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THE POTENTIAL OF 48V HYBRIDS IN INDIA'S LIGHT-DUTY VEHICLE MARKET

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EXECUTIVE SUMMARY

Optimum use of hybrid and electric powertrains is key for reducing CO_2 emissions from new vehicles, and for a variety of reasons, hybrids are expected to become much more prominent in India in the near and medium term. A hybrid vehicle uses a combination of an internal combustion engine and an electric motor to improve vehicle efficiency in many ways, including by turning off the engine at idle, using the electric motor as a generator to recapture energy lost to braking, and improving accessory efficiency by reducing belt losses and replacing mechanical components with electrical components.

In Europe, the market share of 48V hybrids jumped from 2.1% in 2019 to 8.2% in 2020, corresponding with regulations that imposed more stringent CO_2 emission limits. This suggests that for complying with such standards, 48V hybrids have a more attractive cost-to-benefit ratio than many other technologies, and a recent ICCT study focused on Europe found the same. In India, where electric vehicles still have a small market share due to relatively high cost, 48V hybrids have the potential to reduce CO_2 emissions over the next several years at a cost that is affordable to a wider section of customers. Indeed, as CO_2 standards become more stringent in India, manufacturers are likely to turn to 48V hybrids.

To help inform future CO_2 standards in India, this paper estimates the future cost and CO_2 reduction potential of 48V hybrid systems. Using cost learning factors and battery power density data from our European market analysis, this paper first evaluates the 48V hybrid direct manufacturing cost for India (on the New European Driving Cycle test cycle) in both 2025 and 2030. Due to lower labor cost, continued learning, and expected 48V system improvements, we find that the 48V hybrid cost in India in 2025 will be less than half the 2020 cost in Europe. We analyzed a variety of power train configurations, and Figure ES1 shows the percent CO_2 reduction and direct manufacturing cost projections per percent CO_2 reduction for 12V advanced micro-hybrid and several different 48V hybrids versus conventional vehicles without stop-start. Both the CO_2 and the cost estimations are for passenger cars with a 15 kW electric motor and a 375 Wh battery pack.

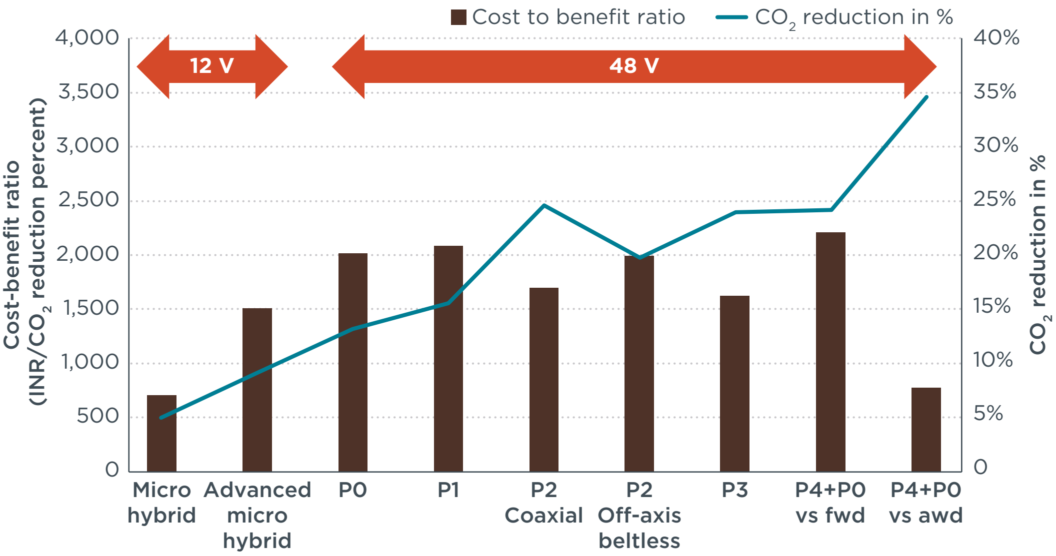

Figure ES1. CO_2 reduction and direct manufacturing cost per CO_2 reduction benefits (%) in 2025 for different configurations of 48V hybrids with 15 kW motor and 375 Wh batteries, versus conventional passenger cars without stop-start.

Although we find the P0, P1, and P2 off-axis hybrid systems all have relatively similar cost-to-benefit ratios, virtually all 48V hybrids manufactured today are P0 systems. This is because of the ability to simply upgrade the existing alternator without having to integrate the motor into the transmission, which minimizes development and redesign costs. Still, as P2 coaxial and P3 systems have significantly better cost-to-benefit ratios, we expect their market share will increase as sales volumes rise and cover the cost of redesigning the power train. For a baseline vehicle with all-wheel drive (AWD), the P4+P0 configuration's incremental cost is quite low, equivalent to that of a P0 hybrid alone on a front-wheel drive baseline; this is because the electric motor can provide the AWD functionality and that eliminates the need for a transfer case and driveshafts.

Note that the cost estimates presented in this paper are likely to be conservative because of conservative learning factors used after 2020. Additionally, the electrical power of 48V systems can be used to provide other benefits that are not quantified in the calculations here, such as electrical assist to turbocharged engines (e-boost) for higher efficiency and high-power electrical features desired by consumers in India.

Passenger cars and light commercial vehicles in India are lighter than in Europe, and that means that smaller electric motors and batteries can be used to further reduce costs for applications in hatchbacks, sport utility vehicles, and light commercial vehicles. Given this, the impact of electric motor size on CO_2 emissions reduction and cost for 48V hybrids was also analyzed. Both the cost and efficiency data were adjusted for a variety of motor and battery pack sizes against a baseline vehicle with micro hybrid configuration. The results suggest that the incremental CO_2 reduction with increasing electric motor power tends to be much higher in hybrid architectures that can separate motor operation from the engine (P2, P3, and P4), and this provides additional cost-effective CO_2 reductions beyond those for the 15 kW motors illustrated in Figure ES1. However, for P0 (belt alternator starter) and P1 (with the motor attached to the engine) systems, engine drag cannot be avoided and that limits the benefit of higher-power motors. Thus, we find that systems offer the best cost-to-benefit ratio with lower electric motor power, generally from 4 kW to 16 kW.

All of society benefits from reduced emissions, and over the life of the vehicle, we find the fuel savings more than pay for the incremental cost of the hybrid technologies analyzed. Therefore, more stringent CO_2 standards that incentivize the deployment of 48V hybrid systems would result in net benefits to vehicle consumers and to India.

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INTRODUCTION AND BACKGROUND

The Government of India first implemented fuel consumption standards for passenger cars in fiscal year (FY) 2017–18 and most manufacturers easily met the first phase of targets by improving the performance of conventional internal combustion engine (ICE) vehicles. This was done through the addition of technologies like a higher compression ratio, a cooled exhaust gas recirculation (EGR) system, better thermal management, and a variable valve timing system (Maruti Suzuki, n.d.-c).

Over the past decade, India has closely followed the technology trends in Europe, and its regulations have typically lagged Europe by 2–3 years. This is to allow manufacturers to apply technologies already developed for Europe, which helps to reduce costs in India. Currently, India's passenger car fuel efficiency standards are much less stringent than those in the European Union, and thus far neither hybrid vehicles nor battery electric vehicles (BEVs) have been necessary in large numbers to comply. However, the second phase of India's standards will go into effect beginning in FY 2022–23. These are more stringent and thus likely to spur manufacturers to consider selling hybrids and BEVs.

Hybrid vehicles use both an ICE and an electric motor to drive the vehicle, and the CO_2 benefits of hybrids can be noticeably higher than conventional gasoline or diesel engine-powered vehicles (Maruti Suzuki, n.d.-a). Hybrids might function as a bridge during the expected transition to electric vehicles, but a hybrid vehicle still needs gasoline or diesel fuel for the engine.

Purchase cost is a major concern for mass-market vehicles in India, as most of them are sold for less than 10 lakh rupees ($13,000 U.S. dollars). Therefore, if hybrid technologies are to achieve widespread implementation, they also need to be cost effective. In Europe, 48V hybrids have recently emerged as cost effective, and the technology is easily implemented in mass-market passenger cars. Indeed, in Europe there was a significant jump in the market share of hybrids below 60 V for passenger cars, from 2.2% in 2019 to 7.8% in 2020; this corresponded with more stringent fuel economy standards.

There is activity in India, as well. Suzuki and Toyota signed a memorandum of understanding (MOU) to jointly develop hybrid vehicles for the Indian market. Toyota greatly improved its powersplit system in the past 20 years and is much further along in terms of learning than manufacturers that are just starting to introduce hybrids in India. According to the MOU, Toyota will share its expertise on hybrid technology with Suzuki and Suzuki will supply its compact car platform to Toyota. Apart from this, Suzuki already has vehicles with 48V hybrid systems for sale in Europe.

Note that the understanding of "mild" and "strong" hybrids is different in India than it is elsewhere. In Europe, for example, anything below 60V is considered a mild hybrid (Dornoff et al., 2022). But in India, hybrids are typically categorized based on the applicability of supercredits in the CO_2 standards. Mild hybrids do not qualify for supercredits, but strong hybrids are given a supercredit factor of 2. The definition in India says that with strong hybrids, the electric motor should be able to propel the vehicle from a standstill. Because vehicles in India tend to be fairly light, 48V hybrids, which are the focus of this paper, are somewhat likely to be able to propel the vehicle. Such 48V hybrids could thus qualify as "strong" hybrids if manufacturers develop the vehicle to qualify for the supercredit. This is a matter of regulatory classification only, however, and the underlying technology is the same.

