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FUEL CONSUMPTION REDUCTION TECHNOLOGIES FOR THE TWO-WHEELER FLEET IN INDIA

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EXECUTIVE SUMMARY

The two-wheeler market in India is currently dominated by internal combustion engine (ICE) technology, and this vehicle segment is not subject to fuel consumption standards. Given that the two-wheeler fleet consumes more gasoline than all other forms of on-road transport combined, it is important to consider ways to improve the technologies adopted in ICE two-wheelers and to reduce fleet average fuel consumption. In this paper, we first assess the technology used in India's existing two-wheeler fleet. We then estimate the technology potential for improving the fuel efficiency of ICE two-wheelers and the costs associated with doing so and compare the cost-effectiveness of ICE two-wheelers and electric two-wheelers (E2Ws) in reducing overall fleet fuel consumption.

The shift from carburetor technology to fuel injection that has come with the implementation of the Bharat Stage VI emission standards provides the basis from which to consider other incremental technologies for fuel efficiency improvement. Indeed, several technologies have the potential to reduce the fuel consumption of ICE two-wheelers in each of the three market segments we evaluated: small motorcycles with engine displacement less than 150 cubic centimeters (cc); large motorcycles with engine displacement more than 150 cc; and scooters with engine displacement less than 150 cc. However, to promote widespread adoption of these technologies, India needs to adopt a fuel consumption standard for two-wheelers.

To identify realistic fuel consumption targets for each of the three segments and for the fleet overall, we evaluated the cost-effectiveness and the payback period of different ICE vehicle technologies. We designed a variety of ICE technology packages, with increasing numbers of fuel efficiency technologies, specifically for each segment. Additionally, we included an E2W with a range of 100 km for a small motorcycle and 75 km for a scooter as one of the technology packages for those segments. We then used two approaches to estimate the cost of complying with fuel consumption standards. In the first approach, the ICE technology packages are exhausted before switching over to E2Ws. In the second, E2Ws are used ahead of certain ICE technology packages if the E2Ws are more cost-effective. We also assessed the impact of counting E2W emissions as zero instead of as gasoline equivalent fuel consumption, as well as the impact of technology multiplier credits for E2Ws. Figure ES1 shows compliance cost curves for a small motorcycle and a scooter in the year 2025 for both approaches, using gasoline equivalent fuel consumption for E2Ws.

