

# MILD-HYBRID VEHICLES: A NEAR TERM TECHNOLOGY TREND FOR CO<sub>2</sub> EMISSIONS REDUCTION

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## EXECUTIVE SUMMARY

In 2015 and 2016, ICCT published a series of technical briefing papers on trends in the energy efficiency of passenger vehicles. This report complements the series by providing a comprehensive overview of mild-hybrid technology and recent developments in 48V mild hybridization of conventional vehicle powertrains. We analyzed a wide variety of data sources regarding the CO<sub>2</sub> reduction potential, as well as current and future system cost, for different mild-hybrid electric vehicle (MHEV) system configurations. Furthermore, we investigated the market penetration trends and future projections of MHEV technology in Europe.

As with full-hybrid vehicles, different powertrain architectures exist for MHEVs, mainly characterized by the position of the electric machine, and thereby system complexity. The architectures are therefore associated with different costs but also benefits regarding CO<sub>2</sub> and pollutant emissions reduction.

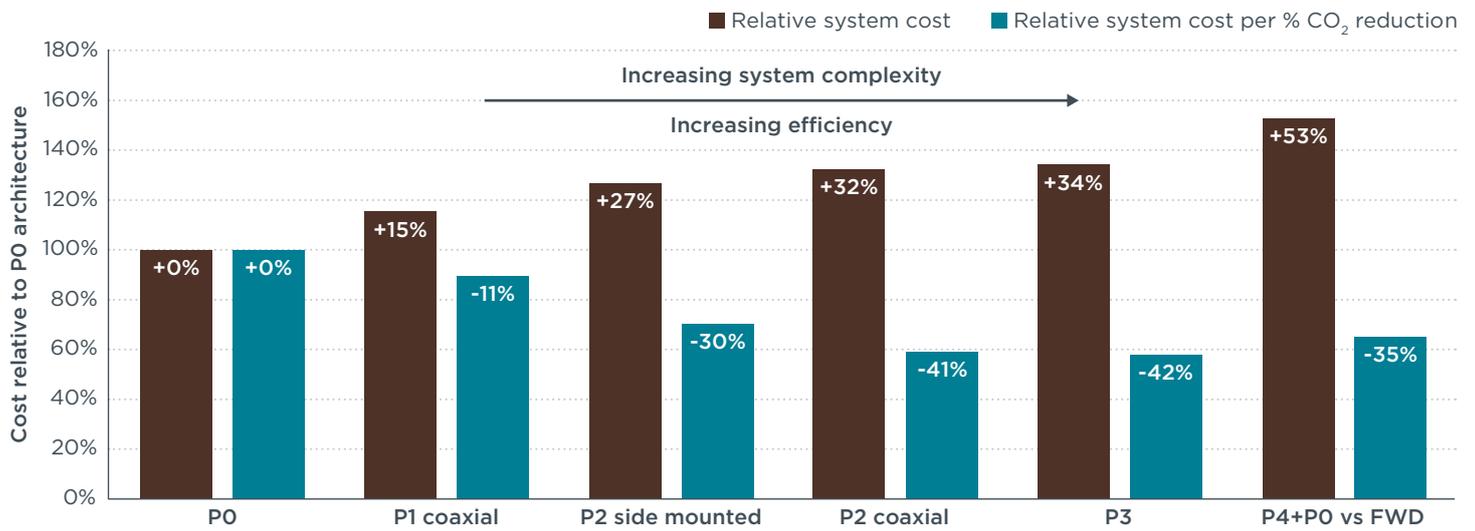
For mild-hybrid systems with comparable technical parameters, including a 15–16 kW electric motor, conservative estimates for the CO<sub>2</sub> reduction potential under type-approval conditions compared with a baseline stop/start system range from about 7% for the currently most common P0 architecture to almost 16% for the more complex P2, P3, and P4+P0 architectures.<sup>1</sup> Optimizing engine operation and increasing electric motor power to 20–30 kW can yield an additional 5% to 10% CO<sub>2</sub> reduction on P2, P3, and P4 architectures. Higher CO<sub>2</sub> reduction potential is also reported for the more complex systems during real-world conditions. However, the achievable CO<sub>2</sub> reduction strongly depends on driving style and speed profile, with highest savings reported for urban and rural driving.

The cost of mild-hybrid technologies increase with system complexity. By combining cost data for a P0 system with annual learning factors and anticipated technology improvements, the P0 manufacturing cost is conservatively projected to drop from €558 in 2020 to €338 in 2030. Based on cost data, we estimate for systems with the same battery capacity of 800 Wh and using 15–16 kW electric machines, about 30% higher cost for a mild-hybrid technology packet with P2 or P3 architecture and about 50% higher cost for a P4+P0 system added to a front-wheel drive vehicle, as shown in Figure ES1.<sup>2</sup>

Combining cost data with CO<sub>2</sub> reduction data, we derived for different architectures the cost incurred for each percentage point CO<sub>2</sub> emissions reduction relative to the P0 architecture (Figure ES1). The increase in overall powertrain efficiency in more complex architectures, due to added functionality and advantageous positioning of the electric machine, outweighs the additional cost and results in lower cost per percentage point CO<sub>2</sub> reduction. While having the lowest absolute cost, the P0 architecture at the same time has the highest cost per percentage CO<sub>2</sub> reduction. The P3 and P2 coaxial architectures are the most cost efficient, with over 40% lower cost than the P0 for the same CO<sub>2</sub> reduction.

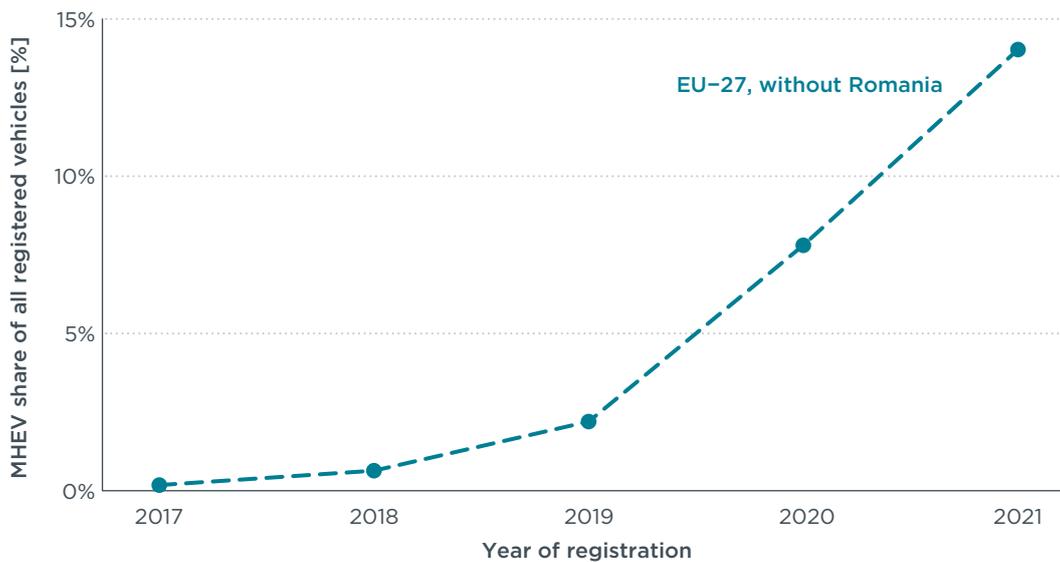
<sup>1</sup> P0 to P4 refer to different mild-hybrid powertrain architectures. In the most common P0 architecture, the electric motor is integrated in the engine's front end accessory drive, where it replaces the standard alternator. P1 and P2 systems place the motor between the engine and the transmission, P3 systems at the transmission output, and P4 systems on the non-drive axle.

<sup>2</sup> Note that P4 systems also add all-wheel drive capability. If a conventional AWD powertrain is replaced with a P4+P0 system, it creates about a 10% cost advantage compared to installing P0 technology only, due to the cost savings from removing the transfer case, differential, and driveshafts.



**Figure ES1.** The manufacturing cost of different mild-hybrid system architectures and the cost per percentage point of CO<sub>2</sub> reduction relative to a 16 kW PO system. All configurations consist of a 15–16 kW electric machine and an 800 Wh battery. The P4+PO system contains an additional 4 kW belt starter generator.

Analysis of MHEV registration data shows that manufacturers are rapidly introducing 48V mild hybridization as a cost-efficient response to the more stringent CO<sub>2</sub> targets in the European Union. While being virtually zero in 2017, the market share of mild hybrid vehicles reached almost 8% in 2020 and about 14% in 2021, as shown in Figure ES2.



**Figure ES2.** Mild hybrid market share across Europe for registration year 2017 to 2021.

Source: Dataforce

Besides improving fuel efficiency, mild hybridization also has the potential to reduce pollutant emissions. Brake particle emissions can be reduced when using the electric machine for regenerative braking. Using the assistance of the electric machine during accelerations can reduce engine-out emissions. The higher power of a 48V system allows the application of electrically heated catalysts and electrical turbochargers, which can substantially reduce emissions at cold start and during transient operation. Introducing mild-hybrid technology for CO<sub>2</sub> reduction therefore also assists in compliance with more stringent pollutant emission limits.

We expect the P0 architecture will continue to dominate the MHEV market in the near future, due to the relatively low cost and easier integration into existing vehicles and powertrains. The significantly higher CO<sub>2</sub> reduction potential of P2, P3, and P4+P0 architectures would allow manufacturers to further reduce the CO<sub>2</sub> emissions of internal combustion engine vehicles at substantially lower cost per CO<sub>2</sub> reduced.

However, with the current EU CO<sub>2</sub> standards only tightening targets from 2025 onwards in 5-year incremental steps, we expect manufacturers can meet their fleet-average targets primarily by increasing the share of electric vehicles, with little need to further reduce the CO<sub>2</sub> emissions of internal combustion engine vehicles or invest in more cost-effective MHEV architectures. Standards that incentivize the use of the more efficient mild-hybridization system layouts, for example by introducing annual CO<sub>2</sub> fleet targets in combination with separate internal combustion engine vehicle-specific CO<sub>2</sub> limits, could achieve a substantial reduction of near-term CO<sub>2</sub> emissions and fuel consumption and help to reduce Europe's dependency on oil imports in the upcoming years, as well as provide a bridge to 100% electric vehicles at moderate cost.

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## ABBREVIATIONS

AC	alternating current
A/C	air conditioning
AWD	all wheel drive
BEV	battery electric vehicle
BSFC	brake specific fuel consumption
BSG	belt starter generator
CMG	crankshaft motor generator
CSG	crankshaft starter generator
DC	direct current
DCT	dual clutch transmission
EGR	exhaust gas recirculation
EHC	electrically heated catalyst
EM	electric machine
FEAD	front end accessory drive
FWD	front wheel drive
FTP	Federal Test Procedure
HC	hydrocarbons
HV	high voltage
ICE	internal combustion engine
ISG	integrated starter generator
LFP	lithium iron phosphate
Li-ion	lithium-ion
MHEV	mild-hybrid electric vehicle
AMT	automated manual transmission
NEDC	New European Driving Cycle
NiMH	nickel metal hydride
NO <sub>x</sub>	nitrogen oxides
PHEV	plug-in hybrid electric vehicle
RDE	real driving emissions
TMG	transmission motor generator
WLTC	Worldwide harmonized Light vehicles Test Cycle
WLTP	Worldwide harmonized Light vehicles Test Procedure

# 1. INTRODUCTION

In 2015 and 2016, ICCT published a series of technical briefing papers on trends in energy efficiency of passenger vehicles. The series was conceived with the aim of summarizing technology developments relevant to passenger vehicle efficiency policy in the United States, but the results are equally applicable worldwide. Understanding advanced vehicle efficiency technologies and their potential to reduce greenhouse gases and pollutant emissions is critical for governments around the world to set appropriate regulatory performance standards. Key questions include the emissions reduction potential of these technologies and the associated costs.

Of course, technology development and innovation have not stood still. The rate of development and deployment of new technologies has accelerated in response to continued adoption of fuel economy and CO<sub>2</sub> standards and long-term goals to transition to zero emission vehicles.

This paper addresses the most important recent development that was not captured in the previous papers, the introduction of mild hybrid technology, which means hybridization below the hazardous voltage level of 60V.

Section 2 provides a comprehensive overview of MHEV technology and discusses the functions enabled by mild-hybrid technology, as well as the advantages and disadvantages of the related powertrain layouts. Due to the wide variety of MHEV architectures, components, and benefits, this paper provides detailed descriptions of the standard mild-hybrid components, as well as components that are facilitated by the higher electric power of an MHEV system.

Based on the analysis of scientific reports as well as supplier and manufacturer information, section 3 presents the CO<sub>2</sub> and pollutant emission reduction potential of mild-hybrid technology and how it is affected by the system layout and specifications.

Historic and projected future mild-hybrid system costs are analyzed in section 4. The investigation is based on cost data from prior tear-down-analyses, as well as cost calculations from engineering service providers and governmental agencies. In addition to analyzing the absolute system cost, it assesses the cost per percentage point CO<sub>2</sub> reduction by combining the cost data from section 4 and CO<sub>2</sub> reduction data from section 3.

Section 5 presents an overview of the market penetration of MHEVs in the European Union and provides an estimate for the MHEV market development in the next years.

The report concludes with a summary of the analysis, highlighting the most relevant findings, in section 6.

## 2. MILD-HYBRID ELECTRIC VEHICLE TECHNOLOGY

A hybrid electric vehicle (HEV) uses two different traction systems, usually a combustion engine with a fuel tank and an electric machine (EM) with a battery, which can operate reversibly as motor or generator.<sup>3</sup> The types of HEVs are classified as micro, mild, or full according to their level of electrification, which typically increases the fuel savings and CO<sub>2</sub> reduction potential.

Some criteria for defining the different types of hybrid vehicles are:

- » the voltage of the high-voltage (HV) battery and circuit,
- » the power of the electric machine,
- » the functions that the electric machine can perform, and
- » the fuel saving and CO<sub>2</sub> emissions reduction potential.

The main differences between mild and full hybrid vehicles are the system voltage and system power. While full hybrid vehicles have the ability for extended electric driving, MHEVs are usually limited to short distances of electric propulsion, although recent developments demonstrate the possibility of higher electric ranges (Kapus et al., 2019; Lauer et al., 2020). Also, most MHEV applications use a system voltage of 48V, which is below the 60V threshold considered the maximum direct current (DC) voltage safe for people (ECMA International, 2002; ZVEI, 2016) and the 75V DC limit set in the Low Voltage Directive 2014/35/EU, above which electrical equipment must comply with higher safety requirements (European Union, 2014).

Even though 24V and 36V systems have been used in a few applications, such as the 24V system in some Mazda models (Mazda, 2019), the mild-hybrid systems and components described in this paper are limited to 48V systems.

Table 1 summarizes the main characteristics of the different types of HEVs, as they are typical for current vehicles. It should be noted that micro hybrids can also have a 24V battery (either NiMH or Li-ion) and that future MHEVs may have electrical power up to 30 kW and higher CO<sub>2</sub> reduction potential.

**Table 1.** Characteristics of hybrid electric vehicles.

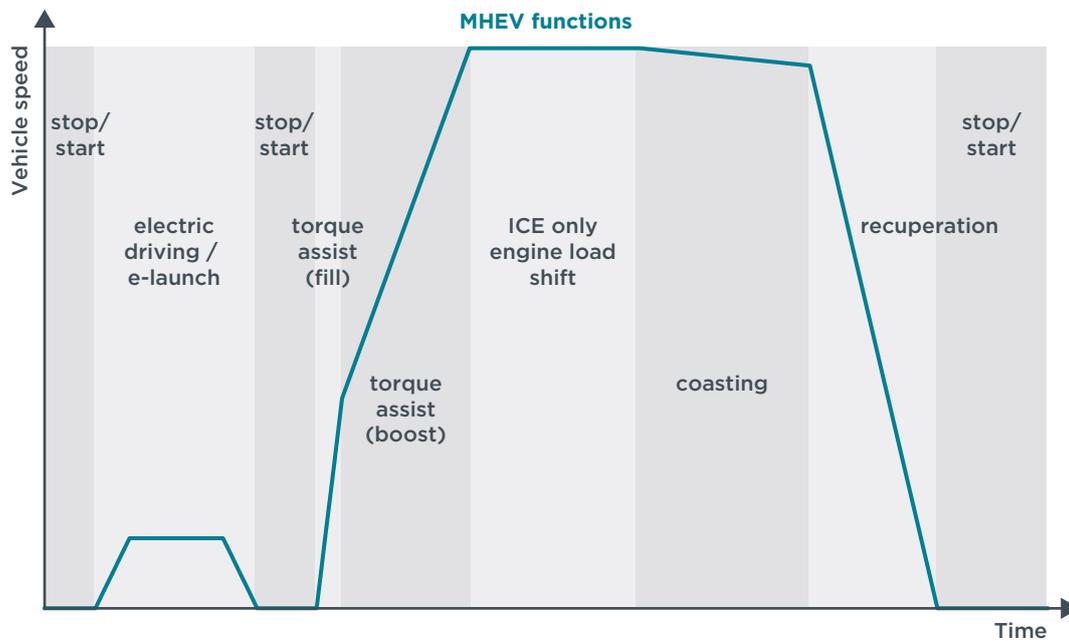
Type of hybrid vehicles	Battery type	HV battery voltage	Electrical power	CO <sub>2</sub> reduction potential
Micro hybrid	Lead-acid	12V	<5 kW	~3%
Mild hybrid	Li-ion	24-48V	5-20 kW	up to 15%
Full hybrid	Li-ion	200-400V	20-80 kW	15-30%

Notes: The CO<sub>2</sub> reduction potential refers to chassis dynamometer type-approval tests, not real-world driving. Sources: Englisch & Pfund (2018), Guzzella & Sciarretta (2013), Herbel (2014).

### 2.1. HYBRID FUNCTIONS AND OPERATING MODES

This section describes the different functions potentially enabled by 48V hybrid systems. The main goal of hybridization is the improvement of fuel efficiency while maintaining or even improving vehicle drivability and comfort and reducing pollutant emissions. Figure 1 illustrates the implementation of functionalities during various phases of vehicle driving that are described in more detail below.

<sup>3</sup> According to the latest European Type Approval (TA) regulation (Regulation (EU) 2017/1151) (European Commission, 2020), "hybrid electric vehicle (HEV) means a hybrid vehicle where one of the propulsion energy converters is an electric machine".



**Figure 1.** Schematic illustration of functionalities enabled by mild hybridization depending on vehicle dynamics. Sources: Bao et al. (2017), Stenzel (2014).