PREVIOUS RESEARCH ON HYBRIDS

ICCT has published several technical analyses of hybrid vehicle development in the United States, and these largely focused on types of hybrid models and their market share. One paper, German (2015), discussed potential hybrid cost reductions primarily for high-voltage hybrids, because lower-voltage hybrids had not yet been introduced. Subsequently, a joint analysis from the ICCT, Eaton, Ricardo, JCI, BorgWarner, Honeywell, and the ITB Group sought to analyze turbocharged, downsized gasoline engine technology developments and trends; however, that paper was primarily oriented toward powering 48V electric turbochargers in 48V hybrid systems (Isenstadt & German, 2016). Since then, hybrid technology development has been continuous, and significant developments have also occurred in transmissions, vehicle body design, and lightweighting, all to complement hybrid vehicle technologies.

Recently ICCT focused on the European market and analyzed the features, costs, and benefits of 48V hybrids on a wide variety of hybrid configurations and systems, each with different costs and benefits based on manufacturers' and suppliers' information (Dornoff et al., 2022). This work is hereafter referred to as "the EU-ICCT paper," and it was done because 48V hybrid systems have emerged as cost-effective alternative to high-voltage hybrids and 12V micro hybrids. According to Bosch (2021), by 2025, around 20% of all new cars in Europe will have a 48V hybrid system.

Depending on the architecture, a 48V system can provide torque assist and electric motor propulsion with more energy recovery from regenerative braking than micro hybrids. Additionally, 48V systems do not require advanced electrical shock protection like higher-voltage hybrids. They also reduce overall system costs, are more easily integrated in existing vehicle designs, and provide additional power for systems such as the electric compressor, the electrically heated catalyst (for faster catalyst light off to reduce pollutants), and the electric turbocharger. These systems are beneficial in meeting future stringent pollutant norms such as Euro 7 or potentially Bharat VII. Safety features such as adaptive cruise control, head-up display, lane keep assist, and parking assist can be powered by a 48V system, as can comfort features.

In this paper, the initial costs and CO_2 benefits for 48V hybrid systems are derived from the EU-ICCT paper. Note that while Europe has transitioned to the Worldwide harmonized Light vehicles Test Cycle (WLTC), India still uses the New European Driving Cycle (NEDC) for standardized testing of passenger vehicles. The cost projections include estimates of learning from 2020 to 2030 and we adapt them to the Indian market. We adjust both the cost data and efficiency data from a baseline motor size of 12kW and 400 Wh battery to the 15kW and 530 Wh motor sizes for comparing all hybrid types. Note that the motor and battery size requirements could vary for different architectures. Hybrids greatly benefit from batteries optimized for high power. The cost of batteries in this paper has been adjusted from a baseline power-to-energy ratio of 28 kW/kWh to 40 kW/kWh based on the new batteries available.

DATA ON THE CO_2 BENEFITS OF 48V HYBRID SYSTEMS

In passenger cars, 48V hybrids mostly use parallel systems wherein both the ICE and the electric motor can drive the vehicle. The efficiency of the vehicle is improved when the engine charges the battery only when the engine is at higher efficiency mode. Once the objective of battery charging at more efficient mode is realized, then it makes more sense to shut off the engine during driving and use the electric motor to drive the vehicle. The difference in efficiency between these two modes of operation must be large enough to compensate for the discharging and recharging losses in the battery pack. This is the core of most hybrid strategies.

The power capacity of the electric motor and the battery each play an important role in the CO_2 benefits from hybrid configurations. Different levels of electric motor power result in a range of fuel savings for the same hybrid configuration and application. Our assessment of the CO_2 emissions reduction benefits of different 48V hybrids in this paper is based on Schaeffler studies, and cost estimates are from a Europe-focused study done by AVL for the ICCT.

An important aspect when assessing the potential for CO_2 emissions reduction and fuel savings from hybridization is the baseline against which the assessment of the hybrid vehicle is made. While the reference for some studies is a micro hybrid, in other words, a vehicle with engine start-stop and possibly an alternator enabling efficient energy recuperation, a number of other studies start from a fully conventional vehicle, and measured against that, the hybrid will show greater CO_2 emissions reductions. Additionally, the benefit of engine start-stop on CO_2 emissions is generally higher in the NEDC, owing to the longer idling period as compared to WLTC; the vehicle stands still for 22.6% of the total time in the NEDC and for 13.4% of the time in the WLTC (Dimaratos et al., 2016, p. 2).

Most cars in India are lighter than in the United States or Europe. In India, compact cars and sport utility vehicles (SUVs) are the majority of the market in terms of body types. These have packaging constraints that limit the feasibility of an additional power train, and the price sensitivity in the market is typically thought to preclude expensive strong hybrids with high voltage.[1] The hybrid systems analyzed in this paper could be used in small hatchbacks, SUVs, and light commercial vehicles (LCVs). Automakers in Europe and Japan have worked on this technology for several years and the available data for CO_2 emissions and fuel consumption are based on simulations and testing of these vehicles.

The data used in our analysis were retrieved from publicly accessible technical journals and reports from automobile organizations. As India continues to base its standards on the NEDC, data based on WLTC was converted to NEDC using ICCT conversion factors for hybrids and advanced engines (Kühlwein et al., 2014).

India follows the modified Indian driving cycle (MIDC), an underpowered NEDC-based cycle in which maximum speed is 90 km per hour. As both the MIDC and NEDC cycles are similar in terms of idle stops, accelerations, and decelerations, this paper assumes that the CO_2 benefits achieved over the MIDC cycle are similar to those for NEDC cycle. The applications of 48V hybrid technology covered in our analysis include gasoline and diesel engines.

1 According to the United Nations Economic Commission for Europe, “high voltage” is the classification of an electric component or circuit for vehicle application when its working voltage is > 60 V and ≤ 1,500 V DC or > 30 V and ≤ 1,000 V AC root mean square (rms). 60V is the maximum permissible contact voltage that is considered safe for humans. Voltages above 60V are classified as a high voltage with the risk of electrical shock for human operators. In an HEV, the electric circuit operates in direct current (DC). Some systems use AC induction motors, but almost all current hybrids use DC brushless motors with permanent magnets and 3-phase windings.

SCHAEFFLER STUDY (2018)

In Eckenfels et al. (2018), Schaeffler assessed all possible 48V hybrid configurations against a constant baseline micro-hybrid car equipped with engine start-stop and 12V energy recuperation, and ran simulations for the WLTC. The starting point of the simulations was a C-segment micro-hybrid front-wheel drive (FWD) car with a 3-cylinder, 1.0 liter gasoline engine with start-stop and a 7-speed dual clutch transmission. Schaeffler used a permanent magnet synchronous motor (PSM) for all 48V hybrid simulations due to its high efficiency and high torque capacity, particularly during cold engine starts. Using PSM also increases the cost, though. Schaeffler modeled 48V hybrid configurations in P1, P2 with off axis and beltless FEAD, P3, and P4+P0. The CO_2 benefits of the different hybrid configurations from the Schaeffler study are used as the "reference cases" for this study. Because these results were originally generated on WLTC cycle, we converted them to the NEDC cycle using the aforementioned ICCT conversion factors. For hybrid systems with 15 kW motors, the CO_2 emissions reduction on the NEDC is 7.8% for P0 (BAS), 10% for P1 with beltless accessories, 18.6% for coaxial P2 with beltless accessories, 18% for P3, and 18.3% for P4+P0 over a baseline FWD vehicle (28.2% over a baseline AWD vehicle). Benefits for an off-axis P2 system were only 14%, likely due to belt losses. On the P2 system, beltless accessories accounted for 1% CO_2 reduction. The CO_2 benefits of the Schaeffler simulations relative to micro hybrids adjusted to the NEDC are illustrated in Figure 1.

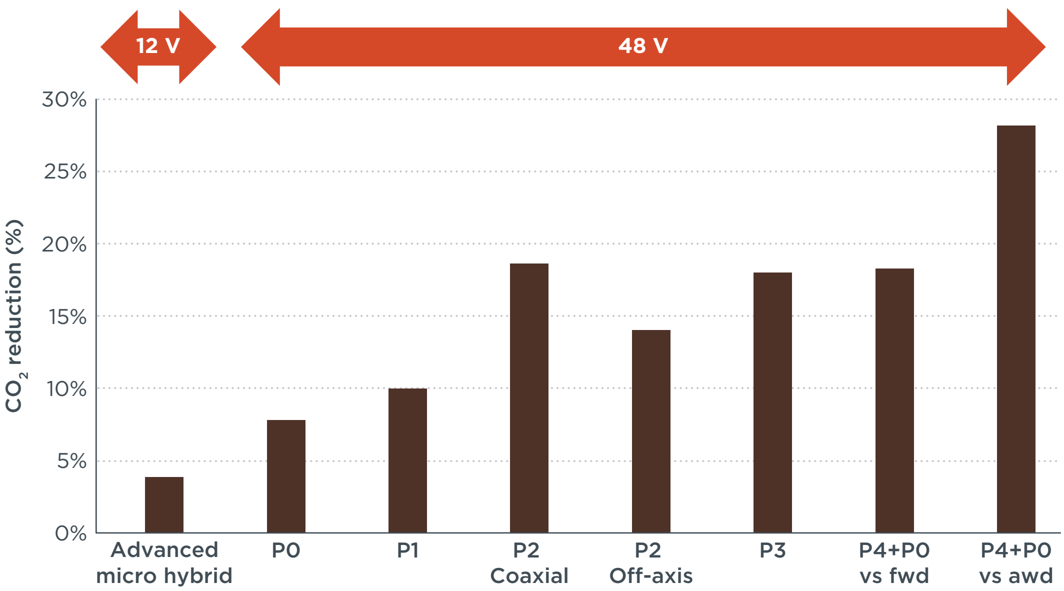

Figure 1. CO_2 emissions benefit of different hybrid architectures with 15 kW motors over the NEDC cycle relative to a micro hybrid in the Schaeffler study.

