (R)	Hot Lap
Map shifter positions					
Focus	Purely electric driving	Maximum efficiency and lowest consumption	Sporty driving style	Best race track performance	Maximum race track performance for one lap
Drive strategy	• Standard settings after start • Range of over 25 km • Maximum 150 km/h	• Either combustion engine or electric motors in operation • Optimised fuel economy	• Combustion engine always in operation • Electric motors for electric boost	• Combustion engine always in operation • Max. electric boost	• Combustion engine always in operation • Max. electric boost up to SOC min

Fig. 9: Overview of the operating modes

Maximum electric driving is enabled in the E-Power operating mode, which can be selected when the battery has a sufficiently high state of charge. This operating mode is selected automatically when the vehicle is started, provided the battery's state of charge (SOC) is sufficiently high.

The pressure point in the accelerator pedal is activated in the E-Power mode of the Porsche 918 Spyder. This feature is already familiar from the Porsche Panamera S E-Hybrid. The resistance of the accelerator pedal is increased from a position of approximately 55 %. Up to this pressure point, the vehicle is driven purely by electric power. When the pedal is pressed beyond this point, the combustion engine is started. This helps the driver to comfortably meter the maximum electric system power up to the pressure point. If the pedal is pressed beyond the pressure point, the full power of the combustion engine becomes available.

In electric all-wheel drive, the drive torque requested by the driver is distributed over both electric motors. This distribution is initially carried out in such a way as to achieve maximum overall system efficiency, thus maximising the electric range (cf. Fig. 10). This efficiency-optimised distribution is determined by drivability and driving dynamics requirements. Fig. 10 shows the basic distribution in per cent of the requested drive torque based on a maximised system efficiency as a function of speed and drive torque at the wheel level. A value of 100 % means that 100 % of the requested torque is distributed to the front axle, and a value of 0 % means that the vehicle is driven entirely by the rear axle.

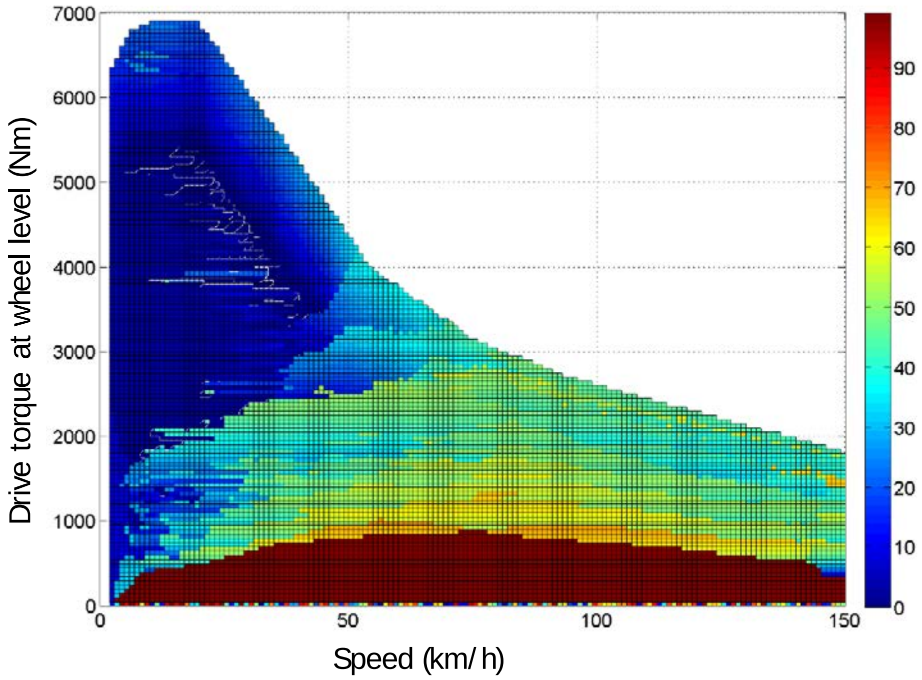


Fig. 10: Illustration of efficiency-optimised all-wheel drive

Distribution calculations incorporate the efficiency of the electric motors and power electronics as well as that of the transmission. Purely electric mode is deactivated at speeds of above 150 km/h and the combustion engine is started as well.

At low states of charge, hybrid mode is selected automatically instead of E-Power mode. Hybrid mode means that the vehicle switches between hybrid and electric operation and the pressure point is deactivated. The hybrid mode has been specially adapted to the requirements of a Sports Car, and involves a continuous attempt to switch to the state with the highest energy efficiency. Electric operation is prioritised at low speeds and hybrid operation at higher ones.