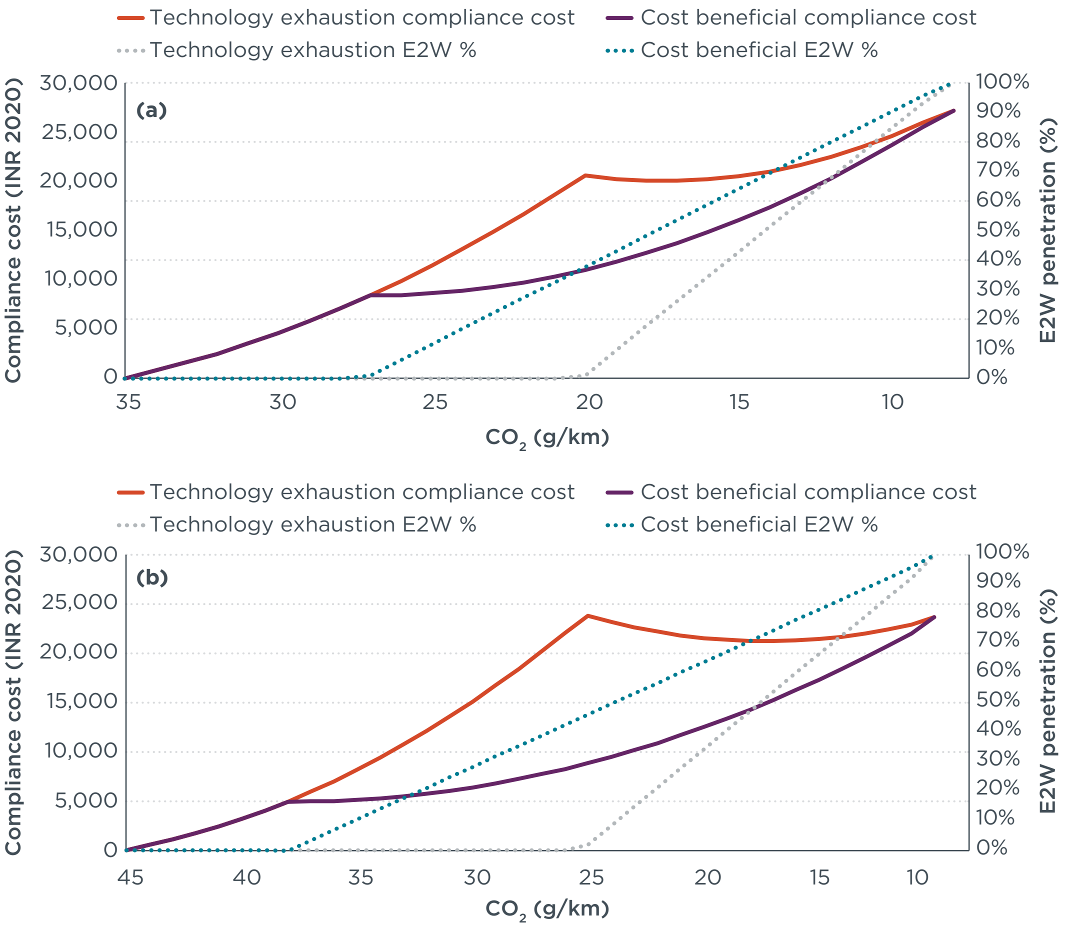

Figure ES1. Compliance cost curves plotted for the ICE technology packages and the E2W package for (a) small motorcycle and (b) scooter in the year 2025.

From internal analysis that will be included in one of ICCT's forthcoming publications, we have observed that on a total cost of ownership (TCO) basis, the E2W motorcycles are cost-competitive well before 2025. However, as the above figure shows, from an incremental cost perspective, the high upfront cost of E2W motorcycles makes the adoption of ICE technologies cheaper until there is a need for 23% fuel consumption reduction for the motorcycle, which corresponds to an emissions level of 27 gCO$_2$/km. We estimate that technology package PK3 can achieve the required 23% benefit for small motorcycles and can be paid back within 6 years of ownership. Technologies such as engine friction reduction, 5-speed transmission, low-rolling-resistance tires, and idle start-stop can be used in the short term to achieve this 23% benefit. Despite providing more fuel savings, the technology package with mild hybridization (package PK5) pays back only after 6 years.

Similarly, the figure shows the incremental cost of E2W scooters and ICE scooters. The compliance cost curves of scooters show that an E2W scooter is more cost effective if scooter emissions need to reduce below 38 gCO$_2$/km. Technology package PK2, which includes idle start-stop, engine friction reduction, and low-rolling-resistance tires, can deliver a fuel consumption reduction of nearly 18% versus a typical scooter. Similar to a small motorcycle, the hybridization technology package (package PK5) has a payback period of 7 years, despite the high operational savings from the technology.

Application of a learning factor adjustment indicates that the incremental cost of the technology packages will be cheaper in 2030 than in 2025. This means that compliance will be less expensive in 2030 for both motorcycles and scooters. The results show that even with no penetration of E2Ws, the fleet average emissions level, 41.2 gCO$_2$/km, can be brought down to 30 gCO_2/km by 2025 with a compliance cost of less than INR 9,400 and a payback period of less than 6 years. Setting a 2025 fuel consumption standard at an emissions level of 25 gCO_2/km or lower would ensure at least a 32% market penetration of E2Ws by 2025 with a compliance cost of INR 9,300. With compliance cost of less than INR 7,100 in 2030, a fuel consumption standard at an emissions level of 20 gCO_2/km can be achieved by more than 60% market penetration of E2Ws in the two-wheeler fleet, without a multiplier.

TABLE OF CONTENTS

ABBREVIATIONS

AGM	Absorbent glass mat
AMT	Automated manual transmission
BSFC	Brake specific fuel consumption
BSG	Belt-driven starter generator
cc	Cubic centimeter
CO_2	Carbon dioxide
CVT	Continuously variable transmission
DC	Direct current
DCT	Dual-clutch transmission
DMC	Direct manufacturing cost
E-clutch	Electronic clutch
E2W	Electric two-wheeler
ECU	Electronic control unit
EFI	Electronic fuel injection
EGR	Exhaust gas recirculation
EMS	Engine management system
EU	European Union
FY	Fiscal year
GDI	Gasoline direct injection
ICE	Internal combustion engine
INR	Indian rupee
ISG	Integrated starter-generator
kWh	Kilowatt hour
MT	Manual transmission
NO_x	Nitrogen oxide
OBD	On-board diagnostics
R&D	Research and development
RPM	Revolutions per minute
RRC	Rolling resistance coefficient
SAE	Society of Automotive Engineers
SoC	State of charge
TCO	Total cost of ownership
Tech PK	Technology package
TWC	Three-way catalyst
VVL	Variable valve lift
VVT	Variable valve timing
WMTC	World Motorcycle Test Cycle