CURRENT MARKET FOR HYBRID VEHICLES IN INDIA

To date, the market for hybrid vehicles in India has been dominated by micro hybrids, and most of these have used 12V lead-acid batteries as the primary energy storage system. Lead-acid batteries have a strong presence in the automobile industry, are highly reliable, and are capable of high discharge rates. These batteries are inexpensive in terms of cost per watt hour and have a well-established manufacturing and supply chain. Moreover, they have the advantage of few maintenance requirements, and their recycling network is also well established. However, major disadvantages of lead-acid batteries are their low energy-to-weight ratio (energy density), short cycle life, and inability to absorb sudden high-charge current during regenerative events, even though maximum power is available. Because of these limitations, lead-acid batteries are suitable only for low-power hybrid systems like micro hybrids.

A conventional micro hybrid with engine stop-start and limited energy recuperation provides a CO_2 emissions benefit of 5% over the NEDC cycle (Melaika et al., 2019). To compensate for the weak charge acceptance of lead-acid batteries, a small lithium-ion battery can be used (Rosenmayr et al., 2012). The vehicles that include this are called advanced micro hybrids and they currently dominate the passenger car market in Japan. In an advanced micro hybrid, the lead-acid battery is maintained at high state of charge for optimal cranking performance, and the small lithium-ion battery is added to absorb recuperation energy and provide torque assist during low-load and low-RPM engine operation. A DC/DC converter[2] integrates the two energy storage systems and allows current to flow from both at the highest possible efficiency to maintain the effectiveness of recuperation energy absorption. An advanced micro hybrid system is estimated to provide 3.9% CO_2 emissions benefits over and above that of a conventional micro hybrid system on the NEDC cycle, and that is half the CO_2 benefit of a 48V P0 hybrid relative to a standard micro-hybrid system.

Maruti Suzuki is using such an advanced system in its SHVS hybrid variants like the Ertiga, Ciaz, S-cross, Baleno, XL6, and Brezza (Maruti Suzuki, 2021a). It has a belt starter and generator (BSG) along with a 12V dual-battery system that consists of a 36 Wh lithium-ion and a lead-acid battery. The advanced micro hybrid system in the Baleno contributes to CO_2 reduction benefits totaling 11.5% compared to a conventional vehicle, and this comes from the combined benefits of the dual-battery system and the Dualjet engine (Maruti Suzuki, n.d.-b).

The market share of hybrids 48V or higher voltage in India in FY 2019–20 was only 0.03%. MG Motor and Mercedes are the only mainstream carmakers in India to use 48V hybrid architecture. The hybrid variants are powered by a 48V lithium-ion battery with CO_2 benefits marketed as 12% (MG Motor, 2019).

Other hybrids, especially models from Toyota like the Camry and Vellfire, are sold with powersplit[3] hybrid technology, which is complex compared to 48V systems. Most of the hybrids sold in India thus far, be them 48V or powersplit systems, have been gasoline versions. In part, the low penetration of hybrids and plug-in hybrid electric vehicles (PHEVs) in India is because of high taxes: a 28% Goods and Services Tax and a 15% compensation cess as most of these vehicles are longer than 4 m with engine size more than 1,500 cc. In comparison, a 1%–3% cess is applicable to conventional vehicles that are less than 4 m but have CO_2 emissions similar to hybrid vehicles.

2 As the electrical energy to charge batteries is produced only by the 48V EM, a direct current (DC/DC) converter is needed in order to convert 48V to lower 12V (step-down operation of the converter). In principle, the boost-mode (step-up) is also possible, where the low voltage is converted to high (bidirectional DC/DC converter). The converter is usually air-cooled and has a typical power output of 1.5 to 3kW and efficiency above 95%.

3 A powersplit is a complex type of hybrid system that uses two electric motors to give multiple combinations of gear ratios. A powersplit hybrid system can give parallel and limited series hybrid-like operation in a vehicle.

Table 1. Different hybrids and PHEVs for sale in India in FY 2020–21.

Make	Model	Hybrid configuration	Body style	Transmission type	Engine capacity (cc)	Fuel preparation	Battery capacity (kWh)	Market share (%)	CO_2 (g/km)	Voltage (V)
Maruti	**Ertiga**	12V advanced micro hybrid	MUV	Manual or Automatic	1,462	Multi-point injection	0.036	2	125.5/132.5	12
Maruti	**XL6**	12V advanced micro hybrid	MUV	Manual or Automatic	1,462	Multi-point injection	0.036	0.9	125.5/132.5	12
Maruti	**Baleno**	12V advanced micro hybrid	Hatchback	Manual or Automatic	1,197	Multi-point injection	0.036	0.7	99.6	12
Maruti	**S-cross**	12V advanced micro hybrid	MUV	Manual or Automatic	1,462	Multi-point injection	0.036	0.6	128.2	12
Maruti	**Ciaz**	12V advanced micro hybrid	Sedan	Manual or Automatic	1,462	Multi-point injection	0.036	0.5	114/118.5	12
MG	**Hector**	48V hybrid	SUV	Manual	1,451	Turbocharged gasoline direct injection	n/a	0.1	149.1	48
Toyota	**Toyota Vellfire**	Powersplit	MPV	CVT	2,494	Multi-point injection	n/a	0.011	145	n/a
Toyota	**Toyota Camry**	Powersplit	Sedan	CVT	2,487	Gasoline direct injection	n/a	0.01	104.5	245
Mercedes	**GLS 450 4Matic Auto**	48V hybrid	Sedan	Automatic	2,999	Turbocharged gasoline direct injection	1	0.01	213.6	48
Volvo	**Volvo XC90**	PHEV	SUV	Automatic	1,969	Gasoline direct injection	9.2	0.002	49.8	n/a
BMW	**BMW 7 Series 745Le xDrive Auto**	PHEV	Sedan	automatic	2,998	Turbocharged gasoline direct injection	12	0.001	59.3	355
Toyota	**Toyota Prius**	PHEV	Hatchback	CVT	1,798	Multi-point injection	4.4	0	87.8	n/a

Source: Analysis of Segment Y data for FY 2020–21.

Figure 2 shows the variety of hybrids sold in FY 2020–21, and most are gasoline variants. Diesel vehicles are more expensive after the implementation of the Bharat Stage VI emission standard because of the aftertreatment technology they require, and diesel engines are unlikely to be able to compete with gasoline hybrid vehicles on price going forward. Diesel fuel consumption benefits are larger than hybrid benefits, but half of this is due to the higher energy and CO_2 density of diesel fuel. The CO_2 emissions benefits of diesels are only about the same as that of current gasoline P0 hybrids. Hybrid costs are expected to come down rapidly in the future and improvements to gasoline hybrid efficiency will increase the incremental fuel savings compared to diesel. Also, many technologies that were traditionally used on diesels, such as direct injection, turbocharging, and cooled EGR systems, are being added to gasoline engines to meet fuel economy and CO_2 standards. Thus, the incremental efficiency gains from shifting to hybrids will be much larger than those that can be gained from a diesel system in the future.

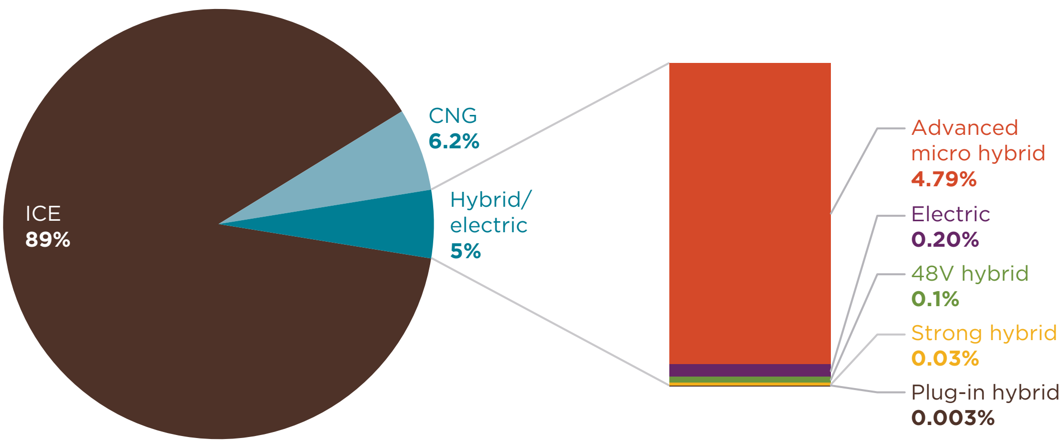

Figure 2. Distribution of hybrids in India for FY 2020–21.