At low states of charge, however, there tends to be less electrical energy available, so a newly developed charging strategy ensures that sufficient electrical power and energy is still available for all-wheel drive. This charging strategy evaluates the energy requirements of the electric front axle and recharges via the rear electric motor while in hybrid mode. This ensures that sufficient energy is also available at low states of charge, for electric all-wheel drive.

The sport, race and hot-lap operating modes were developed to permit a sporty driving style. Sport mode was designed for general sporty driving, whereas the race and hot-lap modes are intended for use on the race track. The full system power is available in all three modes.

In race and hot-lap mode, the overall system is adjusted to a performance-oriented driving style, which means that the operating strategy must also be designed to provide maximum possible performance at all times.

The charging strategy evaluates whether recharging is necessary due to the driver's sporty driving style, thus ensuring that sufficient electrical energy is available in the traction battery in sport mode. The fact that the hybrid module was designed to include the previously mentioned cooling mechanisms also made it possible for charging intensity to be greatly increased for sport mode thanks to a load point shift.

An intelligent boost strategy regulates the electric boost in race mode in such a way that stable lap times can be achieved with an approximately balanced SOC. The driver is given extra support in the form of a specially developed boost display which indicates the available boost and the current boost status. This helps the driver to decide when to end a boost and to see how much energy is available for subsequent boosts.

In hot-lap mode, all of the energy content available is used for the electric boost and the race-mode reserves are activated. The accelerator pedal pressure point is also activated in order to provide the driver with extra boost support in race mode. If the driver presses the pedal beyond this pressure point, the electric boost is activated. This allows the driver to deliberately exploit the energy left in the battery and use it strategically during a race.

Finally, Fig. 11 shows a power chart for the total system. It shows that the 918 Spyder can achieve a maximum power of 887 hp and a peak torque of over 750 Nm.

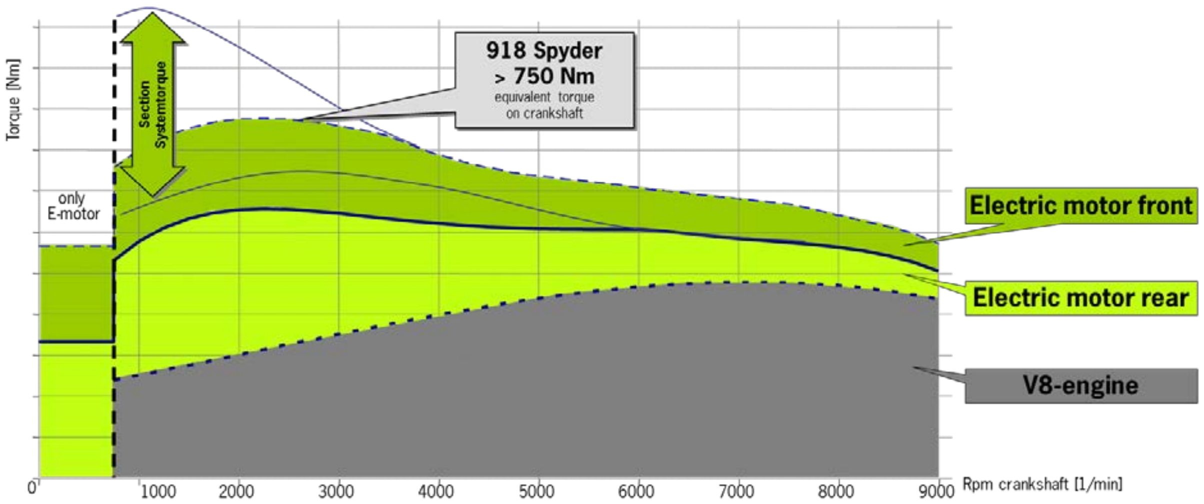


Fig. 11: Illustration of the total power of the Porsche 918 Spyder

An prototype of the 918 Spyder has already achieved a lap time of 6:57 on the Nürburgring thanks to this boost and charging strategy and the continuous availability of the electric system.

6 Summary

The Porsche 918, the world’s first plug-in hybrid super-sports car, has proven that it is possible to have low fuel consumption and high performance from the same car. This paper has provided a detailed look at the most important powertrain components and has presented the powertrain management as well as the 5 operating modes, which allow both efficiency and performance.

Plug-in hybrid technology makes it possible to achieve the very low average fuel consumption levels normally associated with compact cars. In addition, the powerful and efficient electric drive system can propel the vehicle to speeds of up to 150 km/h and achieve a range of up to 30 km. This allows the driver to drive certain routes with no local emissions.

The combination of this electric drive system with the powerful combustion engine gives the performance expected of a super-sports car. This is aided by compensating for the added weight of the additional powertrain components through the use of lightweight design and materials. In this way, lightweight design, high-output powertrain components and an innovative operating strategy all contribute to the overall high performance of the 918.