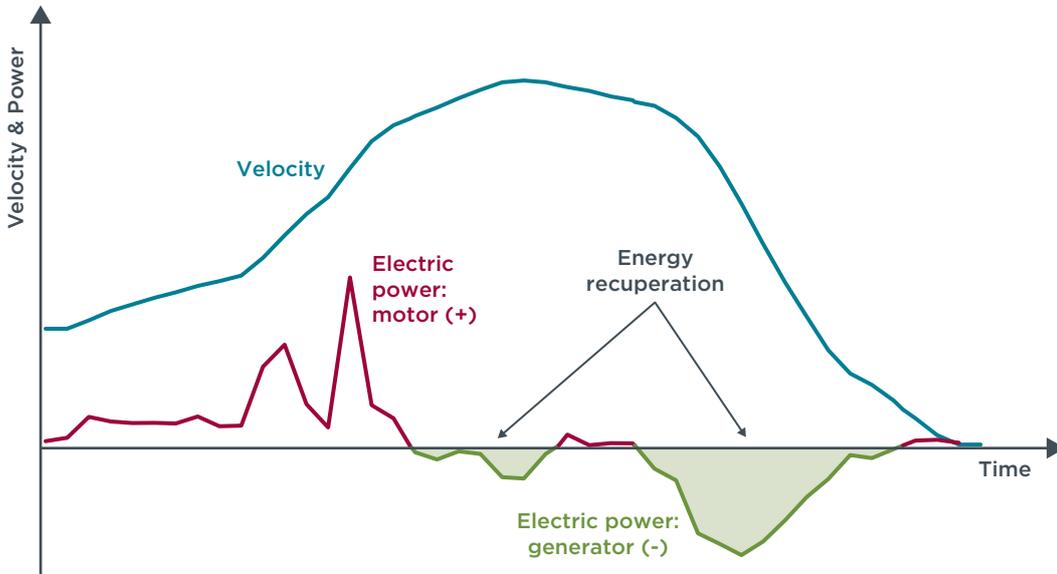
### 2.1.1 Extended engine stop-start functionality

The most basic hybrid function is turning off the combustion engine when the vehicle is stationary, commonly referred to as engine stop/start. This eliminates idle fuel consumption and emissions when the vehicle is stopped, although there is a power demand to restart the engine and engine start can come along with elevated pollutant emissions. A more advanced function is to stop the engine when the vehicle is decelerating at low vehicle speeds, such as when approaching a traffic light. This requires the ability to decouple the engine from the transmission and more advanced controls to be able to restart the engine to quickly respond to driver acceleration demand before reaching full stop.

### 2.1.2 Recuperation of energy during deceleration and braking

Capturing energy normally lost to the brakes during deceleration, commonly called regenerative braking, is the defining characteristic of hybrid systems. For energy recuperation, the EM is switched to generator mode when the vehicle is braking or cruising, i.e., both acceleration and brake pedals are released (Figure 2). Instead of using the conventional friction brakes to slow down the vehicle, the inertial forces that keep the vehicle moving are instead used to generate electricity and slow down the vehicle. The requested brake torque is predominantly generated by the EM. The concurrent activation of the conventional brakes depends on the maximum available brake torque of the EM, the battery state of charge, the system architecture (refer to section 2.2), and the required brake force distribution between front and rear axle. Note that a small amount of energy recuperation is also possible with 12V-24V micro-hybrid systems.

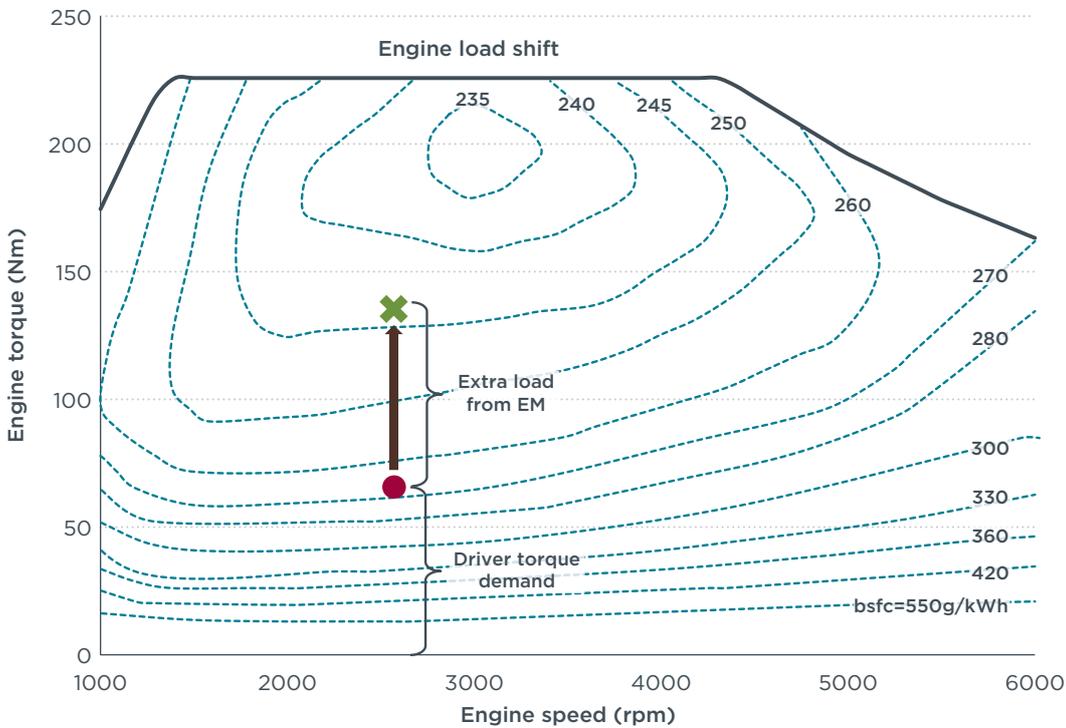
It should be noted that energy recuperation adds an extra resistance to the vehicle during cruising and therefore reduces coasting distances, offsetting part of the efficiency benefits.



**Figure 2.** Example of energy recuperation during deceleration and braking.

### 2.1.3 Increasing the combustion engine efficiency by shifting the load point

One common approach to improve the efficiency of the internal combustion engine (ICE) in a hybrid powertrain is to avoid lower-efficiency operating points at low engine loads. Depending on the battery state of charge, this is achieved by using the EM as an ICE-powered generator to recharge the battery and increase the load on the engine. This shifts the ICE operating point towards higher efficiency (Figure 3). While there are some constraints for this strategy, such as increase in pollutant emissions, engine-load shift strategies can significantly improve the overall efficiency.



**Figure 3.** Engine load shift strategy to improve combustion engine efficiency. The dashed isolines represent schematically the engine brake specific fuel consumption (BSFC) in g/kWh

### 2.1.4 Increasing the powertrain performance by using torque assist

The EM can also be used as a motor to increase the instantaneous total system power. This function, called torque assist, can be used to improve vehicle acceleration, enable engine down-speeding for higher efficiency without loss of performance, and engine downsizing, i.e., using a smaller engine while maintaining performance. The attainable benefit of these measures is to a large extent proportional to the peak power of the electric machine and battery pack. The implementation of an EM with 10–30 kW power in an MHEV enables the torque assist function in two ways, depending on the operating conditions:

- » Torque fill: The high torque at low rpm and instantaneous response of an EM can provide the extra torque needed to fill the gap between driver demand and the ICE torque deficit during the first seconds of a transient event, such as a harsh acceleration (Figure 4). The ICE cannot deliver the demanded torque instantaneously due to its inherent inertia (mechanical and flow), especially in the low engine speed range. So, EM torque fill makes the system more responsive and improves drivability. Torque fill can also be combined with ICE down-speeding to improve efficiency while maintaining good torque responsiveness.
- » Torque boost: With this function, the maximum system torque is increased by the EM, with the final available torque being the sum of ICE and EM outputs (Figure 4). This allows improved torque characteristics for an MHEV, especially at the low engine speed range, and allows ICE downsizing to reduce fuel consumption and emissions while maintaining acceptable vehicle performance and drivability. Torque boost is available only for short periods due to the fast battery depletion and temperature limitation of the electrical components but is sufficient for the majority of acceleration events.

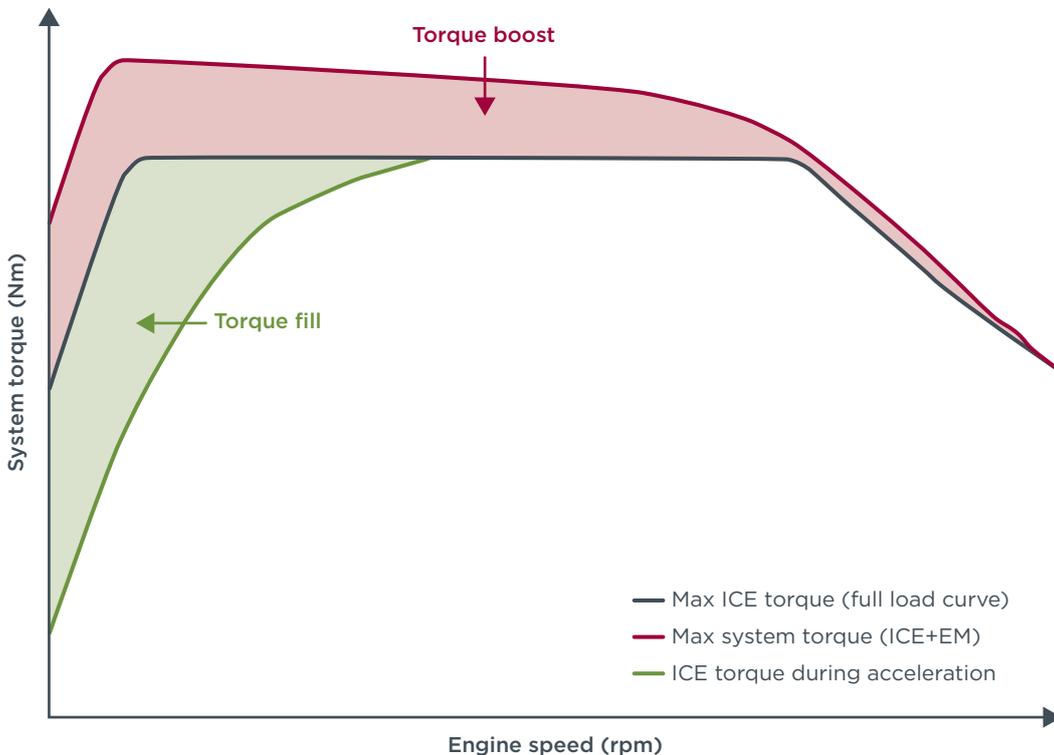


Figure 4. Engine torque fill and torque boost functions with the electric machine.

### 2.1.5 Coasting

Coasting, sometimes also referred to as gliding or sailing, describes when the vehicle freely decelerates without braking and with the engine decoupled from the transmission (either idling or turned off). In MHEVs, the higher battery capacity is used to power accessories even when the ICE is shut off during coasting. Furthermore, the EM can be used to supply extra torque, extending the coasting period without using the ICE at inefficient low load operation (active coasting). It should be noted that in powertrain architectures where the EM cannot be decoupled from the ICE, the EM torque needs to overcome engine and transmission friction, reducing or eliminating the benefits of shutting off the engine during this type of operation.

### 2.1.6 Limited pure electric driving and drive-off

Pure electric driving avoids the inefficient ICE operation at low-speed driving. It is limited by the EM power and battery capacity. In contrast to a full-hybrid, an MHEV has only the ability to drive pure-electric at very low speed, also called creeping, and for short distances. The EM can also be used to perform an “e-launch”, which is starting and accelerating the vehicle in pure electric mode up to a threshold velocity while at the same time accelerating the combustion engine to the same speed without fuel injection. This avoids the inefficient and high pollutant emitting ICE operation at engine start.

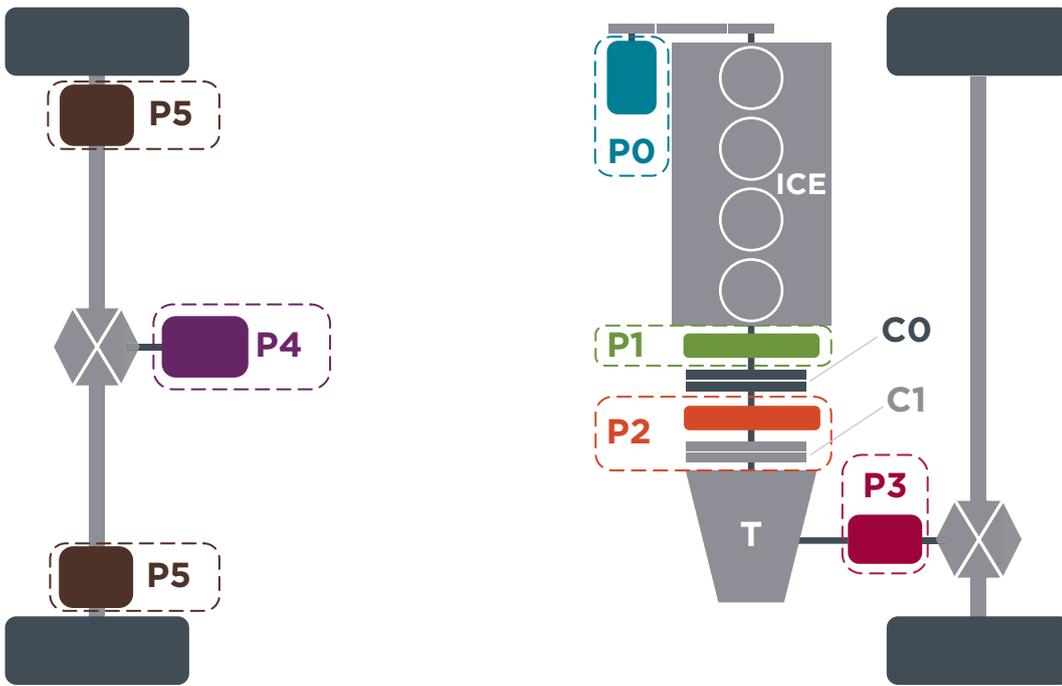
## 2.2. HYBRID VEHICLE POWERTRAIN ARCHITECTURES

Hybrid-electric powertrains can be categorized by three main types according to the way the ICE is connected to the powertrain:

- » Series hybrid: The vehicle is propelled only by a traction EM, while the ICE is only used to power a separate generator, producing the electric energy. The traction EM is supplied with energy by the battery, the ICE generator set, or both devices simultaneously. The traction EM can also act as a generator to charge the battery through regenerative braking. As the ICE is decoupled from the vehicle power demand, it can operate at its optimal efficiency and emissions. However, at least two EMs are needed, increasing weight and cost, and there are energy conversion losses from converting the mechanical energy of the ICE to electricity and then converting the electric power back to motive power.
- » Parallel hybrid: Both the ICE and the EM are connected to the drive shaft and can power the vehicle individually or simultaneously. In this layout, one EM acting as both a motor or generator is sufficient, reducing the weight and cost compared to the series hybrid.
- » Power-split hybrid: The ICE and the EMs are connected to a planetary gear system, which acts as a power split device by distributing the motive power between the ICE, the generator, and the traction motor as needed according to the applied operating and energy management strategy. Although the most complex of the three systems, this type offers higher efficiency with more sophisticated control (Pistoia, 2010). It requires two EMs, resulting in increased weight and cost and more complex packaging.

The current most common type of HEV is the parallel powertrain, followed by the power split type implemented mainly by Toyota (German, 2015). The series layout is used in plug-in hybrid vehicle (PHEV) range extender systems and is not very common. Only the parallel type has been used in MHEVs, where the EM has limited power for driving the vehicle.

Parallel hybrids are further categorized according to the position of the electric machine. The different architectures, ranging from P0 to P5, are shown in Figure 5 and described in more detail below.



**Figure 5.** Components defining the architectures P0 to P5 of parallel hybrid powertrains.  
 Cx: Clutch x, T: Transmission; Px: Position of electric machine(s) in each configuration x.  
 Sources: Bao et al. (2017), Eckenfels et al. (2018)

**P0:** In this configuration, usually called belt starter generator (BSG) or belt alternator starter (BAS), the EM is permanently connected to the ICE in the front-end accessory drive (FEAD) and cannot be decoupled. The accessory drive belt is improved to handle the higher torque transferred between the EM and ICE when supplying power to assist the engine and recovering kinetic energy when braking. The EM starts the engine after shut-off during coasting or stop/start, although the conventional 12V-starter and -battery are maintained for ICE cold starts (Schröder & Stuffer, 2018). A disadvantage of this layout is the permanent EM connection to the ICE through the high-tension belt which causes higher friction losses, and thereby reduces ICE efficiency and energy recuperation potential. However, the P0 configuration is the easiest way of integrating the EM to the ICE as it replaces the 12V alternator, requiring relatively low cost and engineering effort.

**P1:** The EM is attached directly to the crankshaft of the ICE in front of the clutch. This architecture is also called integrated starter generator (ISG), crankshaft motor generator (CMG), or crankshaft starter generator (CSG). The EM is permanently coupled with the engine, so during recuperation the drag torque of the engine reduces the amount of available braking energy. The advantage compared to P0 is that there is no belt connection, therefore increased belt friction is avoided and higher torque can be transferred between the EM and ICE during torque assist and energy recuperation. However, this comes with higher costs and packaging challenges, as the EM must be added between the ICE and the transmission (Figure 5).

**P2:** The standard P2 layout is similar to P1, except an additional clutch is added between the ICE and EM.<sup>4</sup> This allows the EM to be decoupled from the ICE, increasing the energy recuperation potential and allowing the EM to start the ICE, charge the battery when the vehicle is stationary, and perform the electric creeping/launching, pure electric driving, and active coasting functions described in Section 2.1. The EM can be mounted directly on the transmission input shaft (coaxial design), or the connection

<sup>4</sup> There is a special case of P2 (labelled P2.5), where the clutch C1 does not exist, e.g. when the EM is integrated on one of the two shafts of a DCT.

can be established using a belt or chain, allowing the EM to be mounted at the side of the transmission (off-axis or side mounted). Off-axis configurations are more compact, making them easier to package in front-wheel drive vehicles, but introduce losses in the belt or chain. In addition, optimization strategies are needed for engine re-start in order to achieve the best combination of fuel economy and drivability (Eckenfels et al., 2016; Stoffels et al., 2019). The P2 configuration is also referred to as transmission motor generator (TMG).

**P3:** The EM is attached to the output shaft of the transmission and is thereby permanently connected to the wheels. The main advantage of this architecture compared to P0, P1, and P2 is the greater energy recuperation potential, since both the engine and transmission friction and rotational losses do not reduce the amount of energy that can be recuperated. It also enables the use of low-cost automated manual transmissions (AMT), where the inherent interruption of engine torque during gearshifts can be compensated for by the EM. Adversely, unlike the P2 layout, the P3 architecture cannot benefit from the variable transmission gear ratio to optimize the EM operating point and amplify the EM torque. Also, as the EM is constantly connected to the wheels, it cannot be used for engine stop/start operation and a conventional starter or a small P0 system is required to start the engine.