HYBRID COMPONENT COSTS AND METHODOLOGY

In a price-sensitive market like India, consumers will want the minimum cost for a hybrid without sacrificing vehicle attributes like boot space, performance, or fuel economy. This chapter estimates hybrid system costs and analyzes the main factors for future cost reduction in vehicles that still provide the features most desired by customers.

The automobile sector is very competitive, and no manufacturer ever discloses the cost of components. The costs of developing and tooling constitute a large portion of the total vehicle manufacturing cost, and thus increasing the number of vehicles using one particular technology substantially reduces the manufacturing cost per vehicle, because the cost can be distributed over a large number of components. Some components, such as battery cells, can be made common across manufacturers, but economies of scale are typically applicable to individual manufacturers. Currently there is no domestic battery cell manufacturing in India and only imported cells are used. Here we estimate the cost of hybrid components by assuming large-scale domestic production of electric motors and batteries in India. However, as with any new technology, including 48V hybrids, the initial cost would be for a low volume of vehicles and thus much higher than the cost later on, after economies of scale are expected to be achieved.

The costs of hybrids is heavily dependent on the size of battery and the size of the electric motor, but the energy requirements are relatively small compared to the overall power requirements of a vehicle over the NEDC. The electrical energy required during acceleration or generated during braking demands a large amount of power (kW) for short durations. As the *current* and not the voltage is the main driver of the cost of the electrical system, in a 48V system, capturing peak available regenerative braking power will increase the cost with relatively little corresponding CO_2 benefit. Most of the 48V hybrids are also capable of electric-only operation during low-speed, low-load conditions. An electric motor must provide at least a 50% torque boost at low engine speeds to enable significant engine downsizing. Moreover, due to the high cost of lithium-ion battery packs, it is more cost effective to use the ICE to drive the vehicle at higher load conditions than to further charge the battery.

Although the electric motor can be biased to provide its maximum power at relatively low engine speeds, this still requires an electric motor that has at least 15%–20% of the propulsion power of the engine. Even for a small car with little electric-only operation, the electric motor must be at least 8–10 kW in order to capture the majority of available regenerative braking energy and provide significant assist during acceleration. The electric motor power requirements increase with the vehicle curb weight, electric driving range, and additional regenerative braking energy. The lithium-ion battery in a 48V hybrid vehicle must be able to provide the high power demanded by the electric motor during acceleration and recapture large amounts of energy during braking events. Battery packs for hybrid vehicles must be sized to deliver sufficient power without overheating or necessitating additional thermal cooling. Batteries that cannot be designed to provide optimal amounts of power result in more energy storage than is needed for normal driving conditions and this comes at increased cost and weight of the battery pack.

Figure 3 shows the range of electric motors and battery sizes required for the engine sizes of passenger cars sold in India. For all types of 48V hybrid architectures, 8–20 kW motor size with a battery of 100–450 Wh is sufficient.

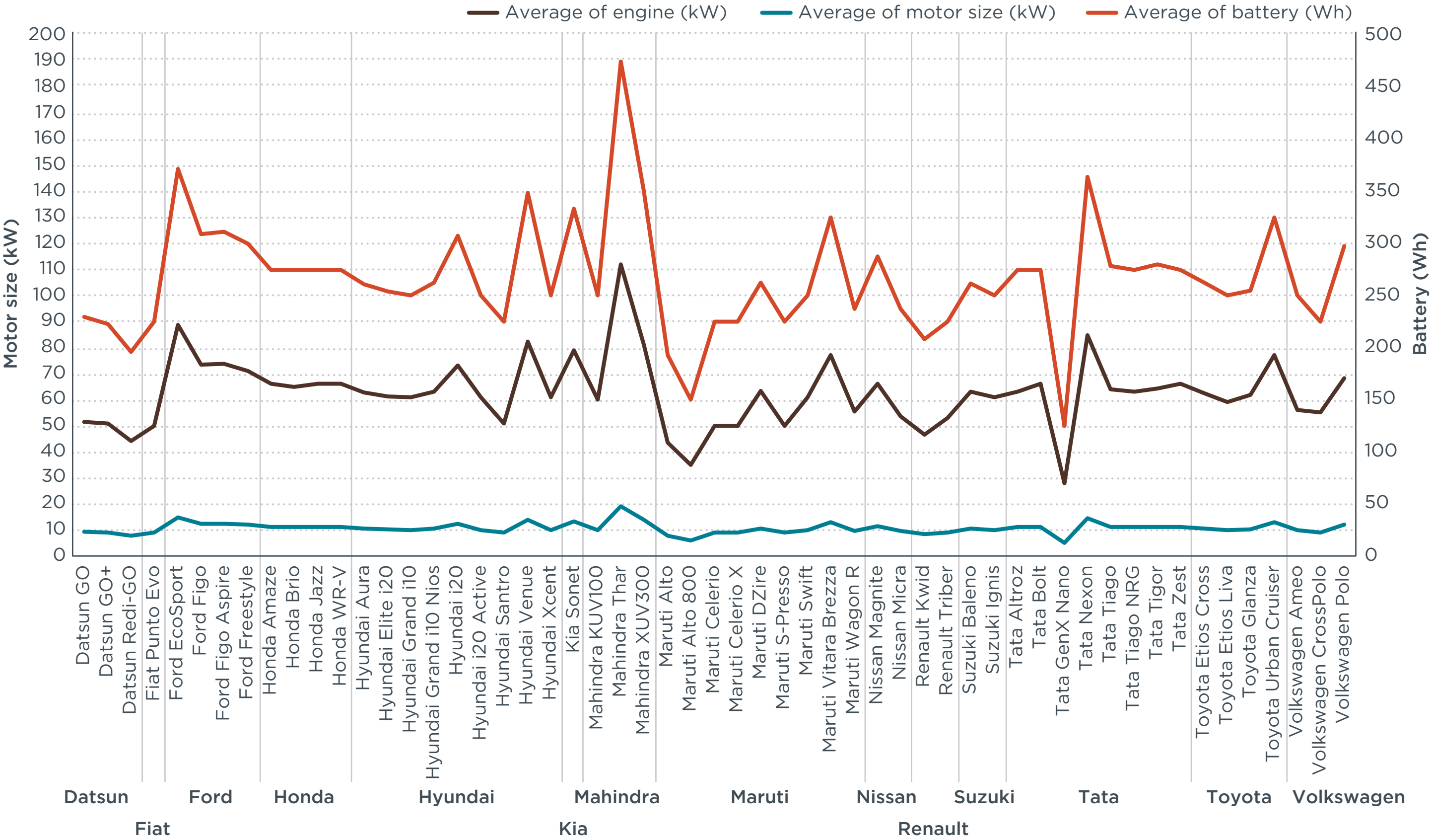

Figure 3. Motor power and battery capacity requirement for passenger car segment.
Source: Analysis of FY 2020–21 new passenger vehicle sales data from Segment Y.

Figure 4 shows the range of electric motors and battery sizes required for the engine sizes used in LCVs in India. Mini trucks and mini vans, which account for more than 50% of the LCV market, are either three-wheeled or four-wheeled vehicles used for last-mile delivery of goods. For all types of 48V hybrid architectures, 2–10 kW motor size with battery of 100–200 Wh is sufficient.