INTRODUCTION

Two-wheelers are the most economical mode of personal transportation in India. The segment constitutes more than 80% of the market for on-road vehicles (Bhowmick et al., 2019) and is responsible for 60% of gasoline consumption (Bansal & Bandivadekar, 2013). Currently there are no fuel consumption standards for two-wheelers. Setting effective standards requires thorough understanding of both the technology potential and the associated costs. This study examines various conventional internal combustion engine (ICE) fuel efficiency technologies for the two-wheeler segment, including mild hybridization technology, and their payback periods. The Government of India has also set an ambitious target of a 30% share for electric vehicles (EVs) in the new passenger car and two-wheeler fleet by 2030 (Shah, 2018). As a result, this study also explores the prospects for EV two-wheelers (E2Ws).

We present vehicle technology compliance cost curves for meeting potential CO_2 targets in the 2025–2030 time frame. We address several key questions:

(1) How much can ICE technology improve fuel efficiency and reduce the CO_2 emissions of the two-wheeler fleet?

(2) What percentage of E2W vehicles within the overall two-wheeler fleet would be needed to meet a particular CO_2 target?

(3) What are the associated costs of meeting a particular CO_2 target?

This analysis is intended to provide Indian policymakers with the groundwork for discussion of fuel consumption targets for the two-wheeler segment.

METHODOLOGY

Using manufacturer specification sheets, we first analyzed the technology built into the existing two-wheeler market. Then, from a thorough literature review, we made a list of all additional technologies that could be adopted in the two-wheeler fleet to improve fuel economy. Because of the transition to the Bharat Stage (BS) VI vehicle emission norms in India, which was accomplished on April 1, 2020, fuel injection technology is one of the key elements being adopted in the two-wheeler fleet to meet those norms. Hence, this study focuses on technologies other than fuel injection that could enable two-wheelers to achieve CO_2 emission reductions.

The costs associated with these technologies and the percentage fuel consumption reduction benefit they would provide were obtained from Society of Automotive Engineers (SAE) papers, previous ICCT publications, and other sources. Because the direct cost information for a particular technology for a two-wheeler was not available in the public domain, we referenced the incremental costs of major technologies in a passenger car from previous ICCT studies. It seems natural that the modern ICE technologies used in today's passenger cars will also be applied in two-wheelers, limited only by cost and packaging constraints. We translated the cost from a high-powered four-wheeler to a low-powered two-wheeler by taking into account the cost-influencing parameters of the components of the technology. Proper scaling parameters were applied to the cost of the passenger car models to estimate the costs of technologies in two-wheelers. Depending on the components of a particular technology, cost scaling was calculated from the torque, number of cylinders, and engine power of a two-wheeler versus those of a passenger car. The reference models used were Class B Western European passenger cars of 2015, and thus the cost translation step also involved adjustments for inflation, labor costs, and currency conversion. The total cost obtained represents the direct manufacturing cost (DMC) for each of the individual technologies.

After categorizing the technologies as either mature or new, a learning factor adjustment was considered for the cost estimations for 2025 and 2030 (German, 2014). Individual technologies were combined for adoption as part of technology packages where the technologies remain mutually exclusive and do not conflict. For the fuel consumption benefit percentage associated with the adoption of each technology, we referred to previous ICCT publications and SAE technical papers.

Electrification of the two-wheeler fleet was also considered as one of the technology packages for small motorcycles and scooters. The DMC of an E2W model was compared with the equivalent ICE model, and the impact of multiplier credits in the cost of an E2W package was compared with the benefits of ICE packages for the years 2025 and 2030. The penetration of E2Ws in the two-wheeler fleet required to reach a particular fleet average CO_2 emission level was estimated by accounting for an E2W as both a non–zero-emission vehicle and a zero-emission vehicle. We also analyzed the compliance cost of the technology adoption for 2025 and 2030 via two scenarios: one where CO_2 emissions are reduced by first exhausting all ICE technologies applicable to small motorcycles or scooters, and one that includes cost-effective E2W penetration of their respective market segments before the most complete ICE technology package is reached. Finally, we analyzed the payback period of these technology packages for the two-wheeler fleet.

TECHNOLOGY BASELINE AND TREND FOR TWO-WHEELERS IN INDIA

Vehicle technologies have changed substantially in recent decades, and there has been a continuous effort to improve fuel economy. Among the key transitions within the Indian automotive industry were the shift from 2-stroke to 4-stroke engines for most two-wheelers during the BS III to BS IV transition and the recent penetration of fuelinjected BS VI models in the two-wheeler market (Mathai, 2020). The baseline of this study is taken from a previous study that showed the two-wheeler fleet average fuel consumption for FY 2017–18; updated for FY 2018–19, it is 41.2 gCO_2/km (Anup & Yang, 2020). The top 10 best-selling two-wheeler models accounted for 55% of the market that year, and so we first investigate the efficiency technologies contained in these models. Of these, six models are motorcycles, three are scooters, and one is a moped.