**P4:** While in all previous layouts the EM is mechanically linked to the ICE drivetrain, in the P4 architecture the EM is connected to the axle that is not driven by the ICE, also called “e-axle”, allowing the vehicle to operate in all-wheel drive (AWD) mode. The P4 configuration has high recuperation potential, as the EM does not have to overcome engine friction, transmission losses, and the associated inertia. However, as with the P3 architecture, the P4 system cannot benefit from the variable transmission gear ratio to optimize the EM operating point and amplify the EM torque and cannot start the ICE. Therefore, a P4 configuration usually requires a clutch to decouple the EM from the axle at high vehicle speeds. Alternatively, a two-gear transmission for the EM can be used, although it increases weight and cost and affects packaging. The P4 layout can be combined with a second EM, usually in P0 or P1 configuration and referred to as “P4+Px”, gaining the advantages of both layouts but increasing cost and complexity.

**P5:** Similar to the P4 layout, the EMs in the P5 configuration also acts on the axle not powered by the ICE. However, in the P5 layout, two EMs are integrated in the wheel hubs, directly acting on the wheels, also called “e-wheel”. The primary advantage is that it enables individual control of the non-driven wheels, providing torque vectoring and individual brake control for improved safety and vehicle handling. It also eliminates the space needed for the driveshaft. The downsides to the P5 configuration are increased cost due to the extra EM and larger unsprung masses and safety risks due to uncontrolled yaw moments when one EM fails.

As mentioned before, not all functions described in Section 2.1 are feasible for every parallel hybrid powertrain architecture. Table 2 summarizes the functionalities theoretically available for the different MHEV configurations described above, even though some may not be very efficient or might raise control and stability issues.

**Table 2.** Overview of hybrid functions theoretically possible for the different MHEV powertrain architectures

Functionality	MHEV powertrain architecture					
	P0	P1	P2	P3	P4	P5
Engine stop/start (extended)	●	●	coaxial: ● off-axis: ○	✘	n/a	n/a
Recuperation during coasting and regenerative braking	○	○	●	●	●	●
Engine load shift	●	●	●	○	○*	○*
Torque assist	●	●	●	●	●	●
Active coasting	○	○	●	●	●	●
Pure electric drive	✘	○	●	●	●	●
Electric all-wheel-drive	n/a	n/a	n/a	n/a	●	●

●: possible; ○: possible but less efficient; ✘: not possible; n/a: not applicable

\* Potentially associated with control and stability challenges.

Sources: Eckenfels et al. (2018), Englisch & Pfund (2018), Lauer et al. (2020), Pels et al. (2017), Schöffmann, Sorger, Ennemoser, et al. (2017)

Engine friction and transmission losses reduce the recuperation energy available in P0 and P1 systems, and recuperation energy in P0 systems is further reduced by belt losses. The P2 configuration can decouple from the combustion engine, although there are still some losses from the transmission. The P3 through P5 architectures eliminate engine friction and transmission losses.

Engine load shift is most feasible where the EM can be coupled to the engine, such as with the P0 to P2 architectures. In principle, engine load shift can be also achieved in P3, P4, and P5 architectures indirectly, although at lower efficiency, while control and stability might be an issue for P4 and P5. The torque assist function in P4 and P5 layouts is essentially the AWD operation.

Active coasting is possible for all configurations in principle, but the benefits are reduced by engine friction and transmission losses in the P0 and P1 configurations. Limited pure electric driving is possible for P2 to P5 systems where the ICE can be decoupled from the electric machine. Electric AWD is possible only in the P4 and P5 configurations where the EM acts on the axle not powered by the combustion engine.

## 2.3. COMPONENTS OF MILD-HYBRID VEHICLES

### 2.3.1 Basic components required for mild hybridization

All MHEVs contain at least one electric machine, a battery to store the propulsion energy, and a DC/DC converter to supply the conventional 12V system with energy from the higher voltage traction battery. The individual components are described in the following sections in more detail.

#### Battery

All MHEVs feature a higher voltage battery in addition to the conventional 12V battery, typically 48V, although 24V and 36V systems have also been used. The preferred battery type in MHEV applications is lithium-ion (Li-ion), due to its high specific energy and power, allowing smaller and lighter battery packs. Unlike batteries for battery electric vehicles (BEVs), which are sized and optimized for high energy capacity, battery chemistries optimized for high power density, such as lithium iron phosphate (LFP), can reduce MHEV battery size and cost while still enabling power assist and recuperation. In order to avoid potential damage, the allowable power flow from or to the battery is usually reduced when the cell temperature reaches 55°C–60°C, although more robust Li-ion cells can withstand temperatures up to 75°C (Bosch Global, 2020).

Air cooling, either active or passive, is usually used for MHEV batteries, although liquid coolant potentially linked to the air-conditioning system is also in development (MAHLE Powertrain Ltd, 2019). Table 3 summarizes typical characteristics of current Li-ion batteries.

**Table 3.** Typical characteristics of current Li-ion batteries for MHEV applications.

Type	Li-ion
Nominal voltage	48V
Dimensions (L×W×H)	300 × 180 × 90 mm
Number of cells	up to 20
Weight	6-8 kg
Energy Capacity	up to 20 Ah / 960 Wh
Power Capacity	Up to 25 kW
State-of-charge operating window	80-30%
Cooling	Natural or forced air cooling

Sources: Bosch Global (2020), Guzzella & Sciarretta (2013), Lee et al. (2018), MAHLE GmbH (2019)

### Electric machine

The electric machine can operate as a motor to provide additional torque and propel the vehicle, or as a generator to produce electric energy to charge the 48V battery. Permanent magnet synchronous motors with 3-phase current are typically used in MHEVs because of their high torque density and high efficiency. The exact type and characteristics of the EM for an application depends on the maximum required torque and power output, space limitations, functional safety requirements, and cost (Smetana, 2014). To avoid damages caused by overheating, air and liquid cooling systems are used.

The efficiency of the electric motor is typically in the range of 95%. In current P0 and P1 systems, the peak power is limited to 10–15 kW, due to torque transfer and packaging. For P2, P3, and P4 systems, where these restrictions are less of an issue, EMs with a power of 20–30 kW can be used.

### Inverter

An inverter is required to convert the DC supplied to and from the battery to AC for powering and controlling the 3-phase EM. The inverter adjusts the frequency and amplitude of the 3-phase current to control the torque and speed of the EM. When the EM is in generator mode, the inverter converts the produced AC current into DC to be stored in the battery. For smaller EMs, as used in MHEVs, the inverter is usually integrated in the same housing with the EM. The inverter is air- or liquid-cooled to remove heat losses. Depending on the load, the inverter efficiency reaches 95%.

### DC/DC converter

An MHEV has two electric networks, the high voltage 48V hybrid system and the low voltage 12V circuit, required for supplying the conventional 12V electric systems. As electric energy is produced only by the 48V EM, a direct current (DC/DC) converter is needed to step down the high voltage. Often the converter is bidirectional, meaning it can also convert low to high voltage, for example during jump-start or to charge a drained battery. The converter is usually air-cooled and has a typical power output in the range of 3 kW and efficiency above 95% (Robert Bosch GmbH, 2021; Romanato et al., 2018).

### 2.3.2 Electrified peripheral components in mild hybrid vehicles

In addition to the standard components, additional systems can be electrified to take advantage of the MHEV 48V electrical system. This includes an electrical compressor or turbocharger, catalyst heaters, air conditioning (A/C) compressor, and auxiliaries such as power steering, power brakes, water pump, and radiator cooling ventilator.

#### Electric compressors and electrically assisted turbochargers

The higher electric power supported by the hybrid system enables the integration of a small EM to the turbocharger (e-turbo) or an electrically driven compressor (e-compressor). The latter can also be integrated with the standard turbocharger, either upstream or downstream with a bypass valve. Both systems allow direct boosting of the engine and reduction of turbo lag. The improvement in engine responsiveness allows downsizing and downspeeding the engine and to reduce the exhaust backpressure, all measures which improve efficiency. In addition, electrified boost enables the use of the more efficient Miller cycle<sup>5</sup> without a variable-geometry turbocharger or two-stage turbocharger.

One advantage of the e-turbo compared to the e-compressor is that it can serve as a waste heat recovery system, recuperating energy from the exhaust gas stream when the driving conditions allow. The EM power of an electric compressor can reach 6 kW (Beer et al., 2016; BorgWarner Inc., 2017; Schaub et al., 2017) and, in the case of an e-turbo, 17 kW (Bontemps et al., 2019; BorgWarner Inc., 2019), which is in the range of the traction EM.

Major manufacturers have already applied electrically assisted boosting systems in premium models (Audi AG, 2014; Hampel, C., 2020), and are planning to equip models with e-turbo (BorgWarner, 2020; Butcher, 2020).

#### Electrically heated catalyst

Peak tailpipe emissions in ICE vehicles occur after cold start before the catalyst heats up to operating temperature. In addition, the frequent engine stops in hybrid vehicles hinder maintaining high exhaust system temperatures and prolonged urban driving at low vehicle speeds may cool down an already warmed-up catalyst. Combustion control strategies for reaching fast catalyst light-off and maintaining catalyst temperature increase fuel consumption and CO<sub>2</sub> emissions, as well as engine-out pollutant emissions (Gao et al., 2019).

An alternative is using an electrically heated catalyst (EHC), also called “e-catalyst”. The system consists of an electric heating element placed directly in front of the main catalyst which can be also coated with catalytic material (Laurell et al., 2019; Ye et al., 2019). The EHC enables faster catalyst light-off and temperature control during low-load operation, and thereby has the potential for reduced catalyst precious metal loadings while reducing the effect of warm-up measures on fuel consumption. The higher electric power supported by a 48V system compared with the conventional 12V allows faster catalyst heating, smaller and lighter packaging, and facilitates pre-heating the EHC just before engine start (Jean et al., 2020; Kapus, 2020; Schöffmann, Sorger, Ennemoser, et al., 2017).

The EHC has been applied in various premium vehicle models (Audi AG, 2014; Continental Emitec GmbH, 2020). According to the latest developments, a European manufacturer plans to apply this technology in two 48V mild hybrid van models, with production scheduled to start in 2022 (Vitesco Technologies, 2020).

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<sup>5</sup> The Miller combustion process is characterized a longer expansion stroke than compression stroke. It allows higher efficiencies than the standard combustion cycle of direct-injection positive-ignition engines but requires for comparable engine performance high boost pressures at low and medium engine load.

### **Electric A/C compressor**

The conventional A/C compressor is belt-driven by the FEAD. The higher voltage and greater energy storage capacity of the 48V system allows the integration of the A/C compressor into the electrical system, significantly reducing the engine accessory losses (Isenstadt & German, 2016). Although the electric A/C compressor is heavier (considering a 5 kW EM), it is more efficient than the belt-driven compressor, avoids losses in the belt, and is decoupled from the engine. Thus, cabin climate control is independent of the engine speed and the latter can turn off during idle without any penalty in passenger comfort. Depending on the battery capacity and its state of charge, pre-cooling (switching on the A/C compressor before starting the engine) might also be possible (Schöffmann, Sorger, & Weissbäck, 2017). The cooling circuit of liquid-cooled batteries can be also integrated with the A/C system (MAHLE Powertrain Ltd, 2019). The greatest benefit comes with the integration of the A/C compressor on the belt of the EM in an off-axis P2 configuration, enabling the operation of the compressor by both the ICE and the EM depending on the operating mode of the powertrain (Schöffmann et al., 2019). Daimler AG has already implemented a 48V A/C compressor in its luxury class models (Daimler AG, 2017).

### **Electrically activated clutch (e-clutch)**

Another component of the drivetrain that can be electrified is the manual transmission clutch. An e-clutch enhances manual transmission by integrating features that can be found in automatic transmission. E-clutch can be utilized in 48V hybrids for reduced CO<sub>2</sub> emissions during coasting, pure electric driving, or creeping (Schöffmann, Sorger, Weissbäck, et al., 2017). The e-clutch offers the “clutch by wire” feature, which connects the pedal with the clutch via electric actuators rather than conventional hydraulic or mechanical components, increasing the driving comfort, as well as safety and efficiency (Schaeffler, 2017).

### **Active suspension systems**

Active suspension systems can adjust shock absorber attenuation and wheel-specific ground clearance to dynamically dampen oscillations and improve handling, based on road and driving conditions. There are various ways to accomplish this, such as Daimler’s E-Active Body Control which uses an air suspension supplemented by hydropneumatics (Daimler AG, 2018) and Audi’s predictive active suspension which uses an air suspension supplemented by electric machines (Audi AG, 2019). Such systems allow the vehicle to remain level independent of the load and the road surface. For handling the high power requirements of active suspension systems, a 48V system is prerequisite for this technology.

### **Electrified front end accessory drive**

Using electrically powered accessories, such as variable valve timing phasers (Schöffmann, Sorger, & Weissbäck, 2017), engine water pump, power steering pump, and vacuum pump, offers significant efficiency improvements. Not only are electric motors more efficient than conventional hydraulic, pneumatic, or mechanical drives, they can also be activated based on need, have no losses when turned off, and can be used to individually control the accessories.

When all auxiliaries are electrified, no accessory belt drives are needed except for the belt starter generator in a PO configuration. This is referred to as beltless front end accessory drive. Removing the belt drives eliminates the system cost, belt maintenance, and efficiency losses caused by the high-tension belts. It also improves engine packaging and allows for a more compact engine compartment (German, 2011).

## 3. EFFECTS OF MILD HYBRIDIZATION ON CO<sub>2</sub> AND POLLUTANT EMISSIONS

Vehicle powertrain electrification plays an important role in the reduction of CO<sub>2</sub> emissions and fuel consumption (Krause et al., 2020). Implementing mild-hybrid technologies can provide a cost-effective fuel economy solution, depending on the specifications of the hybrid components and the selected topology (EIs, 2019; Green Car Congress, 2019d; Schaeffler, 2017).

As mild hybridization is a relatively new technology, the available CO<sub>2</sub> and fuel consumption reduction data are largely based on simulations and prototype testing. There are also some investigations that examine mild hybridization as a means to integrate additional technologies enabled by 48V applications to limit pollutant emissions, such as the electrically heated catalyst and electrically supported air charging.

The information and data presented in this section are retrieved from publicly accessible sources. The data cover a wide range of driving styles, from chassis dynamometer driving cycles to real-world conditions. The applications of mild-hybrid technology covered here include both gasoline and diesel engines.

### 3.1. CO<sub>2</sub> EMISSIONS REDUCTION AND FUEL SAVING POTENTIAL OF MILD HYBRID VEHICLES

#### 3.1.1 Reported mild hybridization benefits for chassis dyno driving cycles

The main target of hybridization is improving the powertrain efficiency and capturing regenerative braking energy, thereby reducing fuel consumption and CO<sub>2</sub> emissions.

Micro-hybrid systems offer limited functionalities, primarily engine stop/start and limited energy recuperation, with a corresponding average fuel economy potential of 7% in NEDC and 3.5% in WLTC (Dimaratos et al., 2016; Ernst et al., 2012). Mild-hybrid systems offer additional functionalities, as described in the previous section. The average CO<sub>2</sub> reduction potential of an MHEV is strongly dependent on the hybrid system configuration (P0 to P5 or combinations), the power and efficiency of the electric machine and battery pack, and driving dynamics and conditions (Eckenfels et al., 2018; Liu et al., 2016; Melaika et al., 2019).

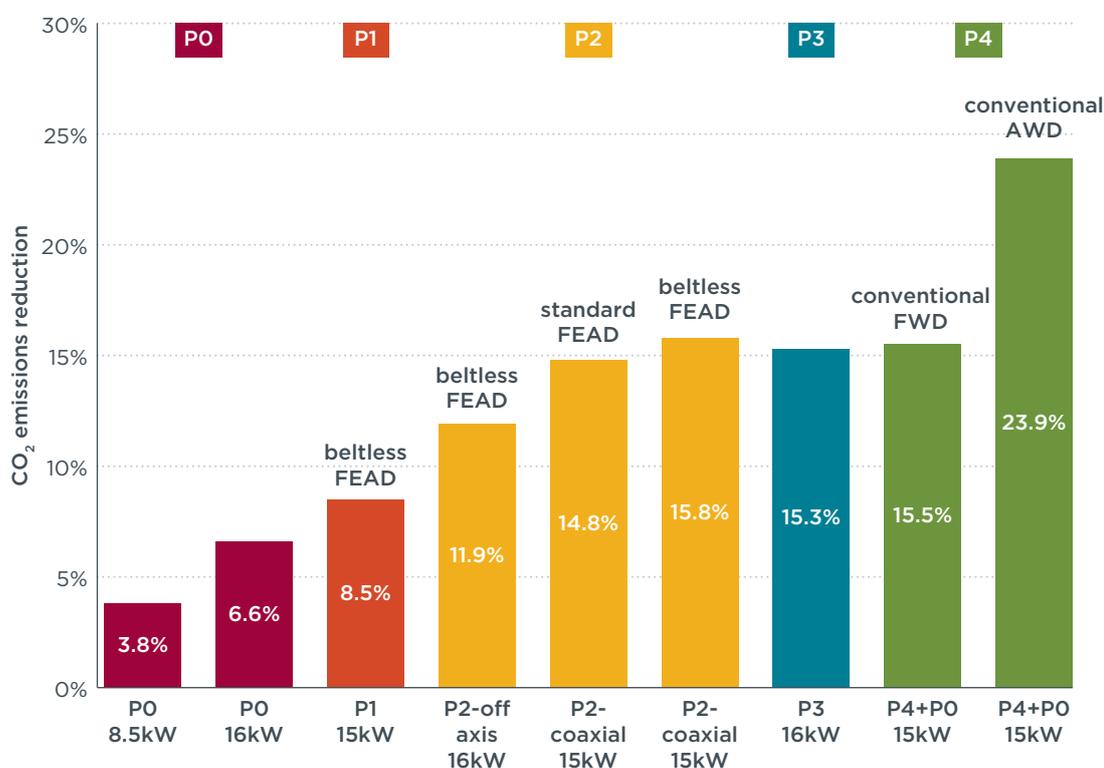
There are a number of factors that affect the assessment of MHEV CO<sub>2</sub> emissions reduction potential. One is the baseline used for the comparison. Some studies use a micro-hybrid vehicle as the baseline while others start from a fully conventional vehicle. Another factor is the power of the EM and the capacity of the battery, which affect fuel savings for the same mild-hybrid configuration and application. Furthermore, many studies incorporate optimization of the ICE and the drivetrain by technologies that are enabled by the 48V circuit, such as electrically assisted air charging, and only the total benefit is reported, making it impossible to isolate the benefit of the powertrain assist from the 48V system.

**Study by Schaeffler.** A study performed by Schaeffler compares the emissions of mild-hybrid technologies by simulating the WLTC CO<sub>2</sub> emissions of different MHEV configurations against a baseline micro-hybrid car (Eckenfels et al., 2018). The starting point of the simulations was a C-segment micro-hybrid FWD car with a 3-cylinder 1.0l gasoline engine with stop/start and a 7-speed dual clutch transmission (DCT). Schaeffler modeled replacing the micro-hybrid powertrain with nine different 48V MHEV system configurations, all using a 1.4 kWh battery:

- » P0 (BSG) with 8.5 kW and 16 kW EM power
- » P1 with 15 kW EM power

- » P2 with off-axis 16 kW EM and beltless FEAD and two configurations with coaxial 15 kW EM, one with standard FEAD and one with beltless FEAD
- » P3 with 16 kW EM power
- » P4+PO with 15 kW EM power, compared against efficiency of conventional FWD and conventional AWD vehicles

This set of data is considered as the reference in this chapter. The simulated CO<sub>2</sub> emissions reductions are illustrated in Figure 6.