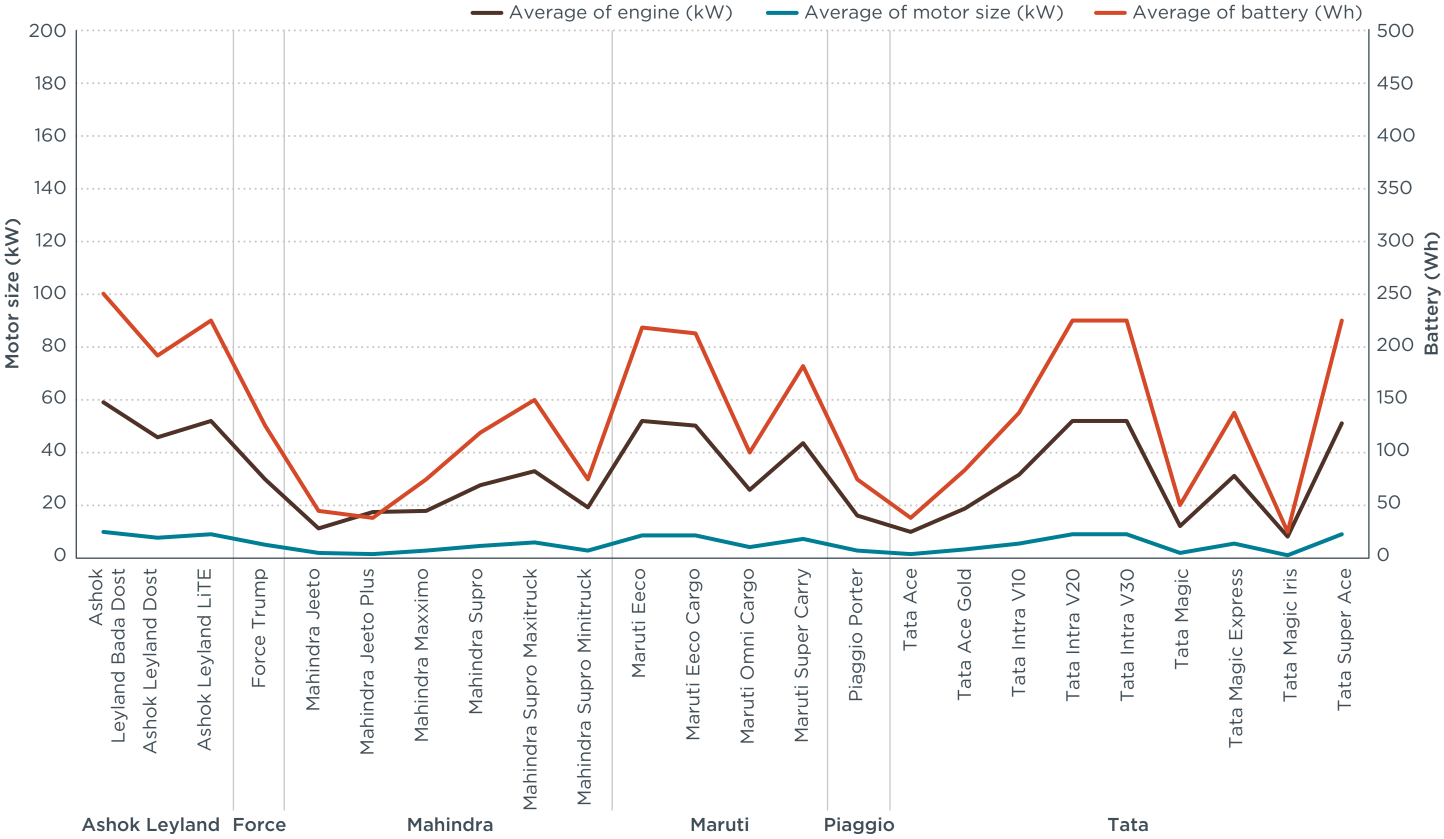

Figure 4. Motor power and battery capacity requirement for light commercial vehicles.
Source: Analysis of FY 2020–21 new light commercial vehicle sales data from Segment Y.

In 48V hybrids, the motor and battery do not consume significant utility space and the voltage being below the 60V threshold significantly reduces the need for complex safety measures (Serrarens, 2015). Therefore, it is reasonable to expect the cost of 48V hybrid systems would be significantly lower than for higher voltage hybridization, and indeed the results below bear that out.

COST ESTIMATION METHODOLOGY

Teardown analyses were one of the innovations introduced by the U.S. Environmental Protection Agency (EPA) when conducting its technology analyses for the 2012–2016 greenhouse gas (GHG) and corporate average fuel economy (CAFE) standards (EPA & National Highway Traffic Safety Administration, 2012). This approach uses consistent methods and assumptions, and the costs are assessed directly rather than being inferred from price. However, a teardown analysis is very complex, costly, and time-consuming; also, it only reflects technologies currently in mass production and depends heavily on knowledge of component, manufacturing, and assembly costs. Such analysis would need to be updated frequently to account for the latest developments and changes in new technologies. In India, most vehicle manufacturers regularly conduct similar teardown exercises to do competitor benchmarking.

In the past, P2 and powersplit hybrid configurations were studied in Europe and the results of the teardown analyses were published (Kolwich, 2012). Additionally, the ICCT commissioned FEV to conduct a detailed assessment of 48V P0 hybrid costs for B and C segment vehicles in the European Union (FEV assumed P2 hybrid systems would be used for segment D and E vehicles) as part of a larger analysis of 2025 technologies published in 2015 (Blanco-Rodriguez, 2015).

Although AVL also made cost estimates of 48V hybrids based upon teardown assessments, the FEV estimates were chosen as the baseline cost of the P0 system for this paper. The FEV estimates (Table 2) were chosen over the AVL estimates due to their transparency. This is because the FEV teardown cost methodology and data have been published in a series of public reports, starting with their initial work for EPA and then in a series of reports for ICCT. Their work has been scrutinized in EPA rulemakings and their assumptions are all publicly available. For this analysis, the FEV P0 costs were adjusted to 2020, 2025, and 2030 vehicles using learning factors derived from Ricardo and AVL cost estimates for 2015 through 2030.

Table 2. FEV hybrid technology manufacturing costs for a 2015 production EU midsize car assuming 450,000 production volume.

	P0 hybrid (2015)
Battery type	Li-ion
Vehicle example	Segment C
ICE power [kW] (hp)	80 (107)
Electric machine power [kW] (hp)	15
Battery capacity [kWh]	0.53
Battery voltage [V]	48
Cost breakdown (INR)	
Battery	26,353
BSG (P0) / Starter (stop/start)	17,568
Converter	8,784
Brake, Tensioner, Pulley, Belt	4,568
Alternator	-3,795
Total	**53,478**

[a] In a hybrid vehicle, the electric motor can also function as a generator to supply electricity to electrical systems and charge the battery used for energy storage. Therefore, the generator can replace an alternator in 48V hybrids.

Note: The FEV study gave costs in Euros, which are converted into INR using conversion factor of 1 Euro = 86.9 INR in 2020.

Technology costs are also constantly coming down due to improvements. For example, further improvements to lithium-ion batteries will allow the 48V battery to cold crank the engine, and then the conventional 12V starter and lead-acid battery can be eliminated (Duren, 2017). A second technology improvement is higher power density battery cells, which will reduce hybrid battery size and cost. Battery cell development has been driven by the high energy needs of BEVs and PHEVs and battery cell manufacturers are developing lithium-ion chemistries with higher power density that will enable hybrid batteries with lower size and energy capacity while maintaining performance. This reduction in battery size and cost is not reflected in the cost studies in this report and thus our estimates are conservative.

The 2015 FEV teardown analysis was conducted on a BSG 48V hybrid system with a 0.53 kWh battery pack and a ratio of power (kW) to energy (kWh) of about 28. However, since then, cell chemistry has been optimized for higher power density using lithium iron phosphate (LFP) (A123 Systems, 2016) and lithium titanate (LTO; MAHLE GmbH, 2019). These batteries still supply 15 kW of power and reduce energy capacity to just 0.36 kWh. LFP batteries do not need active cooling for most applications because of very low impedance and because they contain no cobalt, and this further reduces cost. Using a high power density battery with a power-to-energy ratio of 40 yields a battery pack size of 0.37 kWh with the same power output. Assuming that the cost per kWh remains the same, this reduces the cost of the battery pack. Moreover, the overall price of the battery pack should not increase in the future because neither LFP nor LTO contain cobalt, a rare and expensive raw material.

The costs of the components for hybrid architectures other than P0, which are P1 to P4 architectures, were scaled using AVL-estimated system cost data for the different 48V hybrid architectures (Dornoff et al., 2022). Scaling estimates were also derived to estimate the change in cost for changes in battery and electric motor size, using adjustments for the technology components. Finally, cost adjustments were made for labor costs in India by using a study analyzing the impact of labor costs in Western and Eastern Europe on overall hybrid costs (Kolwich, 2013).

In a 48V configuration, the cost of the electric motor and battery form the major chunk of the total costs. The size of the electric motor needed depends on the weight of the vehicle and it is a significant variable in defining motor rating for optimum performance at an affordable cost. In the AVL analysis, the electric motor used ranges from 12 kW to 20 kW, and that is optimal sizing for most European vehicles. Recall that vehicles in India are lighter, though, and thus lower-rated motors can give the desired performance.

Motor and controller costs are a function of their peak kW rating. This scaling function is probably truer for motors than it is for controllers because the high-power electronics in the controller change as a function of the power rating, but the low-power electronics do not change much. Thus, in this analysis, motor costs were scaled with motor size, but not electronics cost. The cost of different electric motor sizes were estimated using fixed (54%) and variable (46% $/kW) components derived from regressions based on FEV teardown studies.[4] Hybrid battery costs were calculated using a fixed (25%) and a variable (75% $/kWh) component, each derived from the AVL cost data.

The labor cost sensitivity analysis for all technologies includes the average direct labor rate in Germany (€33.28/hour for suppliers and €44.16/hour for OEMs) versus an average of Eastern European labor rates (€7.75/hour for suppliers and €10.29/hour for OEMs). Replacing the Germany labor rates in the cost analyses with the average Eastern European rates reduces the average technology costs by 19%. The minimum wage as fixed by the state government in Delhi from October 1, 2020 onward is ₹723 rupees per day for "skilled workers."[5] The equivalent Euro conversion of the per-day wages is €8.25/day, and that is similar to Eastern Europe labor rate.[6] Hence, in this paper, the FEV cost analysis for different technologies based on Eastern Europe labor rates is utilized.

The costs for P1, P2, P3, and P4 were indexed to P0 cost and ratios for battery, non-battery, and total costs were calculated. The cost scaling factors for 2025 are presented in Table 3. Note that the battery size is dependent on the motor size and remains the same for different hybrid configurations.

4 National Research Council. 2013. Transitions to Alternative Vehicles and Fuels. Washington, DC: The National Academies Press. https://doi.org/10.17226/18264.