**Figure 6.** WLTC CO<sub>2</sub> emissions reduction potential compared to a 12V micro-hybrid baseline according to a 2018 Schaeffler study. Source: Eckenfels et al. (2018)

The P0 (BSG) configuration can save 3.8% CO<sub>2</sub> emissions compared to the baseline 12V micro-hybrid when using an 8.5 kW EM, and the benefit reaches 6.6% when the power is increased to 16 kW. Combining a P1 crankshaft-integrated 15 kW EM with a beltless FEAD results in an 8.5% CO<sub>2</sub> emissions reduction. Using the same 15 kW EM and beltless FEAD in a P2 coaxial system almost doubles the reduction potential to 15.8%, highlighting the positive effect of integrating a second clutch (refer to Figure 5) on recuperation potential and enabling additional functions. With a conventional FEAD on the P2 coaxial system, the benefit is reduced to 14.8%, implying an efficiency benefit of 1% in WLTC when electrifying the auxiliaries. It should be noted that the belt-driven A/C compressor is deactivated during the WLTC test, therefore the benefit of a beltless FEAD is expected to be higher in real-world driving. Replacing the P2 coaxial 15 kW EM with a P2 belt-driven off-axis 16 kW EM reduces packaging constraints but comes at the cost of an efficiency reduction from 15.8% to 11.9%, largely due to the belt losses.

The P3 configuration with a 16 kW EM coupled to the output shaft of the transmission has a CO<sub>2</sub> emissions reduction potential of 15.3%, which is similar to the P2 coaxial architecture. The P4 AWD configuration with a 15 kW EM and a two-speed transmission installed on the rear axle was combined with a P0 (BSG) configuration (P4+PO architecture). Compared to the baseline, the P4+PO architecture results in a CO<sub>2</sub> reduction of 15.5% on the WLTC. Compared to an equivalent conventional AWD vehicle

with higher baseline CO<sub>2</sub> emissions, electrification of the rear axle and elimination of the mechanical AWD system results in a total CO<sub>2</sub> reduction of 23.9%.

**Study by Chalmers University of Technology.** Another simulation-based assessment of the fuel saving potential of mild-hybrid technology against a constant baseline was conducted by the Chalmers University of Technology in Sweden (Melaika et al., 2019). In this multi-parametric study, different MHEV topologies (P0, P1, P2 and P3), the effect of various fuels (gasoline, CNG, ethanol-E85, diesel), driving cycles (NEDC, WLTC, RTS95), and EM power (from 8 to 20 kW) was analyzed. The baseline is a C-segment car without engine stop/start and with a 7-speed DCT. The weight of the conventional vehicle is 1300kg and the additional weight of the 48V components is estimated at 50kg. Two engines were simulated: a 3-cylinder, 1.5l spark ignition engine (gasoline) and a 4-cylinder, 2.0l compression ignition engine (diesel).

Table 4 summarizes the results of the analysis for gasoline and diesel, where the color code denotes the level of the achieved CO<sub>2</sub> emissions reduction, from red (low) to green (high). The baseline for determining the CO<sub>2</sub> emissions reduction is a conventional vehicle without start/stop. The results are shown for both the minimum (8 kW in all cases) and maximum (15 kW in P0 and P1, 20 kW in P2 and P3) EM power investigated. For comparability with the Schaeffler study, the results for the 15 kW EM power in P2 and P3 configurations are presented as well.

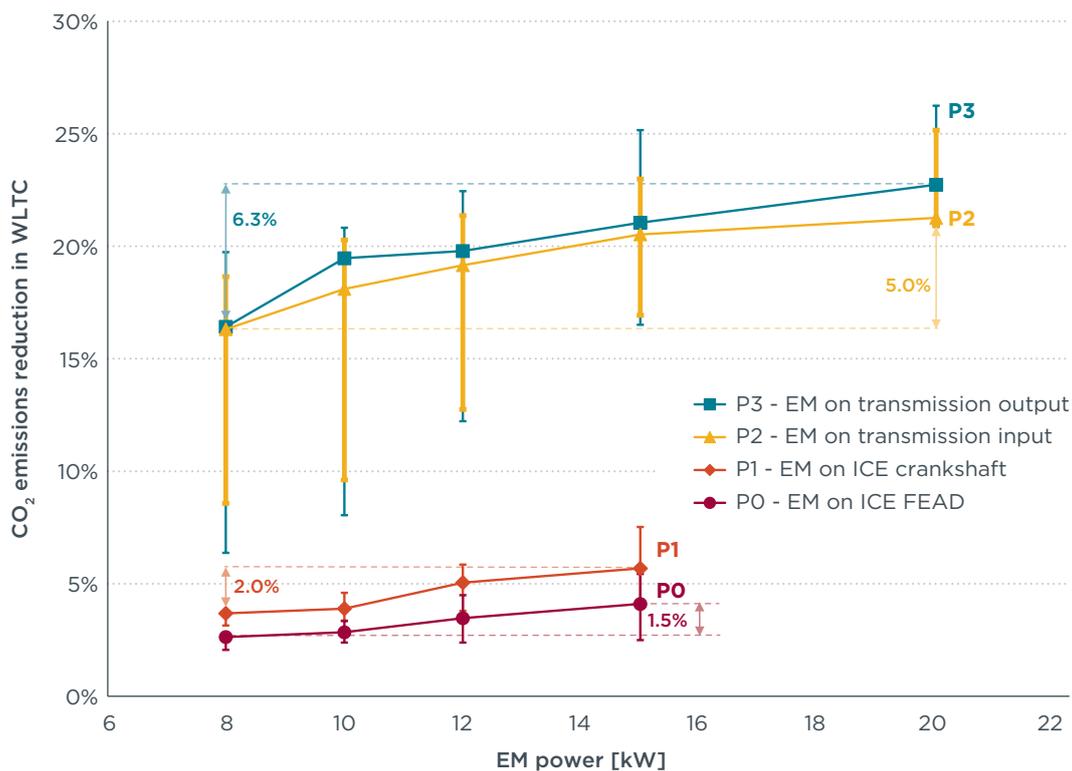
**Table 4.** CO<sub>2</sub> emissions reduction reported by Chalmers University for a C-segment vehicle with 7-speed DCT.

Configuration and voltage	Engine / Fuel	EM power [kW]	CO <sub>2</sub> emissions reduction		
			NEDC	WLTC	RTS95
Micro-hybrid (12V)	3-cyl 1.5l DISI / gasoline	3	7.8%	5.0%	4.3%
	4-cyl 2.0l / diesel	3	5.1%	7.3%	n/a
MHEV P0 (48V)	3-cyl 1.5l DISI / gasoline	8	9.7%	7.5%	6.9%
		15	10.1%	8.9%	9.5%
	4-cyl 2.0l / diesel	15	6.6%	12.0%	n/a
MHEV P1 (48V)	3-cyl 1.5l DISI / gasoline	8	10.7%	8.5%	7.7%
		15	11.5%	10.4%	11.5%
	4-cyl 2.0l / diesel	15	7.1%	13.2%	n/a
MHEV P2 (48V)	3-cyl 1.5l DISI / gasoline	8	25.0%	20.5%	12.5%
		15	29.0%	24.5%	20.5%
		20	31.0%	25.2%	24.3%
	4-cyl 2.0l / diesel	15	28.5%	25.4%	n/a
MHEV P3 (48V)	3-cyl 1.5l DISI / gasoline	8	26.0%	20.6%	10.4%
		15	31.0%	25.0%	20.1%
		20	32.0%	26.6%	24.3%
	4-cyl 2.0l / diesel	15	29.2%	26.3%	n/a

Notes: Baseline for this study is a conventional combustion engine vehicle without stop/start. The colors from red to green denote the level of CO<sub>2</sub> emissions reduction potential from low to high. Source: Melaika et al. (2019)

The results indicate a wide range of CO<sub>2</sub> emission reduction potential, depending on the MHEV architecture, the EM power, the test cycle, and the fuel. Isolating the effect of the 48V system alone (i.e. the MHEV reduction compared with stop/start system results), Figure 7 presents, for the gasoline car, the relation between CO<sub>2</sub> emissions reduction and the EM power for the analyzed MHEV architectures, EM power levels, and drive cycles. The central line corresponds to the WLTC and the error bars cover the NEDC and RTS95. The reduction of CO<sub>2</sub> emissions follows an increasing trend with the EM power. Increasing the power from 8 to 15 kW results in an additional CO<sub>2</sub> emissions

reduction of 1.5% to 2.0% in P0 and P1 architectures, while in P2 and P3 the added benefit is between 5.0% and 6.3% when replacing the 8 kW EM with a 20 kW EM.

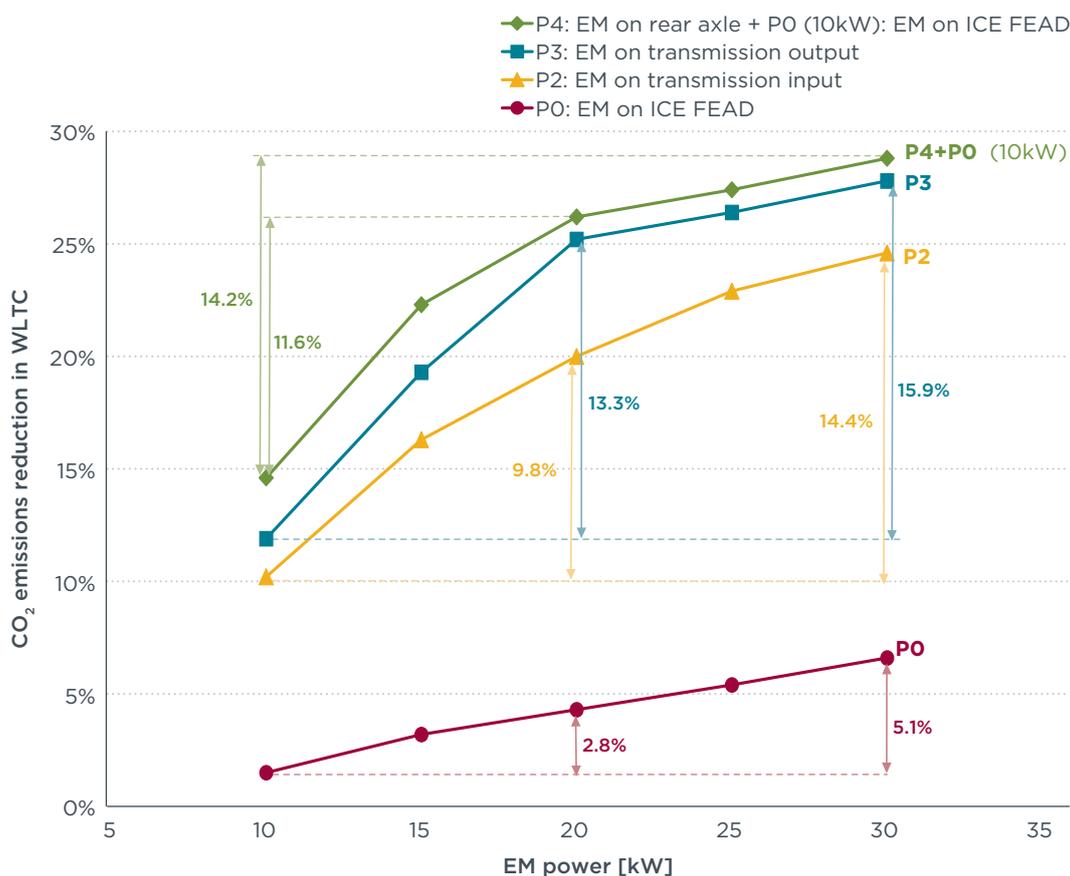


**Figure 7.** Effect of EM power on CO<sub>2</sub> emissions reduction, relative to stop/start baseline, of a C-segment car with a 1.5 l gasoline engine and a dual clutch transmission for different MHEV configurations and driving patterns. The central line corresponds to WLTC and the error bars to the other driving cycles listed in Table 4. Derived from Melaika et al. (2019).

The MHEV configuration has a more pronounced effect on CO<sub>2</sub> emission reduction than increasing the EM power, as Figure 7 clearly shows. Moving the EM from P0 (BSG) to P1 eliminates the belt losses but the energy recuperation potential for both layouts is affected by the ICE friction, resulting in additional CO<sub>2</sub> reduction of up to 1.5 percentage units. For the same EM power, decoupling the EM from the engine (P2 and P3) increases the CO<sub>2</sub> reduction potential by up to 15 percentage points. Similar to the results of the Schaeffler study, moving the EM from the input (P2) to the output (P3) shaft of the transmission seems to offer only a marginal benefit in the order of 1 percentage unit, although the Chalmers University study indicates that the effect may be more pronounced at higher EM power (20 kW). The higher recuperation potential of the P3 configuration due to removing the transmission losses is offset by the P2 advantage of the variable gear ratio for the EM, which allows higher EM efficiencies over a wider operating range.

**Study by the Technical University of Braunschweig.** A third simulation study that compares different MHEV topologies against a constant baseline was conducted by the Technical University of Braunschweig (Werra et al., 2020). A generic C-segment 1520 kg vehicle with an 89 kW ICE and manual transmission was simulated for P0, P2, P3 and P4+P0 powertrain layouts with EM power varying from 10 to 30 kW. For all scenarios, the same operation strategy was applied and the same hybrid functionalities were simulated, including pure electric drive. The CO<sub>2</sub> emissions reduction in WLTC compared to an equivalent conventional vehicle without stop/start is presented in Figure 8 as a function of the EM power for the examined topologies. Although not directly comparable, this study shows higher impacts of EM power on WLTC CO<sub>2</sub> emission reductions than the Chalmers University study (Figure 7). Because of applying the same operating strategy,

the EM is used for pure electric driving even for the P0 layout despite the high losses the EM has to overcome, resulting in the lower benefit determined for this architecture. This study also found 25% larger benefits for the P3 configuration than for P2, while both the Schaeffler and Chalmers University studies found the P3 over P2 benefits to be roughly 1%. The strong effect of the powertrain architecture on efficiency is confirmed, with the engine-mounted configuration (P0) showing the lowest benefit, and the addition of a second clutch (P2) and transmission-output (P3) configurations both offering much higher savings. The integration of a 30 kW EM on the rear axle (P4), combined with a 10 kW EM in P0 position, can reduce fuel consumption by 29%, taking advantage of the additional recuperated energy on the rear axle.



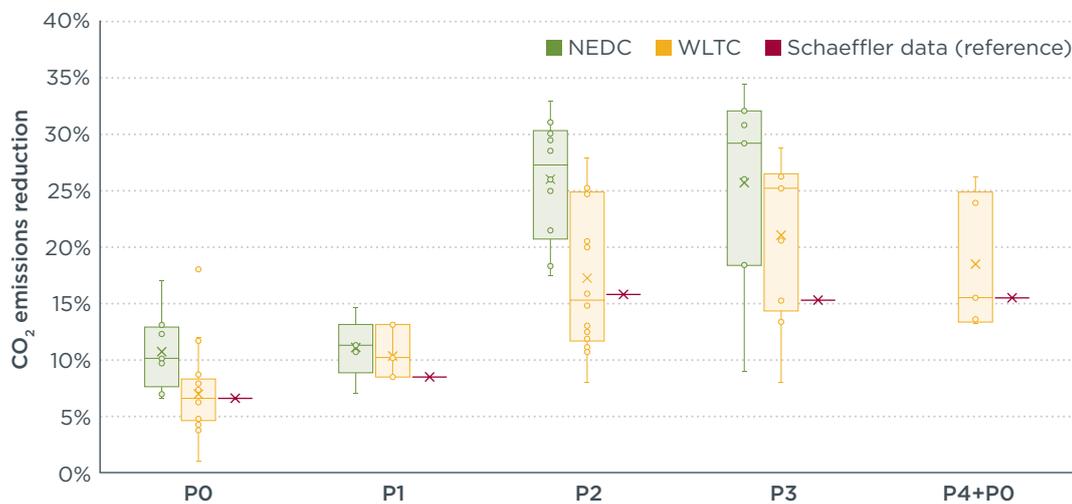
**Figure 8.** WLTC CO<sub>2</sub> emissions reduction versus EM power, relative to C-segment car with stop/start and manual transmission for different MHEV topologies, from the Braunschweig University study (Werra et al., 2020).

**Studies by AVL.** AVL has also conducted a number of studies analyzing the fuel saving potential and associated costs of mild hybridization for different powertrains, driving cycles, and car segments (Kapus et al., 2020; Schöffmann et al., 2019; Schöffmann, Sorger, & Ennemoser, et al., 2017). AVL finds the reduction in CO<sub>2</sub> emissions achieved with a 20 kW EM in P2 configuration is 13% in WLTC for a C-segment car equipped with a turbocharged 1.6l gasoline direct injection engine and stop/start. This is less than the approximately 20% reduction found by the Chalmers University study for a 20 kW EM in P2 configuration, although this may be due, at least in part, to AVL separating the benefits from electrification of auxiliary components (pumps, e-turbo, electrically heated catalyst), for which they estimated a further CO<sub>2</sub> reduction of 7.5%. Similar reductions are presented for the diesel version of the same C-segment car, with the absolute values being at a lower level. Considering other car categories, the studies show a trend of increasing reduction potential in WLTC when

moving from the B to C and to E segments. However, the fuel saving potential becomes significantly lower for SUVs, independent of the position of the EM.

**Other studies.** The studies discussed above evaluate the benefits of mild hybridization for a wide range of EM topologies and power levels against a constant baseline. Additional studies exist that examine CO<sub>2</sub> emissions and fuel consumption reduction for specific configurations, for example different vehicles, fuels, transmissions, micro hybridization, and EM power, however without assuming a consistent starting point. Other studies analyze the saving potential in combination with other fuel saving technologies (Oh et al., 2021). Some studies we examined do not provide sufficient information about the investigated vehicles, such as transmission type or electric machine power (Avolio et al., 2018; Romanato et al., 2018; McKay, 2016; Bassett et al., 2017; Lindemann et al., 2019; Smetana, 2014). While the results of these studies are not directly comparable to each other, they indicate the range of CO<sub>2</sub> emissions reduction achievable with mild hybridization.

Figure 9 summarizes the range of MHEV CO<sub>2</sub> emissions benefits reported in these publications and compares the WLTP estimates with the CO<sub>2</sub> emissions reduction reported by Schaeffler relative to the stop/start baseline. Even though not directly comparable, the data supports that the CO<sub>2</sub> emissions reduction potential increases as the hybrid configuration progresses from P0 to P3, with the largest increase realized when moving from the engine-mounted configurations (P0 and P1) to architectures allowing the decoupling of the EM from the combustion engine (P2 and P3). This is consistent with the reference data from Schaeffler (Eckenfels et al., 2018). Also supporting the results of the Chalmers University study (Melaika et al., 2019), a higher reduction potential in NEDC than in WLTC is reported. This is due to the higher energy available for recuperation on the NEDC, as compared to the total energy demand in each cycle, and to the capability of the EM to handle a larger part of the propulsion power demand (Bao et al., 2017; Bassett et al., 2017; Brown et al., 2016).



**Figure 9.** Summary of CO<sub>2</sub> emissions reduction achieved in NEDC and WLTC for different hybrid architectures, as reported in various studies, compared to Schaeffler WLTC results relative to stop/start baseline.

### 3.1.2 Impact of electric machine power on CO<sub>2</sub> reduction potential

Increasing benefits from increasing EM power is reported by both the Chalmers and Braunschweig Universities studies. The Chalmers University study (Figure 7) showed relatively consistent incremental benefits for increasing EM power up to 15 kW for all configurations (P0, P1, P2, and P3). When increasing EM power from 15 kW to 20 kW, the incremental benefit remained relatively consistent for the P3 configuration but

was smaller for the P2 configuration. The Braunschweig University study results are relatively similar to the Chalmers University results for P0, however the incremental benefits for increasing EM power from 10 kW to 20 kW were much larger for the P2 and P3 configurations (Figure 8). The wider range of EM power examined in the Braunschweig University study suggests that the incremental benefit with increasing EM power drops above 20 kW. For example, when increasing the EM power from 10 to 20 kW in the P3 configuration an additional reduction of 13.3% is achieved, while adding another 10 kW offers only a 2.6% extra benefit. The P4+P0 configuration showed a similar leveling-off above 20 kW, although the P2 configuration benefited somewhat more from EM power up to 30 kW (9.8% benefit from 10 to 20 kW and 4.8% more for 30 kW). Benefits from the P0 configuration did not appear to level off, although they remained very low. In a study by MAHLE and Aeristech on fuel savings via downsizing and mild-hybridization of a D-segment vehicle, it was also shown that increasing the EM power above 20 kW offers reduced benefits in CO<sub>2</sub> emissions (Bassett et al., 2017).

Based on these data and considering only the fuel economy potential, it is clearly preferable to integrate a lower-powered EM with a P2 or P3 configuration, rather than a more powerful EM on the engine (P0/P1), although a high-powered P2 or P3 configuration offers the highest benefits. The preferred architecture and EM power on a vehicle model will likely take into account additional factors, such as cost, complexity, transmission design, and packaging.

### 3.1.3 Reported benefits of mild hybridization in real-world driving

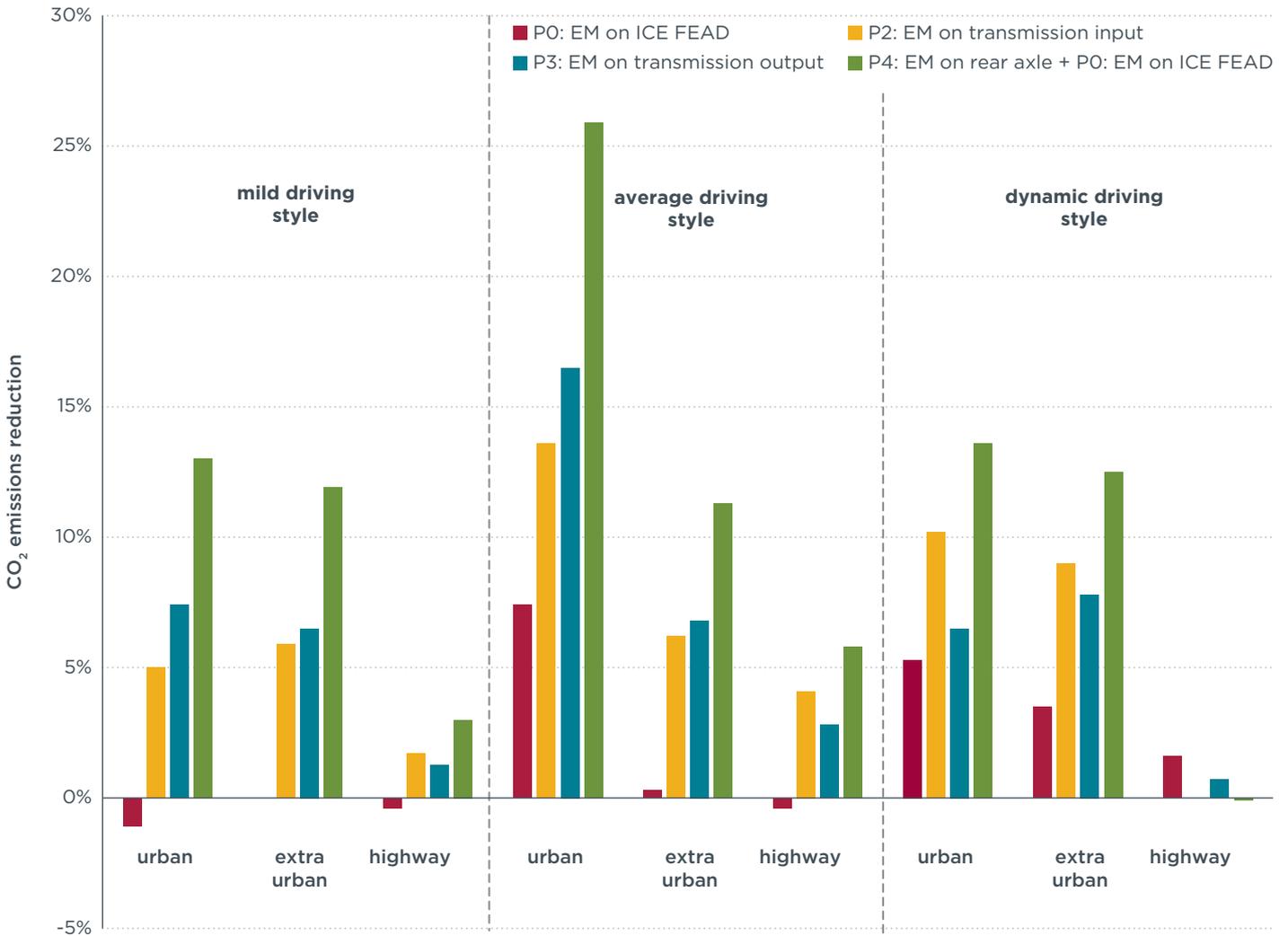
The previously mentioned study from the Braunschweig University also quantifies the fuel saving potential for real world driving using different driving styles for P0, P2, P3, and P4+P0 configurations (Werra et al., 2020), summarized in Figure 10. The greatest benefit is achieved for an average driving style on an urban speed profile. Lower efficiency benefits are generally seen with mild driving styles, which do not allow the exploitation of the full potential of hybridization due to partial load operation and lower recuperated energy. A highly dynamic driving style associated with higher power requirements and vehicle speeds exceeds the capabilities of the electric powertrain components.<sup>6</sup>

For the P0 layout, the study predicts no benefit or even an increase in fuel consumption for mild driving due to the extremely low recuperated energy in combination with the DC/DC converter losses when supplying the 12V circuit with electric energy. A low or even negative effect on efficiency is also expected when driven normally (average driving style) on extra-urban roads and highways or dynamically (aggressive driving style) on the highway. Only under urban conditions when driven normally or dynamically, or under extra-urban conditions when driven dynamically, does this configuration offer significant CO<sub>2</sub> savings.

The benefits of P2 and P3 configurations are similar and much larger than P0, except for during dynamic urban and highway driving. The P4+P0 layout outperforms all other configurations for real-world driving while for WLTC, the P4+P0 benefits are closer to P2 and P3, as shown in section 3.1.1. In general for all configurations and driving styles, the largest hybridization benefit is seen during urban driving and the least during highway driving (Werra et al., 2020).

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<sup>6</sup> Instead of “dynamic” driving style, the term “sporty” is used in the original paper.



**Figure 10.** Impact of driving style under real-world conditions on CO<sub>2</sub> emissions reduction potential for different MHEV topologies (Werra et al., 2020).

### 3.1.4 Manufacturer reported CO<sub>2</sub> emissions reduction

Table 5 summarizes the MHEV model specific CO<sub>2</sub> emissions reduction potential, as reported by manufacturers. The P0 configuration is used in all but one case, likely due to its low cost and limited complexity. In some models, additional 48V technology is integrated (e.g. e-compressor). Detailed system data, such as EM power, are not reported in most instances and values for CO<sub>2</sub> savings are often not comparable as they refer to different or unknown baselines and mostly relate to the outdated NEDC test procedure.

**Table 5.** CO<sub>2</sub> emissions reduction with 48V technologies as advertised by manufacturers.

Manufacturer	Model	Engine	Power [kW]	MHEV system	CO <sub>2</sub> emissions reduction	Source
Audi	S6 S7	2.9l TFSI V6 Gasoline	326	48V PO e-compressor	22% (EPA estimation)	(Audi AG, 2020; Green Car Congress, 2020a)
BMW	320d 520d	2.0l Diesel	120-140	48V PO	4.5% (NEDC) 7.7% (NEDC)	(de Prez, 2020; Dorofte, 2020)
Chevrolet	Orlando	1.4l Ecotec Gasoline	101	48V PO	9%	(GM Corporate Newsroom, 2020; Green Car Congress, 2020b)
FIAT	Panda Hybrid	1.0l 3-cyl. Gasoline	52	48V PO	up to 20%	(FCA Italy S.p.A., 2020)
Ford	Fiesta	1.0l EcoBoost Gasoline	92-114	48V PO	5%	(Ford, 2019; Green Car Congress, 2019a)
Hyundai	Tucson	1.6-2.0l CRDi Diesel	100	48V PO	11% (NEDC)	(Green Car Congress, 2019b; Hyundai, 2019)
Kia	Sportage	1.6l Diesel	100	48V PO	4% (WLTP) 7% (NEDC)	(Groves, 2018)
Mercedes-Benz	S500	6-cyl. Gasoline & Diesel	320	48V P1	22% (NEDC)	(Green Car Congress, 2017)
Range Rover	Evoque	3.0l Ingenium Gasoline	294	48V PO	12% (NEDC)	(Butcher, 2020; Jaguar Land Rover, 2019)
Suzuki	Swift Sport Vitara S-Cross	1.4l Gasoline	95	48V PO	15% (WLTP)	(de Prez, M., 2019; TESTDRIVEN, 2019)
Volvo	XC90 XC60 XC40	2.0l Gasoline & Diesel	145-220	48V PO	up to 15% (real world)	(Green Car Congress, 2020c; Volvo Cars, 2020a, 2020b)
VW	Golf eTSI	1.0l TSI 1.5l TSI ACT Gasoline	80-110	48V PO	10% (WLTP)	(Green Car Congress, 2019c; Helbing et al., 2020)

### 3.2. POLLUTANT EMISSIONS REDUCTION POTENTIAL OF MILD HYBRID VEHICLES

While the main target of mild hybridization is the reduction of CO<sub>2</sub> emissions and fuel consumption, this technology also offers possibilities for pollutant emissions reduction. The technologies enabled by the 48V technology and their pollutant and CO<sub>2</sub> reducing effects are listed in Table 6 and are discussed in this section. Both beneficial and adverse effects on CO<sub>2</sub> emissions may appear from these auxiliary technologies, strongly depending on the calibration and control strategy of the complete system (Avolio et al., 2018; Lindemann et al., 2019; Netterscheid et al., 2020).

**Table 6.** Overview of 48V technologies and mechanisms that affect pollutant and CO<sub>2</sub> emissions.

Technology	Impact on pollutant emissions	Impact on CO <sub>2</sub> emissions
<b>Hybrid functions</b>	<ul style="list-style-type: none"> <li>• Reduction of raw (engine-out) emissions during transient operation</li> <li>• Zero emissions during limited pure electric drive (e-launch/e-drive)</li> <li>• Reduction of brake particle emissions via regenerative braking</li> </ul>	<ul style="list-style-type: none"> <li>• No negative impact</li> </ul>
<b>Electrically assisted air charging (e-compressor/e-turbo)</b>	<ul style="list-style-type: none"> <li>• Reduction of emissions overshoot in transients</li> <li>• EGR range extension and optimization</li> <li>• Enable catalyst before T/C</li> </ul>	<ul style="list-style-type: none"> <li>• Reduced pumping work via electric boosting during transients</li> <li>• Increased low-end torque</li> <li>• Recuperation from T/C (e-turbo)</li> </ul>
<b>Electrically heated catalyst (EHC)</b>	<ul style="list-style-type: none"> <li>• Catalyst pre-heating for faster light-off after cold start</li> <li>• Maintain catalyst temperature when ICE is shut-off or operates at low load</li> </ul>	<ul style="list-style-type: none"> <li>• Impact dependent on calibration of hybrid functions and catalyst control strategy</li> </ul>

**Hybrid functions.** The torque assist function (see section 2.1.4) reduces peak engine loads and combustion temperatures. Therefore, less nitrogen oxides (NO<sub>x</sub>) and particulates are formed in the engine. Regenerative braking reduces friction brake particle emissions and extends the lifetime of the discs/drums and brake pads/shoes (Benajes et al., 2019; Bosch Mobility Solutions, 2020; Nica, 2020), although component rust and corrosion due to limited use may be experienced as an adverse effect (Discover EV, 2020). These pollutant emission reductions have no negative impact on the efficiency benefits described in Section 3.1.

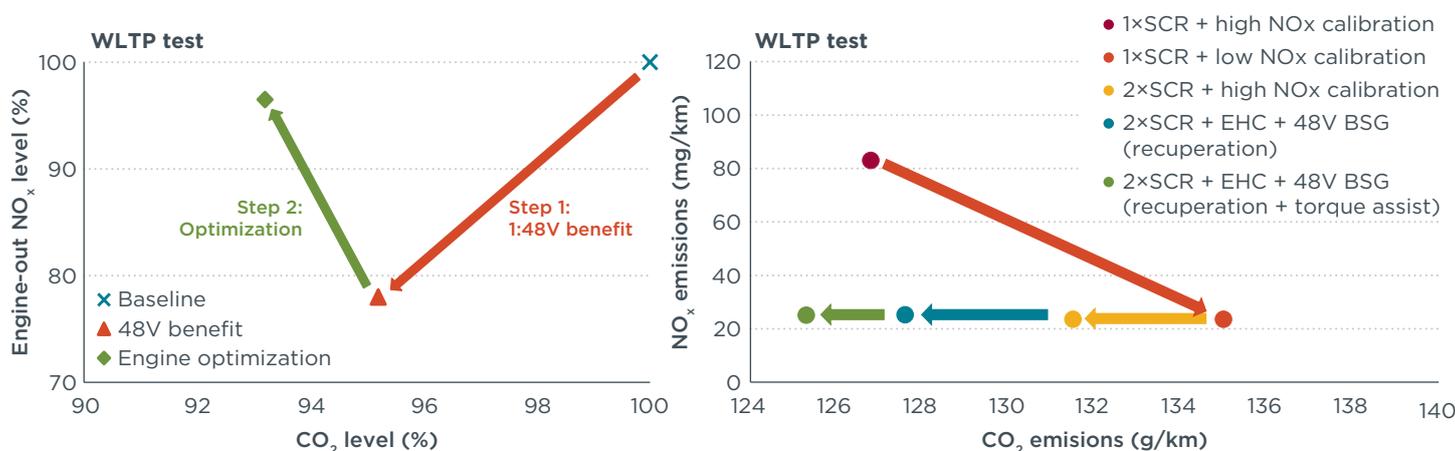
**Electrically assisted air charging.** Electrically assisted air charging (e-compressor/e-turbo), supported by the 48V system, improves engine transient response and reduces turbo lag (Romanato et al., 2018). This limits engine-out NO<sub>x</sub> and particulate emissions during acceleration from low engine speed. The additional transient boost and faster boost pressure control also enables exhaust gas recirculation (EGR) in engine operating areas where it was not possible and extends the rate of low pressure EGR in engines with dual loop recirculation systems (Schaub et al., 2017). An additional possibility that substantially improves tailpipe emissions is the installation of the exhaust after-treatment system upstream of the conventional turbocharger, resulting in faster catalyst light-off (Lindemann et al., 2019; Schönen et al., 2019). In this setup, the electric machine compensates for the boost pressure build-up lag, caused by the pressure drop and exhaust gas temperature loss across the catalyst before reaching the turbocharger (Angerbauer et al., 2020; Beidl et al., 2020). No adverse effects on fuel consumption are expected.

**Electrically heated catalyst.** The energy consumption of an EHC comes with a fuel penalty, but it eliminates the need for engine-based heating of the exhaust gas and the associated fuel consumption (Gao et al., 2019). A particularly beneficial feature of the EHC is the possibility for catalyst pre-heating before the engine start (Kapus et al., 2019; Ye et al., 2019). An EHC is considered a standard component to fulfill future emissions standards for both light- and heavy-duty vehicles (Bennet & Auld, 2020; Hopwood & Shalders, 2020; Laurell et al., 2019).

Two specific examples of the positive effects of mild hybridization combined with e-compressor and EHC are illustrated in Figure 11. The left diagram of Figure 11 illustrates the CO<sub>2</sub> benefits through a two-step optimization approach (Romanato et al., 2018). The introduction of a 48V PO MHEV system in Step 1 results in a simultaneous

reduction of CO<sub>2</sub> emissions by 4.8% and engine-out NO<sub>x</sub> levels by 22%. To yield maximum CO<sub>2</sub> reductions, the engine is recalibrated in a second step, resulting in another 2% reduction in CO<sub>2</sub> emissions while increasing the engine-out NO<sub>x</sub> level back close to the original level. In total, a 6.8% efficiency improvement was gained while keeping NO<sub>x</sub> emissions 3.5% below the baseline level.

The right diagram of Figure 11 illustrates how Continental followed a series of steps to offset the CO<sub>2</sub> emission increase of 3.5% caused by a second selective catalytic reduction system, which was added to achieve a 70% reduction in tailpipe NO<sub>x</sub> emissions (Avolio et al., 2018). For that purpose, Continental applied a 48V P0 MHEV system together with an EHC and a recuperation strategy. This technology package compensated for most of the CO<sub>2</sub> penalty already. To further improve the efficiency, the torque assist function was calibrated, resulting in an overall CO<sub>2</sub> emissions reduction of 1.8% compared to the baseline while reducing the tailpipe NO<sub>x</sub> emissions by 70% to 25 mg/km in WLTP.



**Figure 11.** Simultaneous CO<sub>2</sub> and NO<sub>x</sub> emissions reduction enabled by 48V technologies. Data derived from Romanato et al. (2018) (left side) and Avolio et al. (2018) (right side).

Table 7 summarizes literature reported effects of introducing 48V technologies and the additional emissions control system technologies enabled by the 48V system on pollutant emissions and the associated consequences on fuel consumption.