5 Labor rates in Delhi from https://www.simpliance.in/minimum-wages/delhi

6 The currency conversion ratio used for the analysis is 1 Euro = 86.9 INR

Table 3. 2025 cost indexed to P0 for different hybrid configurations, and various motor and battery sizes.

48V hybrid configurations	8 kW (200 Wh)		10 kW (250 Wh)		12 kW (300 Wh)		15 kW (375 Wh)		20 kW (500 Wh)	
	Total	Non battery	Total	Non battery	Total	Non battery	Total	Non battery	Total	Non battery
P0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
P1	1.29	1.47	1.26	1.44	1.24	1.42	1.22	1.39	1.19	1.35
P2 side mounted	1.63	2.03	1.58	1.98	1.54	1.93	1.48	1.86	1.41	1.78
P2 coaxial	1.76	2.23	1.70	2.17	1.64	2.11	1.58	2.04	1.49	1.93
P3	1.61	1.99	1.56	1.94	1.52	1.89	1.46	1.83	1.39	1.75
P4+P0 versus AWD	0.92	0.86	0.95	0.91	0.97	0.96	1.01	1.02	1.07	1.14
P4+P0 versus FWD	1.82	2.33	1.82	2.38	1.82	2.42	1.83	2.49	1.85	2.61

The factors for cost reduction from learning for all architectures are 6.0% from 2015 to 2020, 2.9% from 2020 to 2025, and 2.1% from 2025 to 2030. The cost translation step also involved adjustments for labor costs of 19% and currency conversion. The total cost obtained represents the direct manufacturing cost (DMC) for each of the individual technologies (Table 4, below).

All of the DMC cost estimates reflect the cost of material, labor required to assemble the component for the technology, and the inflation rates over the period of years to the assessment year. DMC does not include indirect costs such as research and development, corporate operations, dealer support, or marketing, and does not cover profit. DMC can be considered as the incremental difference in the cost of components between the new technology configuration and a baseline technology configuration. The cost estimation for the 48V hybrids for 2020 in India was done using this formula:

$$DMC_i = FEV\ cost_i \times scaling\ factor_i \times EU\ factor \times Currency\ conversion\ to\ INR$$

Where,

DMC_i refers to direct manufacturing cost of 48V hybrid in INR

$FEV\ cost_i$ refers to direct manufacturing cost of P0 hybrids in Euro for year 2020, 2025, and 2030.

$scaling\ factor_i$ refers to the scaling factors used converting the electric motor and battery to different sizes and the hybrid system to different architectures

EU factor refers to the adjustment factor used to convert labor cost to the Eastern European market from the Western Europe cost

Currency conversion to INR refers to the factor used to get the DMC to INR in 2020

Table 4. Hybrid cost projections for a 48V P0 BSG with 15kW motor until 2030 versus a baseline vehicle without stop-start.

	Learning applied		Year	Direct manufacturing cost		
				Battery	Non-battery	Total
Baseline with 0.53 kWh battery			2015	₹26,353	₹27,126	₹53,478
Learning 2015–2020	Ricardo	6.0%	2020	₹19,340	₹19,908	₹39,248
Higher power battery (0.37 kWh)				₹13,493		
Elimination of 12V starter					-₹2,811	
FEV 2020 + adjustments				₹13,493	₹17,077	₹30,569
Learning 2020–2025	Ricardo	2.9%	2025	₹11,646	₹14,740	₹26,386
Learning 2025–2030	Ricardo	2.1%	2030	₹10,474	₹13,256	₹23,730

Note: The FEV study gave costs in Euros, and these were converted to INR using conversion factor of 1 Euro = 86.9 INR in 2020.

Figure 5 gives the 48V hybrid cost for different motor sizes and hybrid architectures. The battery size and its cost for each motor size is estimated from power to energy ratio of 40 kW/kWh. (Details of battery and non-battery costs are given in Appendix Table A1.) The motor sizes selected are suitable for most of the passenger car segment sold in India. For each motor size, P2 coaxial is the most expensive, as it needs a higher level of modification in the vehicle for integration.[7] AVL and Ricardo estimates for 2030 assume a diminishing learning cost over time, resulting in an average annual learning factor of 2.1% between 2025 to 2030 for all architectures.

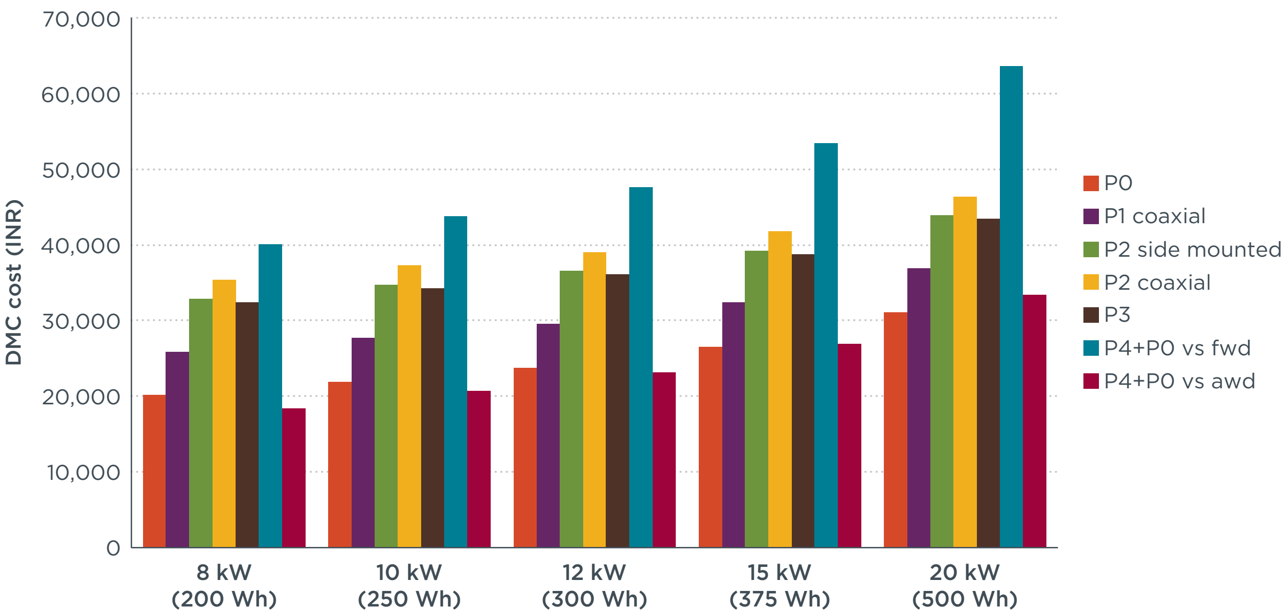

Figure 5. DMC cost of 48V hybrids in 2025.

Note: The battery sizes reflect a 40 kW/kWh power-to-energy ratio for the respective motor sizes.

The higher electric power provided by 48V systems can also reduce the cost of adding other technologies. While it is difficult to quantify these cost reductions, it is important to at least acknowledge that conventional hybrid system cost analyses such as this one do not include potential cost synergies. For example, 48V hybrid systems can

7 Adding a P4+P0 system to a FWD vehicle is more expensive than a P2 coaxial system, but it adds part-time AWD that may be of some value to many customers. Adding P4+P0 to a conventional AWD vehicle is less expensive than a P2 coaxial system.

deliver the power needed for an electric motor integrated within the turbocharger or a separate electric compressor, and these would reduce the cost of adding e-boost systems.

ADVANCED MICRO HYBRID COST CALCULATION

The costs in Table 5 are scaled for an electric motor with 2.3 kW of power and a battery size of 0.036 kWh. Compared to 48V and 60V hybrid systems, the cost of a DC/DC converter in an advanced micro hybrid will be much lower because of low power levels. Additional adjustments were made for the much lower power requirements on the belt drive and pulley systems for the starter generator motor.

Table 5. DMC cost estimates for advanced micro hybrid with 2.3 kW motor and 36 Wh Li-ion battery using Eastern Europe labor rates, relative to a conventional C segment gasoline vehicle without start-stop.

	Micro hybrid (2025)	Micro hybrid (2030)	Advanced micro hybrid (2025)	Advanced micro hybrid (2030)
Vehicle example	Segment C	Segment C	Segment C	Segment C
Battery type	AGM	AGM	Li-ion/Pb-acid	Li-ion/Pb-acid
ICE power [kW] (hp)	80 (107)	80 (107)	67	67
Electric machine power [kW] (hp)	—	—	2.3	2.3
Battery capacity [kWh]	—	—	0.04	0.04
Battery voltage [V]	12	12	12	12
Costs				
Battery	₹579	₹520	—	—
BSG (P0) / Starter (stop/start)	₹890	₹801	₹6,795	₹6,111
Brake, Tensioner, Pulley, Belt	—	—	₹2,894	₹2,602
Sensors	₹1,603	₹1,441	₹1,603	₹1,441
Alternator:	₹445	₹400	(₹2,404)	(₹2,162)
36Wh Li-ion battery	—	—	₹4,815	₹4,330
TOTAL DMC	**₹3,517**	**₹3,163**	**₹13,702**	**₹12,322**

COST ESTIMATES AND PAYBACK CALCULATIONS

Figure 6 compares the CO_2 reduction potential on the NEDC of the different 48V hybrid technologies in a small gasoline passenger car with their DMC costs. The values are absolute values, not relative, and they show the total cost of every package with respect to the total CO_2 reduction potential. The industry average CO_2 value of 121.3 gCO_2/km for FY 2020–21 was used to calculate the total CO_2 reduction potential for each 48V hybrid. The results help us to understand the technologies that might be more attractive to vehicle manufacturers in order to reduce CO_2 emissions, and illustrates to regulators that more cost-effective solutions are available than the P0 systems generally being used on first-generation 48V hybrid systems. These other cost-effective hybrids can do more to reduce the fleet average CO_2 emissions and to meet stringent fuel efficiency standards.