**Table 7.** Reported impact of mild hybridization on pollutant and CO<sub>2</sub> emissions.

<b>Impact on pollutant emissions</b>	<ul style="list-style-type: none"> <li>• <b>NO<sub>x</sub></b>: 28.6% tailpipe reduction in WLTC, down to 2 mg/km in WLTC, 36 mg/km in TfL, 17 mg/km in BAB130, 22 mg/km in RDE</li> <li>• <b>HC</b>: 56% tailpipe reduction in WLTC, down to &lt;50 mg/km in real-world driving conditions</li> <li>• <b>HC+NO<sub>x</sub></b>: 83% tailpipe reduction in first 60 seconds of FTP</li> <li>• <b>CO</b>: 22% engine-out reduction in WLTC, &lt;500 mg/km in real-world driving conditions</li> <li>• <b>Soot</b>: 36% engine-out reduction in WLTC</li> </ul>
<b>Consequences on fuel consumption / CO<sub>2</sub> emissions</b>	<ul style="list-style-type: none"> <li>• Impact dependent on calibration of hybrid functions and catalyst control strategy</li> <li>• Reduction up to 19%</li> <li>• Penalty ~1.5%</li> </ul>

Sources: Avolio et al. (2018); Benajes et al. (2019); Lindemann et al. (2019); Netterscheid et al. (2020); Romanato et al. (2018); Schönen et al. (2019); Wancura et al. (2019); Ye et al. (2019).

## 4. MILD-HYBRID SYSTEM TECHNOLOGY COST

Mild-hybrid systems require smaller electric machines and batteries than full hybrid electric vehicles, since they are not designed to autonomously power the vehicle for longer distances. Furthermore, keeping the system voltage below the 60V lethal threshold significantly reduces the need for complex safeguard measures (Serrarens, 2015). Therefore, the cost of mild-hybrid systems is significantly lower than for full hybridization.

Toyota introduced its input powersplit, full-hybrid technology in the European Union and United States in 2000 and has improved its system with each new generation. However, most manufacturers that have only recently started production of hybrid vehicles have opted for mild-hybrid systems. Due to the relatively early stage of development and the multitude of potential system designs, an assessment of the current and future mild-hybrid system cost is difficult (German, 2015). This chapter estimates the system cost and analyzes the main factors for future cost reductions.

### 4.1. EFFECTS OF ECONOMICS OF SCALE ON COST

Costs for development and tooling constitute a large portion of the total vehicle manufacturing cost. Therefore, increasing the number of vehicles using one technology, also referred to as the platform approach, substantially reduces the manufacturing cost per vehicle. Only large-scale production costs estimates are presented in this chapter in order to make them comparable, but economics of scale are an initial barrier to the introduction of any new technology and initial cost for low-volume vehicles is much higher.

### 4.2. HISTORICAL COST ESTIMATES AND OBSERVED LEARNING EFFECTS OVER TIME

“Tear-down” studies, for which the total cost of the technology is calculated by accumulating the cost of individual system components and their assembly, are often used to derive technology cost estimates. In 2009, U.S. EPA began contracting with engineering service provider FEV for tear-down cost studies, including a cost study of a 2010 Ford Fusion with an input powersplit hybrid system. FEV also used this as basis to estimate costs for a P2 hybrid system (U.S. EPA & NHTSA, 2012) and the agencies scaled the teardown data to estimate the cost of a 110V P0 (BSG) system. Their direct manufacturing cost estimates for the hybrid components in 2012 for a 2010 standard-size U.S. car were \$3,139 for a powersplit hybrid, \$2,463 for a P2 hybrid, and \$1,087 for a 110V P0 hybrid.

To obtain cost estimates for the European market, ICCT contracted with FEV to update and extend the U.S. hybrid component cost estimates to Europe (Kolwich, 2012; Kolwich, 2013). In addition to adjusting the U.S. P2 and power-split results for EU production costs, FEV revised the battery technology to Li-ion instead of NiMH for power-split and P2 hybrids, and added a tear-down assessment of the 36V P0 mild hybrid system from the 2007 compact SUV Saturn Vue using a NiMH battery. The hybrid costs were scaled to six different vehicle types, representative of most vehicles sold in Europe.

FEV estimated the 2010 EU manufacturing costs for mild hybridization to be 1,175 EUR for a large car (e.g. VW Passat), whereas the manufacturing cost for a full hybrid system is almost twice as high, as shown in Table 8.

**Table 8.** FEV hybrid technology manufacturing costs for a 2010 production EU large car, assuming a production volume of 450,000 units.

	Power-split hybrid	P2 hybrid	P0 hybrid (BSG)
Power transmission/clutch system	€434	€214	—
Integrated electric machine/ generator/ sensors/ controls	€1,084	€482	€351
Battery Subsystem	€982	€982	€576
Electricity power distribution, inverters/ converters	€271	€271	€83
Brake, body, climate control systems	€329	€329	€41
Transmission, engine, service battery, alternator	(€869)*	(€197)	€124
<b>Total</b>	<b>€2,231</b>	<b>€2,081</b>	<b>€1,175</b>

\*Values in parenthesis are cost savings

ICCT contracted FEV again in 2014 for a study focusing on five improvements in the electric machine/generator, clutch assembly, and system integration of a P2 hybrid system from 2010 to 2013 (Lefief, 2014), summarized in Table 9. The total cost reduction from 2010 to 2013 was estimated to be €103 for a mid to large P2 full hybrid passenger vehicle. This represents a cost reduction of approximately 15% over three years, or roughly 5% per year, relative to the 2010 cost estimates for the electric machine/generator and clutch assembly of €696.

**Table 9.** FEV estimated cost reductions from 2010–2013 for selected P2 hybrid subsystems.

Improvement	Benefit	Savings
Better integration of electric machine and clutches	Smaller case	€19
Improvements in clutch design	Elimination of clutch hydraulic system	€9
Development of oil accumulator	Eliminated need for auxiliary oil pump	€19
More efficient electric machine	Downsized traction motor	€26
Expand engine cooling system capacity and electric pump	Replaced separate hybrid cooling system	€30
<b>Total</b>		<b>€103</b>

The ICCT also commissioned FEV to include a detailed assessment of 48V P0 hybrid costs for small and medium cars in the EU (Blanco-Rodriguez, 2015). The results of this assessment are shown in Table 10. Compared to the 2010 estimates, FEV increased P2 system voltage from 188V to 350V, increased the Li-ion battery capacity from 0.99 to 1.1 kWh, and did not include a credit for engine downsizing. Despite these changes, the overall P2 cost estimate dropped from €2,081 to €1,945. For P0 mild hybrids, FEV increased the system voltage from 36V to 48V, changed the battery type from NiMH to Li-ion, and decreased the battery capacity from 0.66 to 0.53 kWh (in recognition of the higher power density of Li-ion). The updated 48V P0 cost estimate dropped from €1,175 to €761, or by about a third. Relative to the cost of a P2 full hybrid system, the cost of the MHEV P0 technology dropped from 57% in the earlier analysis to approximately 40%.

**Table 10.** FEV hybrid technology manufacturing costs for 2015 production EU midsize car, assuming 450,000 production volume.

	P2 hybrid	P0 hybrid	Stop/start
Vehicle example	Segment D	Segment C	Segment C
ICE power [kW]	110	80	80
Electric machine power [kW]	35	15	---
Battery capacity [kWh]	1.10	0.53	---
Battery voltage [V]	350	48	12
Battery type	Li-ion	Li-ion	AGM
Costs*			
Battery	€610	€375	€13
Transmission	€220		
ISG, PowerUnit, Converter (P2)	€980		
BSG (P0) / Starter (stop/start)		€250	€20
Converter		€125	
HV wiring, HCU/VCU, electric A/C	€315		
Brake, Tensioner, Pulley, Belt		€65	
Sensors			€36
Alternator:	(€60)	(€54)	€10
Starter, Auxiliary drive:	(€120)		
<b>Total</b>	<b>€1,945</b>	<b>€761</b>	<b>€79</b>

Note: Values in parentheses are savings, i.e., negative cost.

Suppliers provided hybrid cost estimates as part of a joint ICCT/supplier technical working paper series (Isenstadt & German, 2016). The ITB group, an automotive consulting company, provided cost estimates for four different hybridization levels, shown in Table 11. The 48V P0 cost estimate was about \$800, in line with the 2015 FEV findings and only about 25% of the cost of a full-hybrid system. Without providing dollar amounts, IDTechEx also estimated 48V hybrid cost was 25% of the cost of a full-hybrid system (Das, 2015) and Delphi estimated the cost was 30% of a full-hybrid system (Kendall, 2015). Valeo found a 48V hybrid system should have a direct manufacturing cost of less than \$1,000 (Vint, 2014). Overall, the estimated incremental cost for 48V hybrid systems in the technical working paper was \$600-\$1,000. This is significantly lower than the EPA 2012 estimate of \$1,087 for a 110V mild hybrid and is also slightly less than the 2015 FEV estimate for Europe of €761.

**Table 11.** ITB Group estimates of hybridization costs.

2020 Cost Estimates (\$)	Micro hybrid	48V P0	48V-P0 e-boost	48V P2 e-boost	Full hybrid
Electric machine power Battery capacity		8-10 kW 320 Wh	10-15 kW 450 Wh	15-20 kW 700 Wh	Prius
<b>Total Cost (\$)</b>	275	800	1200	1350	3200

Note: Total cost includes the battery, motor, and power electronics.

As part of its mid-term review for the 2022-2025 standards, EPA updated its hybrid cost estimates in 2016 (U.S. EPA, 2016). The updated estimate of direct manufacturing cost for 2017 model year 48V hybrid systems was \$724, or \$314 for the battery pack and \$410 for all other components, continuing the downward trend in 48V hybrid cost estimates over time.

Table 12 summarizes the cost reduction estimates by EPA and FEV for full- and mild-hybrid systems. Being a mature technology with high sales in the United States by 2010, full hybrid systems show an annual compound cost reduction of approximately 1.5% over 7 years in the United States and 5 years in Europe. The annual percent cost reductions for mild-hybrid systems are four to six times higher, 5.6% (U.S.) and 8.3% (EU), illustrating that MHEVs are at much earlier stages of learning and economics of scale.

**Table 12.** Summary of U.S. and EU hybrid system costs over time.

Source	Model Year	US		Europe	
		Full hybrid	PO hybrid	P2 hybrid	PO hybrid
EPA 2012	2010	\$ 3,139	\$ 1,087		
FEV 2013	2010			€ 2,081	€ 1,175
FEV 2014	2013			€ 1,975	
FEV 2015	2015			€ 1,945	€ 761
EPA 2016	2017	\$ 2,826	\$ 724		
Absolute cost reduction*		\$ 313	\$ 363	€ 135	€ 415
Relative cost reduction*		10.0%	33.4%	6.5%	35.3%
Annual compound cost reduction*		1.5%	5.6%	1.3%	8.3%

\* Comparing model year 2017 to 2010 in the United States; Comparing model year 2015 to 2010 in Europe.

The MHEV annual cost reductions are consistent with values observed for the early generations of Toyota’s powersplit full hybrid. The 2015 ICCT hybrid technology report showed that Toyota achieved about a 5% annual cost reduction from 2001 to 2011 for their full-hybrid system. As P2 hybrids were introduced much more recently and 48V systems are just starting to reach the market in high volume, annual cost reductions of about 5% should be expected for mild-hybrid technology from 2015 to at least 2020 or 2025.

### 4.3. EXPECTED COST REDUCTION THROUGH FUTURE LEARNING EFFECTS

This section forecasts future learning and cost reduction based on the estimates in section 4.2. In addition, EPA has explicitly forecasted future cost learning in its rulemakings and Ricardo and AVL have estimated costs out to 2030, from which their estimated future learning can be calculated.

EPA included a learning curve to estimate direct manufacturing costs for 48V hybrid batteries from 2017 to 2025 in their 2016 Technical Support Document for the Proposed Determination (U.S. EPA, 2016). Shown in Table 13, EPA estimated an average annual compound cost decrease for 48V hybrid batteries of 4.8% from 2017 to 2025. The annual learning cost reduction is estimated to diminish over time, starting at 9.6% from 2017 to 2018 and decreasing to 2.8% from 2024 to 2025.

**Table 13.** EPA estimated direct manufacturing costs for MHEV 48V Battery.

Year	2017	2018	2019	2020	2021	2022	2023	2024	2025
48V battery production cost	\$314	\$284	\$265	\$251	\$240	\$231	\$223	\$217	\$211
Annual cost reduction		9.6%	6.7%	5.3%	4.4%	3.8%	3.5%	2.7%	2.8%

In a 2016 study for the European Commission, Ricardo provided estimated cost data for 48V hybrid systems for 2015 and projected costs for 2020, 2025, and 2030 (Ricardo, 2016). The study estimates direct manufacturing costs for the entire mild-

hybrid system of a lower-medium car at €1,184 for 2015, €869 for 2020, €750 for 2025, and €674 for 2030. The results implicitly estimate a diminishing reduction of direct manufacturing cost over time, with a compound average cost drop of 6.0% per year from 2015 to 2020, 2.9% per year from 2020 to 2025 and 2.1% per year from 2025 to 2030. Ricardo's system learning factors are lower than EPA's battery pack learning factors.

In 2020, AVL provided projected system cost data generated in 2018 for 2020, 2025, and 2030 48V hybrid systems. The cost was calculated for six different system configurations and broken down by five different components. For the P0 configuration comparable to the systems analyzed by EPA and FEV, AVL estimates direct manufacturing costs of €637 in 2020, €547 in 2025, and €492 in 2030. This corresponds to an average annual cost reduction, which can be considered as an annual learning factor of 3.0% between 2020 and 2025 for the entire system, with 2.5% for the battery pack and 3.3% for the non-battery components. Similar to Ricardo and EPA, AVL assumes a diminishing annual learning factor of 2.1% between 2025 to 2030 (1.9% for the battery pack, 2.2% for non-battery components). Overall, the AVL and Ricardo learning factors are almost identical. AVL's learning factors for a P1 coaxial system and a P3+P0 system were similar to their P0 system estimates, while P2 systems with larger motors and battery packs had slightly lower learning factors, and a P4+P0 system had slightly higher learning factors.

Toyota achieved cost reductions due to learning and increased production volume of about 5% per year for several generations of the Prius. As the Prius introduced in the United States in 2001 was actually the second generation (the first generation was sold only in Japan), 48V mild hybrid development and sales in 2015 were roughly equivalent to the Prius in 2001, implying that mild hybrid annual cost reductions due to learning and higher sales should average about 5% out to roughly 2025. However, to be conservative, for this analysis we are adopting the Ricardo estimated annual learning factors of 6.0% from 2015 to 2020, 2.9% from 2020 to 2025 and 2.1% from 2025 to 2030. Ricardo's estimates are not only lower than EPA's and AVL's, they also drop to only 2.9% per year after 2020, much earlier than estimated from Toyota's experience with the Prius.

#### **4.4. EFFECT OF HYBRID SYSTEM TECHNOLOGY IMPROVEMENTS ON FUTURE COST**

A number of mild-hybrid system improvements are likely in the near future, especially as rising sales allow development costs to be spread over more vehicles.

An important development with the potential to reduce future costs is cold cranking the engine with the 48V battery. As proposed by A123,<sup>7</sup> further improvements to the 48V battery will allow it to support cold cranking the engine with the EM, allowing the elimination of the 12V starter motor and the 12V battery on P0, P1, and P2 configuration hybrids (Duren, 2017).

There are also potential opportunities to reduce P2 configuration system costs by fully integrating a standard electric machine into the transmission. This would allow for increased synergies regarding casings, lubricating, and coolant systems, reducing the cost of having separate components for the hybrid systems. Another potential cost reduction would be to drive the A/C compressor with the hybrid traction motor instead of using a separate motor, a technology that is already offered by BorgWarner for P2 hybrid systems (BorgWarner Inc., n.d.). Because none of these improvements existed when the tear-down cost analyses were done, none are currently incorporated into mild hybrid cost projections.

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<sup>7</sup> A123 Systems is a wholly owned subsidiary of the Chinese Wanxiang Group

The higher electric power availability of 48V systems can also reduce the cost of adding other technologies. While we have not included these potential cost reductions in our analysis as they are difficult to quantify, it is important to at least acknowledge that mild-hybrid system cost analyses do not include the potential cost synergies and, therefore, the achievable cost reduction is likely higher than the analyses suggest. Possible examples include:

- » 48V hybrid systems can deliver the power needed for an electric machine integrated within the turbocharger or a separate electric compressor.
- » 48V hybrid systems can be used to replace conventional AWD systems with a second electric machine on the non-drive axle, enabling part-time AWD with higher efficiency at modest cost. AVL estimated the cost difference between a front-wheel drive vehicle and AWD to be €560.<sup>8</sup> When instead enabling partial all-wheel drive by adding an EM on the rear axle (P4), the cost would only be €283 higher than for the mechanical AWD vehicle, while allowing more mild-hybrid functionalities and a better vehicle efficiency.
- » P2, P3, or P4+PO hybrid configurations can provide the torque needed for vehicle launch, allowing the torque converter to be removed from automatic transmissions.

#### **4.5. EFFECT OF AN INCREASE IN BATTERY POWER DENSITY ON FUTURE SYSTEM COST**

Sections 4.2 and 4.3 evaluated the impact of learning on overall hybrid system costs, including battery costs. However, the power density of the battery cells also affects hybrid battery size and cost. Battery cell development has been driven by the high energy storage capacity needs of BEV and PHEV applications. In MHEVs, batteries with a comparably low storage capacity can be used, as energy charged during recuperation is usually consumed during the next acceleration. At the same time, the MHEV battery needs to rapidly store the energy generated by high power during deceleration events. The high energy cells used in BEVs and PHEVs are not well suited for this application. Thus, battery cell manufacturers are developing Li-ion chemistries with higher power density, which will enable mild hybrid batteries with lower size and energy capacity while maintaining acceleration and energy recuperation performance. This reduction in battery size and cost is not reflected in the cost studies referenced above.

The latest FEV teardown analysis was conducted on a 2015 PO 48V hybrid system with a 15-kW motor and a 0.53 kWh battery pack, resulting in a power to energy ratio of about 28 kW/kWh. The company A123 Systems has developed a battery optimized for higher power density using lithium iron phosphate (LFP) cell chemistry instead of nickel manganese cobalt (NMC) (A123 Systems, 2016). The battery has a power to energy ratio of over 40 kW/kWh, which means a battery of only 0.36 kWh capacity can provide a peak power of 15 kW. In addition, LFP does not use any cobalt and does not need active cooling for most applications due to very low impedance, both further reducing cost. In November 2019, Mahle Powertrain announced a new 48V hybrid battery using lithium titanate (LTO) chemistry to boost power output. Their new battery also achieves a peak power to energy ratio of 40 kW/kWh (MAHLE GmbH, 2019).

#### **4.6. INDIRECT COSTS**

The cost estimates from FEV discussed in the previous sections are direct manufacturing costs, which are essentially the total capital and variable costs of the

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<sup>8</sup> Cost of components needed to convert a front wheel driven vehicle to AWD: Transfer case, cardan shaft and differential

technology to the vehicle manufacturer. Such costs do not include various indirect expenses that are included in the vehicle price charged to the consumer, such as warranty, research and development, corporate overhead, and sales and distribution costs. Indirect cost factors were developed by the EPA for their 2017–2025 U.S. light-duty vehicle greenhouse gas standards rulemaking (U.S. EPA & NHTSA, 2012), shown in Table 14. These indirect cost multipliers (ICM) vary with the current state of development and complexity of an associated given technology. For mild hybrids, EPA estimated that the battery was at a relatively early stage of development and assigned it therefore a “High-1” ICM complexity, while the non-battery components were classified as “Medium”. This results in a higher near- and long-term ICM for the battery than for the non-battery components. For the battery, the near-term ICM is applied out to 2024 while the switch to long-term ICM is expected after 2018 for the non-battery components.

**Table 14.** 48V hybrid indirect cost multipliers (ICM).

	ICM complexity	Near term period end	Near term ICM	Long term ICM
<b>Battery</b>	High 1	2024	1.564	1.345
<b>Non-Battery Components</b>	Medium	2018	1.387	1.290

#### 4.7. COST PROJECTIONS FOR THE PO ARCHITECTURE UNTIL 2030

The historical data, trends, and forecasts presented above can be used to estimate future 48V hybrid system costs for 2025 and 2030. Ricardo, AVL, and FEV have all conducted cost estimates for 48V hybrid systems in Europe, so the first step is to evaluate which data to use.

Ricardo and AVL both provided projected costs for 2020, 2025, and 2030. The modest learning factors of 2.9%–3% applied from 2020 to 2025 and 2.1%–2.2% from 2025 to 2030 indicate that no significant technology improvements to the 48V hybrid system from 2020 to 2030 were assumed. However, as discussed in Sections 4.4 and 4.5, smaller, higher power density battery packs and the ability to drive the A/C compressor by the hybrid motor are already being offered by suppliers. Thus, the Ricardo and AVL cost projections for 2025 and 2030 can be considered a conservative estimate.

FEV estimated direct manufacturing costs of €761 for a 2015 C-segment PO BSG with a 15-kW motor and 0.53 kWh battery pack. To compare this directly with the AVL and Ricardo 2020 cost estimates, shown in Table 15, Ricardo’s annual compound learning factor of 6.0% from 2015 to 2020 is applied to FEV’s 2015 direct manufacturing cost; note that the Ricardo learning factor is lower than EPA’s battery pack learning factors for this period. This results in an FEV cost estimate adjusted to 2020 of €558. AVL estimated 2020 costs for a PO system with a smaller 12 kW motor and 0.4 kWh battery pack to be €637. AVL provided battery cost estimates of €250 for a 0.4 kWh pack and €430 for a 0.8 kWh pack—prorating these estimates to match the FEV battery size of 0.53 kWh yields a battery cost of €309 and a total PO system cost of €696. Ricardo estimated 2020 costs for a not further defined MHEV system in a lower medium car to be €869.

The FEV (€275 after learning) and AVL (€309) cost estimates for a 0.53 kWh battery pack in 2020 were similar. However, AVL’s 2020 non-battery costs were €387, while FEV’s 2020 non-battery costs were substantially lower at €283 after applying 6.0% annual learning from 2015 to 2020.

**Table 15.** Comparison of PO system direct manufacturing cost adjusted to 2020 based on FEV, AVL and Ricardo studies.

Year: 2020	FEV PO, 15 kW, 0.53 kWh	Ricardo Vehicle not defined	AVL PO, 12 kW, 0.53 kWh
<b>Total system cost</b>	558	869	696
<b>Battery cost</b>	275	N/A	309
<b>Non-battery cost</b>	283	N/A	387

AVL and FEV provided more detail about their hybrid systems than Ricardo and, unlike Ricardo, both of their cost estimates are based upon tear-down assessments. In addition, the FEV and AVL cost estimates were closer to each other than either was to Ricardo. For the following cost analyses, FEV numbers are used because their tear-down cost methodology and data have been published in a series of public reports and was scrutinized in EPA rulemakings. However, it should be noted that using the average FEV and AVL costs would increase the MHEV system costs by only about 12% compared to using the FEV numbers alone.

Table 16 shows the results of our cost projections based on the FEV 2015 data through 2030. As discussed above, we determined the 2020 baseline by applying the Ricardo annual learning factor of 6% to the 2015 data. After 2020 there are likely to be many improvements in the MHEV system design, as discussed above, although we conservatively include only higher power density batteries and elimination of the 12V starter and battery in our cost analysis.

The 2015 FEV battery has a power-to-energy ratio of 28 kW/kWh while the latest batteries yield ratios of 40 kW/kWh. The battery size was adjusted to the higher power density by multiplying the 0.53 kWh with 28/40, resulting in a battery pack size of 0.37 kWh with the same power output. While the cost per kWh is likely to increase for a higher power density battery, this is offset by the fact that neither LFP nor LTO contain cobalt and further improvements in power density above 40 kW/kWh are likely. We therefore assumed constant cost per kWh, which results in a battery pack cost reduction from €275 to €192.

The second adjustment assumes that further improvements to mild hybrid batteries will allow the 48V battery to support cold cranking the engine with the EM, discussed in Section 4.4, allowing the elimination of the 12V starter motor and the 12V battery. FEV's 2015 report estimated the related cost savings of eliminating the 12V starter to be €55, which reduces to €40 after applying the 6% annual learning from 2015 to 2020. FEV did not estimate the cost of the conventional 12V battery. Omitting the savings from the 12V battery makes the €40 cost reduction in 2020 conservative and is expected to cover any additional improvements of the 48V battery or DC-DC converter required to eliminate the 12V battery.

The last step is to apply learning to the 2020 cost estimates. As discussed in section 4.2, Ricardo's mild hybrid learning factors are lower than EPA's and slightly lower than AVL's, plus their learning rates drop faster than Toyota was able to sustain on the Prius. Thus, the use of Ricardod's learning rates is conservative.

To estimate the total retail-level costs, indirect cost multipliers as described in section 4.6 are applied to the direct manufacturing cost.

**Table 16.** Hybrid cost projections through 2030 of a 48V PO BSG with 15 kW electric machine for a baseline vehicle without stop/start.

Cost reduction effect	Year	Annual learning*	Direct Manufacturing Cost			Total Cost with ICM
			Battery	Non-battery	Total	Total
Baseline with 0.53 kWh battery	2015		€ 375	€ 386	€ 761	€1,122
Learning 2015-2020	2020	6.0%	€ 275	€ 283	€ 558	€ 796
Higher battery power to energy ratio and elimination of 12V starter	Adjusted for post-2020 tech		€ 192	€ 243	€ 435	€ 614
Learning 2020- 2025	2025	2.9%	€ 166	€ 210	€ 376	€ 494
Learning 2025-2030	2030	2.1%	€ 149	€ 189	€ 338	€ 444

\* Learning factors from Ricardo study

Note: Separate indirect cost multipliers (ICM) adjustments from Table 14 were applied to battery and non-battery direct manufacturing costs.

#### 4.8. SYSTEM COST AND COST PER CO<sub>2</sub> REDUCTION FOR DIFFERENT MILD HYBRID ARCHITECTURES

The FEV data used for the 2030 mild hybrid cost projections contained detailed estimates for PO mild hybrids but no data for other mild hybrid architectures. Therefore, the data provided by AVL is used to make these adjustments, as AVL included cost estimates for six different 48V hybrid systems architectures for 2020, 2025, and 2030. Table 17 presents the ratio of estimated 2020 system cost for five different mild-hybrid configurations relative to a front wheel driven PO vehicle, based upon the AVL data. Not surprisingly, the PO configuration comes at the lowest cost, followed by the P1 configuration. And as expected, the P4+PO is the most expensive option due to the presence of two electric motors with the highest system power and more complex wire harness and controls. On the other hand, it also allows some all-wheel drive functionality while all other concepts only power a single axle. The added cost for hybridization when converting a conventional AWD to a P4+PO is only 44% higher than for a PO-only system due to savings in the mechanical parts of a conventional AWD powertrain.

**Table 17.** 2020 hybrid configuration cost indexed to PO architecture, based on AVL data.

Architecture	Motor power	Battery capacity	Cost indexed to PO		
			Battery	Non-battery	Total
PO	12 kW	400 Wh	1.00	1.00	1.00
P1 coaxial	12 kW	400 Wh	1.00	1.41	1.25
P2 side mounted	20 kW	800 Wh	1.72	2.05	1.92
P2 coaxial	20 kW	800 Wh	1.72	2.24	2.03
P3+PO	12 kW + 4kW	800 Wh	1.72	2.34	2.10
P4+PO vs. FWD	20 kW + 4kW	800 Wh	1.72	2.71	2.32
P4+PO vs. AWD	20 kW + 4 kW	800 Wh	1.72	1.27	1.44

The relative cost effectiveness of the different hybrid architectures was determined by comparing the system cost provided by AVL with the CO<sub>2</sub> reduction potential determined by Schaeffler (Figure 6). Since the hybrid system configurations deviated between the two data source, adjustments were necessary to make the data comparable:

- » AVL assumed a battery size of 800 Wh for P2 through P4 system, that is twice the size as used for P0 and P1, while Schaeffler assumed a fixed battery size of 1,400 Wh for all systems. To align the AVL and Schaeffler assumptions while minimizing the potential error introduced by scaling, we used the 800 Wh battery cost provided by AVL for all configurations.
- » AVL assumed a P3+P0 system and, therefore, added the cost of a micro-hybrid system (4 kW P0) to the P3 cost. According to ITB, stop/start systems are about one third the cost of a P0 system (Table 15). Thus, the P3+P0 non-battery cost is reduced by one third of the AVL 2020 P0 total system cost, to estimate the cost of a P3-only system.
- » Schaeffler assumed an EM power of 15–16 kW for all architectures, while EMs with different power were considered in the AVL cost analysis. The AVL electric drive unit (EDU) cost, which contains the EM, was adjusted based on the P0 costs, as the P0 EDU cost is mainly EM cost. Therefore, for all architectures we scaled the P0 EDU cost by motor power and added the EDU cost offset between the original and adjusted motor power to the EDU cost of the respective architecture.
- » Schaeffler determined the CO<sub>2</sub> reduction potential for the different mild-hybrid system architectures against a FWD vehicle as baseline, except for the P4+P0 layout which was also compared to an AWD vehicle because of the added AWD functionality a P4+P0 system provides. AVL considered for their cost analysis an AWD vehicle as baseline. For this analysis we assume that the additional cost for adding P0, P1, P2 and P3 mild hybrid functionality is the same for an FWD and AWD vehicle. For analyzing the cost for adding a P4+P0 system to an FWD vehicle, we assumed the same cost as for converting a mechanical AWD vehicle to a P4+P0 mild hybrid vehicle minus the cost savings related to removing components no longer required for the mechanical AWD functionality.

Based on the adjusted cost, the cost per percentage point CO<sub>2</sub> reduction was calculated for each architecture. Table 18 shows the result of this calculation normalized to the cost and CO<sub>2</sub> reduction for a P0 vehicle. The analysis reveals that, even though it is the cheapest architecture, the P0 configuration has the highest cost per percentage point CO<sub>2</sub> emissions reduction. The most cost-efficient architecture to reduce CO<sub>2</sub> emissions are P3 and P2 coaxial configurations, with about 40% lower cost than the P0 configuration. While having higher absolute cost due to adding some AWD functionality, the cost per percent CO<sub>2</sub> reduction for adding a P4+P0 system to an FWD vehicle is unexpectedly better than the cost-benefit of a P2 side mounted system. Converting an AWD vehicle to a P4 + 4 kW P0 system has a 9% lower system cost and 75% lower cost per percent CO<sub>2</sub> reduction than adding a 16 kW P0-only system to a conventional AWD vehicle, due to the high CO<sub>2</sub> reduction and the cost savings from eliminating the conventional AWD powertrain components.

**Table 18.** Hybrid architecture cost in 2020 and cost per percentage point CO<sub>2</sub> reduction.

Architecture	System specifications		Cost normalized to P0			WLTP CO <sub>2</sub> reduction	Cost per % CO <sub>2</sub> reduction -normalized to P0
	Motor	Battery	Battery	Non-battery	Total		
<b>P0</b>	16 kW	800 Wh	1.00	1.00	1.00	6.6%	1.00
<b>P1</b>	15 kW	800 Wh	1.00	1.29	1.15	8.5%	0.89
<b>P2 side mounted</b>	16 kW	800 Wh	1.00	1.51	1.27	11.9%	0.70
<b>P2 coaxial</b>	15 kW	800 Wh	1.00	1.62	1.32	14.8%	0.59
<b>P3</b>	16 kW	800 Wh	1.00	1.65	1.34	15.3%	0.58
<b>P4+P0 vs. FWD</b>	15 kW + 4kW	800 Wh	1.00	2.01	1.53	15.5%	0.65
<b>P4+P0 vs. AWD</b>	15 kW + 4 kW	800 Wh	1.00	0.82	0.91	23.9%	0.25

Notes: Based on AVL and Schaeffler data with battery and motor size adjusted to match Schaeffler CO<sub>2</sub> analysis.

Note that the cost-effectiveness calculations in Table 18 are based upon 15–16 kW electric motors. As discussed in Section 3.1.2, larger electric motors (up to 30 kW) provide larger efficiency improvements on P2, P3, and P4 architectures than P0 or P1, likely widening the cost-effectiveness advantage of P2, P3, and P4 systems.

## 5. MILD HYBRID VEHICLE MARKET DEVELOPMENT

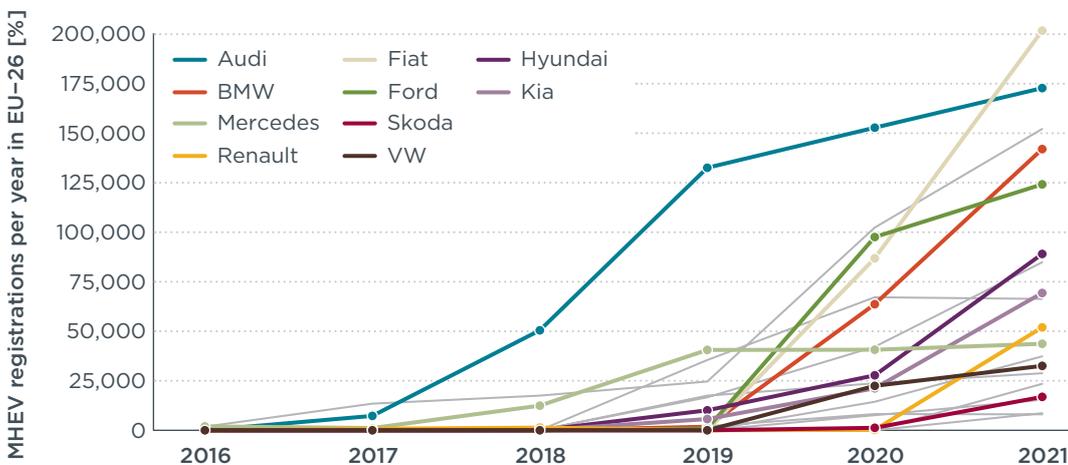
Historically, mass-market acceptance of the hybrid cost increment has been challenging because most customers severely discount future lifetime fuel saving (U.S. EPA & NHTSA, 2020) and fuel costs were until recently a declining part of the overall cost of owning and operating a vehicle due to improvements in conventional vehicle efficiency. Initially hybrid purchasers were primarily early adopters, who are not risk averse and are willing to pay much more than the average customer for new technology and future fuel savings (Greene et al., 2014).

Recent hybrid market trends appear to be driven by government fuel efficiency requirements and the development of lower cost MHEVs, especially in Europe. The EU CO<sub>2</sub> targets for 2021 and the targets for 2025 and 2030 require manufacturers to substantially improve fuel economy. Therefore, manufacturers must not only consider consumer acceptance, but also the cost-effectiveness of mild hybrids compared with other technology options for meeting the CO<sub>2</sub> standards, especially as real-world fuel consumption can be used in the future to define/adjust the manufacturer targets (Regulation (EU) 2019/631, 2019). Improvements in hybrid efficiency, cost reductions, and use of the high electric power to add features desired by customers have tipped the balance toward accelerating market penetration of MHEVs in meeting the EU CO<sub>2</sub> standards.

### 5.1. MILD HYBRID VEHICLE MARKET TRENDS IN THE EUROPEAN UNION

Based on MHEV registration numbers for 26 European countries (EU-27 without Romania), we analyzed the market uptake of MHEVs for the period 2016 to 2021. The data for this analysis was generously provided by Dataforce.<sup>9</sup>

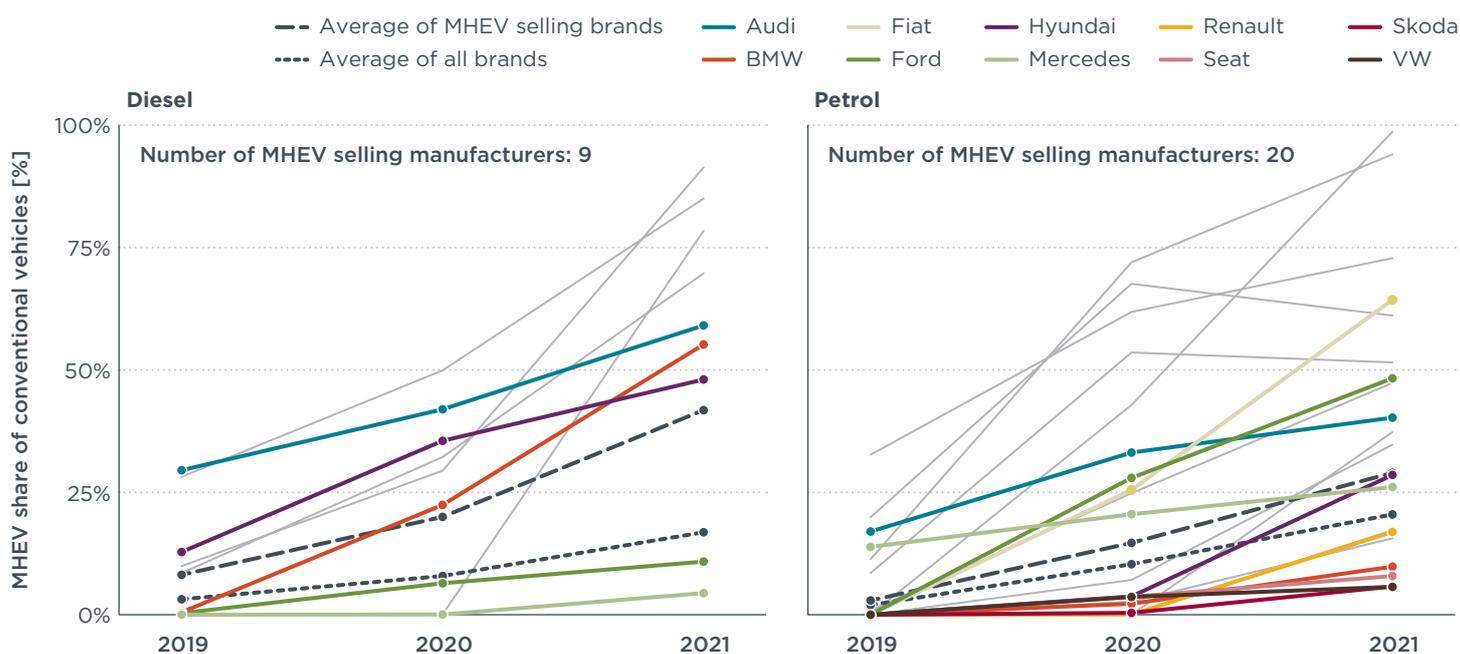
Although Mercedes and Honda offered a limited number of models with mild-hybrid technology prior to 2016, manufacturers in general focused on diesel technology for the European market instead of hybrids to reach their earlier CO<sub>2</sub> targets. As shown in Figure 12, Audi started selling significant numbers of MHEVs in 2017, reached a sales volume of over 50,000 vehicles in 2018, and was the leader until 2020. Although Audi sold 173,000 MHEVs in 2021, Fiat exceeded these numbers with almost 202,000 units sold. Fiat's rapid rise is remarkable considering that they sold almost no MHEVs until 2019, similar to BMW and Ford. With the exception of Mercedes, MHEV sales numbers for the ten largest manufacturers are increasing quickly since they first introduced MHEVs to the market. This rapid increase coincides for most brands with the new CO<sub>2</sub> fleet limits, which entered into force in 2020.