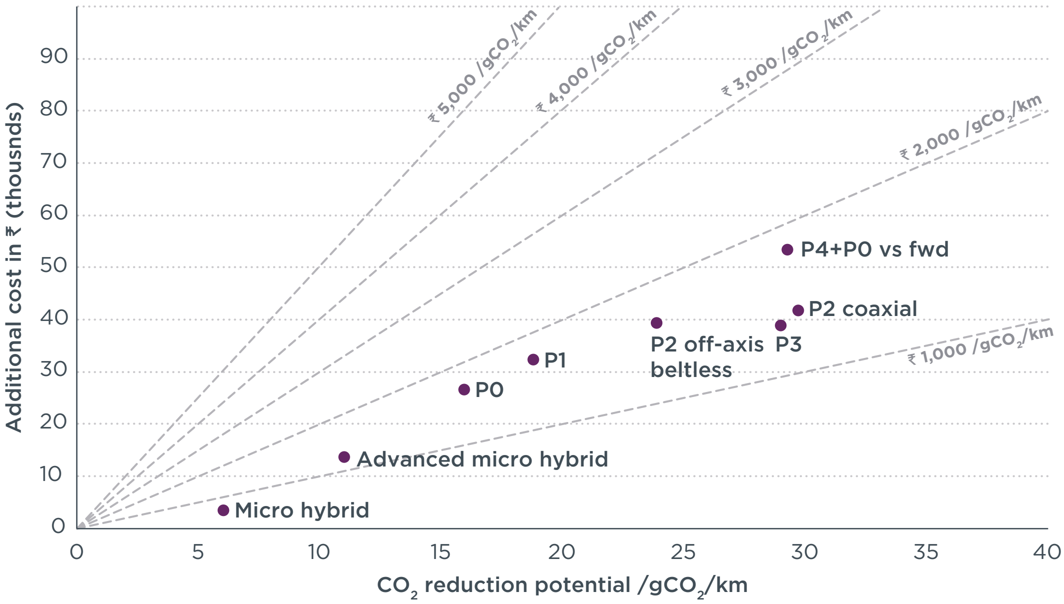

Figure 6. DMC cost of 48V hybrids with respect to total CO_2 reduction potential for a gasoline vehicle in 2025 on the NEDC cycle. All systems use 15 kW motors except micro and advanced micro hybrids.

As illustrated, most architectures have a DMC cost of about ₹2,000/gCO_2/km, although the P2 coaxial and P3 systems appear to be somewhat better at about ₹1,500/gCO_2/km. A point to note is that in India there is still no penalty imposed on manufacturers if CO_2 emissions limits are exceeded. Based on the analysis presented here, establishing a penalty of ₹2,500/gCO_2/km is suitable for passenger cars, keeping in view that some manufacturers might have higher DMC cost because they do not enjoy large economies of scale. This would mean that using 48V hybrid technologies will be cheaper to apply than paying the fine.

CONSUMER PAYBACK PERIOD

All of the cost estimates discussed above are direct manufacturing costs, which are borne by the vehicle manufacturer. Such costs do not include various indirect expenses included in the purchase price paid by the customer, such as warranty, research and development, depreciation, maintenance, corporate overhead, and sales and distribution costs. Consumer payback period, meanwhile, refers to the number of years it takes for the operational savings that accrue to the owner to recover their investment in the vehicle technology. In the case of hybrid vehicles, this is the time it takes for savings on gasoline to recoup the higher upfront cost of a hybrid as compared to a conventional vehicle.

The U.S. EPA developed indirect cost factors for its 2017–2025 U.S. light-duty vehicle GHG standards rulemaking (EPA, 2012). These indirect cost multipliers (ICM) vary with the state of development and complexity of the given technology. For hybrids, the EPA estimated that the battery was at a relatively early stage of development and assigned it a "High-1" ICM complexity; meanwhile, the non-battery components were classified as "Medium" and this results in a higher near- and long-term ICM for the battery than for the non-battery components. For the battery, we apply the near-term ICM out to 2024, and the switch to long-term ICM is expected after 2022 for the non-battery components (Table 6).

Table 6. 48V hybrid indirect cost multipliers (ICM).

	ICM complexity	Near-term end	Near-term ICM	Long-term ICM
Battery	High 1	2024	1.564	1.345
Non-battery components	Medium	2022	1.387	1.290

The payback period is also a function of the individual daily driving distance, fuel consumption, and fuel price. For calculating fuel savings, small cars and SUVs are assumed to travel 10,000 km per year (less than 30 km a day) and LCVs 36,500 km per year (100 km a day). Also, real-world fuel consumption is assumed in this analysis to be 20% higher than the certified value (K. & Singh, 2020) and the fuel price is the April 2022 retail price in Delhi (Petroleum Planning & Analysis Cell, 2022).

The payback period needed for the incremental fuel savings to offset the incremental cost of the 48V systems is summarized for 2025 vehicles in Figure 7. P0 is simple technology and easy to implement on passenger cars, but the fuel saving benefits are less. As a result, it takes more time to recover the additional cost spent on the technology. As we increase the level of complexity in P2 or P3, the cost of technology is higher, but at the same time, the large fuel savings help recover the initial investment faster.

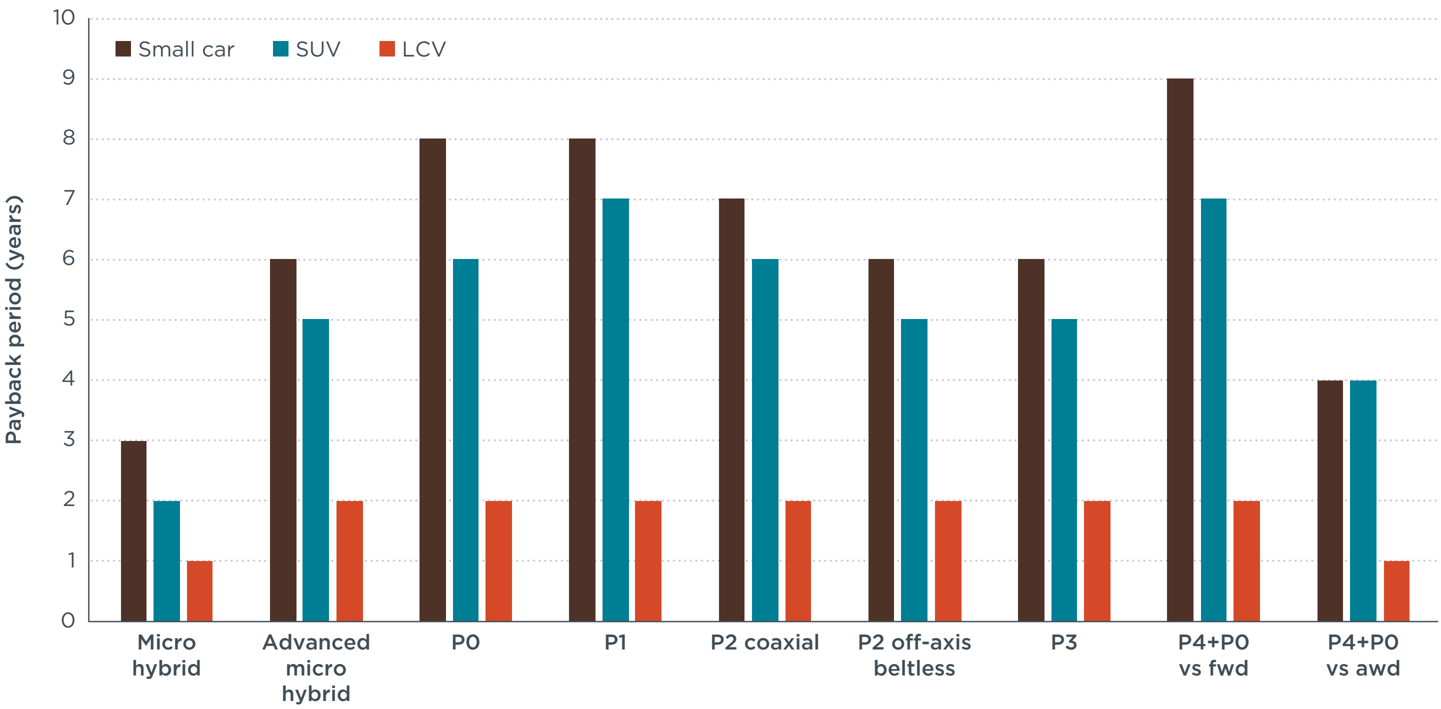

Figure 7. 48V hybrids payback period (years) in 2025 for small car, SUV (10,000 km per year), and LCV (36,500 km per year) at a gasoline price of ₹120/liter.