**Figure 12.** Number of registered mild-hybrid vehicles per manufacturer and year of registration. Colored curves present the 10 largest manufacturers in terms of total vehicle registrations in 26 EU countries between 2016 and 2021. The data includes EU-27 countries except Romania. Source: Dataforce.

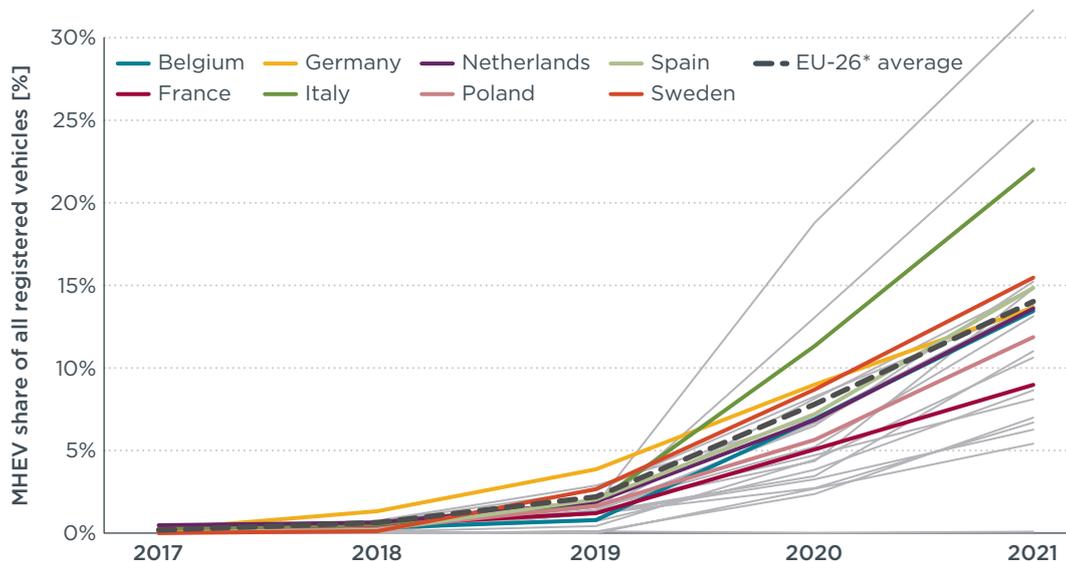
<sup>9</sup> More information available at <https://www.dataforce.de/en/>.

Figure 13 shows separately for petrol and diesel the number of new MHEVs relative to the total number of conventional vehicles defined as pure-ICE, micro-hybrid, and mild-hybrid vehicles powered by these fuels. More than twice as many manufacturers apply mild hybridization in petrol than in diesel vehicles, likely due to the already much higher cost and lower CO<sub>2</sub> emissions of diesel powertrain, as well as decreasing sales numbers that give less leeway for additional technology investments. The data shows that even the largest manufacturers offering MHEVs introduce this technology at different scales. While the MHEV share of all conventional petrol vehicles in 2021 is less than 10% for VW, Skoda, Seat, and BMW, it is almost 50% for Ford and over 64% for Fiat. At 59%, Audi has the highest diesel MHEV share of the 10 largest brands, followed by BMW with 55%. Lower volume brands like Land Rover and Volvo have even higher market shares of diesel MHEVs, reaching 85% and 91% in 2021, respectively. Lancia reached an almost 100% share of petrol MHEVs in 2021, followed by Suzuki with 94%.



**Figure 13.** Mild-hybrid vehicle share of all newly registered conventional internal combustion engine vehicles, by manufacturer and year of registration, for diesel and petrol. Conventional ICE vehicles exclude battery electric, full-hybrid, plug-in hybrid, and alternative fuel vehicles. Manufacturers listed are the largest MHEV selling manufacturers in terms of total conventional vehicle registrations in the EU-27, except for Romania, between 2019 and 2021. Source: Dataforce.

The high MHEV sales numbers are also reflected in the average market share in the 26 EU countries, shown in Figure 14. Note that Figure 14 depicts the MHEV share of all vehicles registered in a year while Figure 13 shows the number of MHEVs relative to the number of conventional vehicles only. The EU-wide market share of MHEVs increased rapidly from a mere 0.2% in 2017 to 0.6% in 2018, 2.2% in 2019, 7.8% in 2020 and 14.0% in 2021. Of the eight largest vehicle markets in the EU, representing about 84% of the total vehicle market for the period 2017 to 2021, six countries show MHEV market uptakes similar to the EU average, with the exceptions of Italy and France. In Italy, the MHEV market share increased much faster starting in 2019 and reached 22.0% in 2021, more than 50% higher than the EU average. France has experienced slower MHEV uptake than the other major markets and reached only about 9.0% in 2021. Of the other countries, Hungary has the fastest growing and highest MHEV market share in the EU, starting at only 1.7% in 2019, reaching 18.8% in 2020 and 31.7% in 2021.

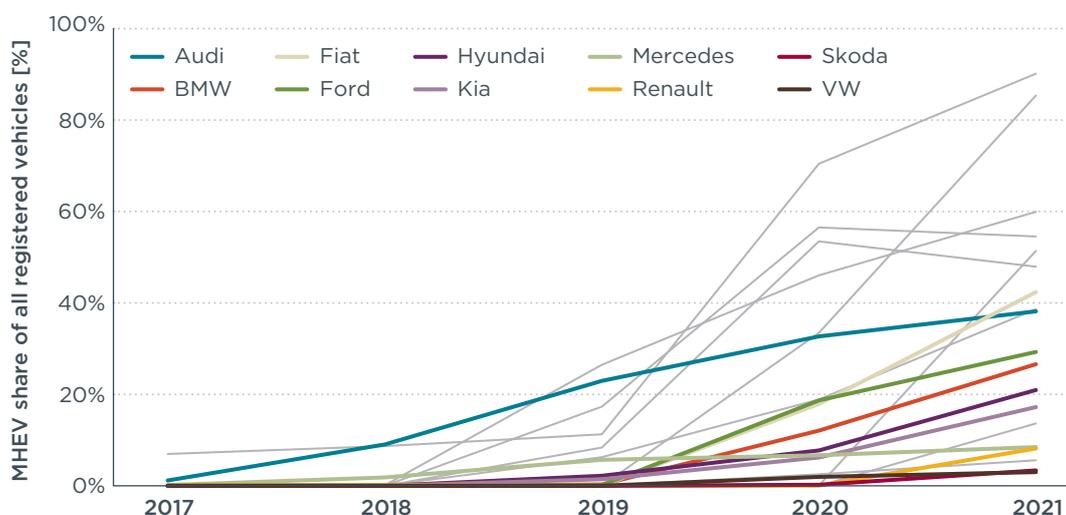


**Figure 14.** Mild hybrid market share by country and year of registration. The colored lines reflect the 8 EU countries with the highest total registration numbers between 2017 and 2021. The dashed line shows the EU-average\*. *Source:* Dataforce \*EU-27 without Romania

These market developments suggest that mild-hybridization is a cost-effective and mainstream customer-acceptable solution for CO<sub>2</sub> reduction, due to ongoing efficiency improvements (section 3) and cost reductions (section 4). This is confirmed by manufacturers having started to make mild-hybrid technology as standard equipment on their models, such as the 2020 BMW 320d (Dorofte, 2020).

## 5.2. MILD-HYBRID VEHICLE MARKET PROJECTIONS

Fiat/FCA projected in 2018 that 40% of its vehicles sold in Europe by 2022 would be MHEVs, which seemed an ambitious projection considering that Fiat sold no such vehicles in 2019 (Pollard, T, 2018). However, Fiat exceeded this market share in 2021 with 42.4% of its newly registered vehicles being MHEVs (Figure 15). Other brands also showed rapid MHEV market share increases within a short time. In this light and considering that passenger cars with 48V systems had already a market share of 14.0% in 2021, Bosch’s projection that the annual share of new passenger cars and light commercial vehicles equipped with 48V systems will rise from 5% in 2020 to 20% in 2025 in Europe, is almost certainly a conservative estimate (Bosch Global, 2020).



**Figure 15.** Mild hybrid market share by year of registration and brand in 26 EU countries (EU-27 without Romania). The ten brands listed are those with the highest total registration numbers from 2017 to 2021. *Source:* Dataforce.

Manufacturers have used PO layouts almost exclusively until recently, likely due to their lower absolute cost and low integration complexity. However, using P2, P3, and especially P4+PO architectures enable much larger CO<sub>2</sub> reductions, both on chassis dynamometer and during real-world operation, and a lower cost per percentage point CO<sub>2</sub> reduction. These technologies could contribute to substantial savings in total greenhouse gas emissions. However, the moderate tightening of CO<sub>2</sub> targets in 5-year incremental steps foreseen by the CO<sub>2</sub> standards in effect, and the fast market uptake of electric vehicles will allow manufacturers to meet the targets without substantial improvements in ICE-vehicle efficiency, passing up the CO<sub>2</sub> saving potential the more advanced MHEV technologies provide. Therefore, the implementation of this cost-efficient measure for reducing the CO<sub>2</sub> emissions of ICE-vehicles will depend on the design of the future EU CO<sub>2</sub> regulatory framework.

## 6. SUMMARY AND IMPLICATIONS

Due to concerns about energy security and global warming, all major vehicle markets in the world have adopted efficiency or CO<sub>2</sub> requirements. Until recently, manufacturers have been able to meet these standards by improving the combustion engine and transmission in combination with mostly emission test-cycle targeted reductions in driving resistance. Manufacturers continuing to focus on internal combustion engines must deploy much more extensive technology solutions to comply with the more stringent 2025 and 2030 targets, especially in combination with the shift from NEDC to the more representative WLTP drive cycle in Europe.

Despite better fuel economy, manufacturers have not had much success in convincing customers to pay large price premiums for hybrid vehicles in the past. The mild-hybrid technology offers the potential to reduce fuel consumption and CO<sub>2</sub> emissions more cost-effectively but has only recently gained a considerable market share. This is partially due to the large variety of possible mild-hybrid system architectures, each with different costs and benefits. Many reports have been published investigating the relative advantages and costs of the different mild-hybrid system configurations, such as voltage level, battery type, powertrain architecture and the electrification of auxiliaries and other vehicle components.

**CO<sub>2</sub> emissions.** The most transparent and systematic data on CO<sub>2</sub> reduction potential comes from a Schaeffler study, which we used as the reference case. All efficiency improvements are relative to a baseline micro-hybrid vehicle with stop/start technology and assume an electric machine power of 15–16 kW. They project for 15–16 kW MHEV systems a reduction of CO<sub>2</sub> emissions in WLTP between 6.6% for a P0 configuration and up to 15.8% for a coaxial P2 architecture when all auxiliaries are powered electrically. For an off-axis P2 layout, the efficiency is reduced to 11.9%. The CO<sub>2</sub> reduction is 15.3% for the P3 architecture. Schaeffler also investigated an all-wheel-drive (AWD) vehicle configuration, where an EM in P0 position is combined with an electric machine on the rear axle replacing the mechanical drive from the combustion engine (P4). This configuration yields an efficiency improvement of 23.9%, compared to the conventional AWD vehicle. And, even compared to a front-wheel drive vehicle, an efficiency gain of 15.5% is reported.

Studies conducted by the Swedish Chalmers university and the German university of Braunschweig also investigated the effect of the electric machine power on the CO<sub>2</sub> saving potential and found that increasing the power up to 20–30 kW can substantially reduce CO<sub>2</sub> emissions in P2, P3, and P4 systems by another 5–10 percentage points. Both studies also confirmed the higher efficiency of P2, P3, and P4 architectures compared to a P0 and P1. Compared to other studies, the Schaeffler results appear to be slightly more conservative.

**Cost.** An analysis of estimated cost for mild-hybrid technology revealed a fast decline in direct manufacturing cost. Based on a tear-down cost analyses for Europe, cost for a 48V P0 system with a 15-kW motor and 530Wh battery decreased from €1,175 to €761 between 2010 and 2015, an annual reduction of 8.3%. EPA's mild hybrid cost estimates for the United States dropped from \$1,087 in 2010 to \$724 in 2017, a 5.6% annual reduction.

Mild hybrid costs are expected to drop further in the future. A 2015 ICCT hybrid analysis reports for the Toyota Prius an 5% annual cost reduction for a period of almost 10 years (2001 to 2010). This is in a similar range as the annual 6% cost drop predicted by Ricardo for mild-hybrid technology in the EU between 2015 to 2020. Mild hybrids are still at a relatively early stage of the learning curve, so 5% annual reductions similar to those of the Toyota Prius are likely through at least 2025. However, more

conservative estimates of a 2.9% annual reduction from 2020 to 2025 and 2.1% annual reduction from 2025 to 2030 predicted by Ricardo were used in this study.

Applying the Ricardo learning factors and modest technology improvements reduce PO direct manufacturing costs from €761 in 2015 to €558 in 2020, €376 in 2025, and €338 in 2030. This adjustment takes into account developments in high-power battery technology that can reduce the battery energy capacity to 370 Wh and eliminate the 12V starter by 2025–2030. The total cost of a 48V PO 15 kW MHEV technology package to the customer, including indirect costs, drop from €1,122 in 2015 to €796 in 2020, €494 in 2025, and €444 in 2030.

AVL provided cost data for different hybrid architectures. The data was analyzed to understand the effect of the architecture on cost and, together with the Schaeffler CO<sub>2</sub> reduction potential, to assess their cost efficiency with respect to reducing CO<sub>2</sub> emissions. As AVL assumed different battery sizes and electric machine power than Schaeffler, it was necessary to scale the component cost accordingly. The analysis reveals that cost for a P1 system is about 15% higher than for a PO system, and P2 and P3 costs are both about 30% higher than PO costs, with a P2 side-mounted system having a cost advantage of about 5 percentage points compared to a P2 coaxial system. If a front-wheel drive vehicle is converted to an MHEV with all-wheel drive capability (P4+PO), the cost is about 53% higher than for a PO system. However, replacing a conventional AWD powertrain with a P4+PO system creates a 9% cost advantage compared to installing PO technology only, due to the cost savings from removing the transfer case, differential, and driveshafts.

When comparing the cost per percentage point CO<sub>2</sub> reduction normalized to the PO cost, the picture is different. The PO and P1 are the least cost-efficient architectures in regard to CO<sub>2</sub> reduction, while the coaxial P2 and P3 architectures require the lowest investment per percentage point CO<sub>2</sub> reduction. It was unexpected that the cost for achieving the same CO<sub>2</sub> reduction is lower when converting a front-wheel drive vehicle to an AWD capable MHEV (P4+PO) than applying a side mounted P2 configuration.

**Market.** The push of increasingly stringent CO<sub>2</sub> requirements and the pull of mild-hybrid technology improvements and consumer features have caused a recent surge in European mild hybrid sales numbers. The mild hybrid market share has risen rapidly from just 0.2% in 2017, to 0.6% in 2018, 2.2% in 2019, 7.8% in 2020, and 14.0% in 2021, with some manufacturers being far ahead of the average. Considering manufacturer announcements and supplier projections, the increase in vehicles with mild-hybrid technology will further accelerate in upcoming years. While there are numerous ways to comply with the EU CO<sub>2</sub> standards, the fact that most manufacturers are moving rapidly towards MHEVs provides strong evidence that the cost to CO<sub>2</sub> benefit ratio has improved and is considered better than competing technologies. The expected future cost reductions might have also influenced this decision. Furthermore, the upcoming Euro 7 standards in combination with the increasingly stringent CO<sub>2</sub> emission limits might make the use of an electrically heated catalyst powered with a 48V system even more favorable.

While manufacturers have advertised and sold full-hybrid vehicles as individual models, manufacturers will increasingly offer the 48V technology as standard in their existing vehicle models, which indicates also that the mild-hybrid system costs and benefits are at a level that is acceptable or even desirable for the consumer. BMW has already started making 48V technology standard equipment on most models (WELT, 2020).

**Outlook.** We assume that PO architecture will continue to dominate the MHEV market in the near future. This is due to the relatively low cost and effort for integration in existing vehicles and powertrains. The P2, P3, and P4+PO architectures allow for a much higher CO<sub>2</sub> reduction at a lower cost per percentage point CO<sub>2</sub> reduction than

P0. Still, due to the larger redesign effort required, we expect the exploitation of this greenhouse gas saving potential by manufacturers will depend strongly on the regulatory framework.

Making use of the more efficient mild hybrid P2, P3, and P4+P0 system layouts could achieve a substantial reduction of near-term CO<sub>2</sub> emission and fuel consumption of ICE vehicles and thereby help to reduce Europe's dependency on oil imports in the upcoming years as well as bridge the pathway to 100% electric vehicles at moderate cost.

However, with the current approach of further tightening the EU CO<sub>2</sub> targets only from 2025 onwards and only in 5-year incremental steps, we expect manufacturers can meet their fleet average targets in 2025 and 2030 by increasing the share of electric vehicles without the need to further reduce the CO<sub>2</sub> emissions of ICE vehicles (Mock, 2021). Annual CO<sub>2</sub> fleet targets on the other hand, preferably in combination with separate ICE-vehicle-specific CO<sub>2</sub> limits, would help to ensure that manufacturers also reduce the CO<sub>2</sub> emissions of ICE vehicles in parallel to the transition to electric mobility.

To make sure that mild hybridization does not only reduce type approval CO<sub>2</sub> emissions but has at least the same effect on real-world emissions, it is furthermore important to ensure by regulatory means that the real-world to type-approval gap does not grow when more vehicles use this technology.

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