The payback period is relatively earlier for SUVs than for passenger cars because SUVs consume more fuel and thus there are greater fuel savings from hybrid technology under similar mileage. P4+P0 hybrid offers maximum fuel saving benefits and is the most expensive if added to a FWD vehicle. This delays its initial cost recovery to 8–9 years for vehicles with less daily driving. When a P4+P0 hybrid architecture is used on an AWD vehicle, then there is a substantial cost reduction because the electric motor itself can provide the AWD functionality and there is no need for expensive mechanical equipment such as transfer case and cardan shaft.

Those who drive a lot will see payback much sooner. For example, the payback period is less 1 year for LCVs. Additionally, long-term reductions in battery, motor, and power electronics cost will further reduce the payback period.

Importantly, all of society benefits from reduced emissions. Over the life of the vehicle, the fuel savings more than pay for the incremental cost, and thus more stringent CO_2 standards that incentivize the deployment of 48V hybrid systems would result in net benefits to consumers and to all of India.

CONCLUSION AND POLICY IMPLICATIONS

Increasingly stringent fuel consumption standards and concerns about energy security have stimulated interest in hybrid vehicles globally, and India is no exception. The analysis above shows that 48V hybrid systems have the potential to reduce fuel consumption in combustion engine vehicles cost effectively in India, more so than complex solutions such as variable compression ratio and further engine downsizing. Additionally, a 48V hybrid system helps manufacturers meet the ever-increasing electrical demands from new equipment such as electric compressors, catalytic converter heating, and active chassis systems.

The introduction and production of hybrids has been slower in India than in other regions, partially because current fuel economy standards can be met without them and partially because of how taxes are structured. For example, in India today, Toyota hybrid models like the Camry, Prius, and Vellfire are assessed a 28% Goods and Services Tax (GST) and 15% compensation cess. Meanwhile, a small car less than 4 m in length is taxed at 28% GST and a 1%–3% compensation cess, and this is despite the small car being similar to the Toyota models in terms of CO_2 emissions. **Changing to a CO_2-based tax system in India would reward the efficiency of hybrids.**

From the manufacturer point of view, the choice of 48V architecture is important. Integrating a P0 system into an existing engine does not have packaging constraints, but P1, P2, and P3 architectures all require that modifications be made to existing vehicles to accommodate the electric motor. Manufacturers particularly focus on the CO_2 emissions savings, and customers benefit from the fuel savings. This analysis shows that the P2, P3, and P4 architectures offer substantially better fuel efficiency (16% on average) than a conventional vehicle without a start-stop system because of high recuperation energy and engine management. However, the efficiency benefit over a start-stop system for P0 and P1 architectures is only about half that of the P2 to P4 architectures, due to the inability to eliminate engine friction. The P4+P0 architecture has the highest CO_2 benefit among all hybrids due to high recuperation energy and relatively lower losses in drive train. Increased electric power levels (from 8 kW to 20 kW) allowed more brake energy to be recovered, reducing CO_2 emissions by an additional 6% with the P3 architecture and 5% with P2.

Any payback analysis is highly sensitive to fuel price and daily distance traveled. Using the April 2022 gasoline price in Delhi (₹120/liter) and a daily driving distance of 66 km per day, we estimated the payback period for most of the 48V hybrids can be 2–4 years. Indeed, 48V hybrid costs are declining rapidly in Europe and dropped 6% per year from 2015 to 2020. This annual cost reduction is expected to slow considerably, though, to 2.9% per year from 2020 to 2025 and then 2.1% per year from 2025 to 2030. In addition, hybrid battery packs are currently oversized to be able to assist acceleration and capture regenerative braking energy. The recent development of battery cells with higher power density should enable further cost reductions, as should the development of 48V batteries that can handle cold temperature engine starts and eliminate the need for the redundant 12V battery and starter.

This study found that P1 costs are about 25% higher than P0 (BSG) costs. P2 coaxial and P3 costs are both about 50% higher than P0 costs, with P2 side-mounted systems about 10% cheaper than P2 coaxial systems. The P4+P0 system cost versus a conventional AWD vehicle is about the same cost as P0, due to the cost savings from removing the conventional 4WD transfer case, differential, and driveshafts. If P4+P0 is added to a FWD vehicle, the cost is about 114% higher than P0, although some consumers will value the addition of part-time AWD.

If policymakers wish to support the market success of hybrids in India, they should focus on two related factors. The first is the value to society. Given the lifetime fuel savings and reduced CO_2 emissions, the societal value of hybrids is much greater than their incremental cost, and consumers will recoup their higher upfront investment. **Thus, the second major factor is future adoption of more stringent emission standards for passenger cars.** As CO_2 standards become more stringent, manufacturers will be encouraged to turn to 48V hybrids as a cost-effective solution, just as is already occurring in Europe.

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APPENDIX A. DETAILS OF BATTERY AND NON-BATTERY COSTS FOR DIFFERENT ELECTRIC MOTOR SIZES

Table A1. Estimates of battery cost, non-battery cost, and total cost of different electric motor sizes for 48V hybrids shown in Figure 5 using AVL data.

Motor size	DMC cost	P0		P1 coaxial		P2 side mounted		P2 coaxial		P3	
		2025	2030	2025	2030	2025	2030	2025	2030	2025	2030
8 kW	Total	20,115	18,111	25,914	23,114	32,874	29,824	35,395	31,944	32,403	29,335
	Battery	7,725	6,934	7,725	6,934	7,725	6,934	7,725	6,934	7,725	6,934
	Non-battery	12,389	11,177	18,189	16,180	25,148	22,890	27,670	25,010	24,678	22,401
10 kW	Total	21,950	19,753	27,750	24,756	34,709	31,466	37,231	33,585	34,239	30,977
	Battery	8,884	7,974	8,884	7,974	8,884	7,974	8,884	7,974	8,884	7,974
	Non-battery	13,066	11,778	18,866	16,781	25,825	23,491	28,347	25,611	25,354	23,002
12 kW	Total	23,786	21,394	29,585	26,397	36,545	33,107	39,066	35,227	36,074	32,618
	Battery	10,043	9,015	10,043	9,015	10,043	9,015	10,043	9,015	10,043	9,015
	Non-battery	13,743	12,380	19,542	17,383	26,502	24,092	29,023	26,212	26,031	23,603
15 kW	Total	26,539	23,857	32,338	28,859	39,298	35,569	41,820	37,689	38,827	35,080
	Battery	11,781	10,575	11,781	10,575	11,781	10,575	11,781	10,575	11,781	10,575
	Non-battery	14,757	13,282	20,557	18,285	27,517	24,994	30,038	27,114	27,046	24,505
20 kW	Total	31,127	27,960	36,927	32,963	43,887	39,673	46,408	41,793	43,416	39,184
	Battery	14,678	13,175	14,678	13,175	14,678	13,175	14,678	13,175	14,678	13,175
	Non-battery	16,449	14,785	22,249	19,788	29,208	26,498	31,730	28,618	28,737	26,009

Table A1 continued.

Motor size	DMC cost	P4+P0 vs FWD		P4+P0 vs AWD	
		2025	2030	2025	2030
8 kW	Total	18,430	16,207	36,600	36,450
	Battery	7,725	6,934	7,725	6,934
	Non-battery	10,705	9,273	28,875	29,516
10 kW	Total	20,773	18,279	39,935	39,775
	Battery	8,884	7,974	8,884	7,974
	Non-battery	11,888	10,305	31,051	31,800
12 kW	Total	23,177	20,406	43,332	43,171
	Battery	10,043	9,015	10,043	9,015
	Non-battery	13,134	11,391	33,289	34,156
15 kW	Total	26,900	23,698	48,544	48,398
	Battery	11,781	10,575	11,781	10,575
	Non-battery	15,119	13,123	36,762	37,823
20 kW	Total	33,416	29,457	57,540	57,466
	Battery	14,678	13,175	14,678	13,175
	Non-battery	18,737	16,282	42,862	44,291

APPENDIX B. AVAILABLE ENERGY FOR RECUPERATION FOR HYBRIDS IN THE WLTC

The total available energy for recuperation is higher in the more dynamic WLTC than it is in the NEDC (Bao et al., 2017). At the same time, the power requirements are higher in the WLTC, and thus the positive impact of recuperation diminishes. In addition, the higher power requirements of the WLTC necessitate greater contribution from the ICE, while the NEDC has more phases with low and constant speed that can be partly covered by the electric motor. The available braking energy correlates also with the size of the electric machine. Table B1 gives the availability of recuperation energy in the WLTC for different motor sizes. The latter is dimensioned so as to recover the available power during the braking events, while increasing the electric motor power capacity does not offer any additional benefit.

Table B1. Availability of additional recuperation energy in P2, P3, P4 as compared with P0 in 48V architectures in WLTC.

Electric motor power (kW)	Recuperation energy in kWh			Additional recuperation energy available in P2	Additional recuperation energy available in P3, P4
	P0, P1	P2	P3, P4		
5	0.25	0.35	0.34	41%	36%
8	0.36	0.50	0.51	37%	41%
10	0.41	0.59	0.61	45%	48%
12	0.44	0.66	0.70	49%	57%
15	0.49	0.75	0.79	51%	61%
20	0.52	0.84	0.92	60%	75%
25	0.55	0.90	1.00	63%	81%
30	0.56	1.02	1.02	81%	81%

Note: Data is based on a typical E segment car in Europe. *Source*: AVL.