Small motorcycles, those with engine displacement less than 150 cc, occupy 54% of the market; scooters represent 33%; and large motorcycles and mopeds follow at ~9% and 4%, respectively. The fuel consumption of a large motorcycle (Class 2 two-wheeler) is the highest, followed by scooter, moped, and small motorcycle (Class 1 two-wheeler). All motorcycles have manual transmissions, and all scooters use continuously variable transmissions (CVTs). This study focuses on the technology potential for three categories: small motorcycles with engine displacement less than 150 cc, large motorcycles with engine displacement more than 150 cc, and scooters with engine displacement less than 150 cc. The representative models in this study are actual models available in the market today. The baseline vehicle technology levels were derived from manufacturer specification sheets, and the trends in engine and transmission technologies included in these models are summarized in Table 1.

Table 1. Technology baseline for small motorcycles, large motorcycles, and scooters.

Parameter	Small motorcycle (BS IV)	Small motorcycle (BS VI)	Large motorcycle (BS IV)	Large motorcycle (BS VI)	Scooter (BS IV)	Scooter (BS VI)
Model year	2017–18	2020–21	2017–18	2020–21	2017–18	2020–21
Engine	4-stroke single cylinder, single overhead camshaft, 97.2 cc, compression ratio 9.9:1		4-stroke single cylinder, single overhead camshaft, 346 cc, compression ratio 8.5:1		4-stroke single cylinder, 109.2 cc, compression ratio 9.5:1	4-stroke single cylinder, 109.5 cc, compression ratio 10.0(±0.2):1
	Constant-velocity carburetor, digital capacitor discharge ignition	Digital electronic fuel injection, digital capacitor discharge ignition	Constant-velocity carburetor, twin-spark transistorized coil ignition	Digital electronic fuel injection, single-spark electronic ignition	Constant-velocity carburetor, spark ignition	Digital electronic fuel injection, spark ignition
	Maximum torque 8.05 Nm @ 5,000 rpm	Maximum torque 8.05 Nm @ 6,000 rpm	Maximum torque 28 Nm @ 4,000 rpm		Maximum torque 9 Nm @ 5,500 rpm	Maximum torque 8.79 Nm @ 5,250 rpm
Transmission	4-speed manual, wet clutch, constant mesh		5-speed manual, wet clutch, constant mesh		Automatic, continuously variable transmission (CVT)	
Thermal management	Air-cooled		Air-cooled		Air-cooled	Fan-cooled

FUEL CONSUMPTION REDUCTION TECHNOLOGIES FOR A TWO-WHEELER

This section discusses the fuel-saving technologies not currently available in India's two-wheeler fleet that are included in this analysis. A literature review was performed to identify individual technologies that are already available on other vehicles and could be commercialized in the 2025–2030 time frame. These include engine, transmission, and vehicle technologies. Table 2 shows the applicability of these technologies in the three representative segments of the two-wheeler market. A brief description of each of the evaluated technologies follows the table.

Table 2. Technology applicability in the representative two-wheeler segments.

Type of technology	Specific technology	Applicability in small motorcycle	Applicability in large motorcycle	Applicability in scooter
Engine technology	Engine friction reduction	✓	✓	✓
	Lubricating oil additives	✓	✓	✓
	Cam phasing		✓	
Transmission technology	5-speed manual transmission	✓		
	6-speed manual transmission		✓	
	Dual-clutch transmission		✓	
	Improved CVT			✓
	Electronic clutch	✓		
	AMT	✓		✓
Vehicle technology	Start-stop	✓	✓	✓
	Low-rolling-resistance tires	✓	✓	✓
	Low-drag brake calipers	✓	✓	✓
	Mild hybridization	✓	✓	✓
	Electrification	✓	✓	✓
Advanced engine technology	High compression ratio	✓	✓	✓
	Variable valve lift		✓	
	Atkinson cycle		✓	
	Gasoline direct injection		✓	
	Exhaust gas recirculation		✓	

ENGINE TECHNOLOGIES

(1) Engine friction reduction

Modern automotive engines use direct modifications in pistons, piston rings, bearings, and valve train components to reduce friction. Other methods include split cooling and the use of a variable oil pump and an electric water pump. Executing some of these technologies on a two-wheeler can be difficult because of their relatively high cost and the need for compactness. Additionally, motorcycles are air-cooled, so split cooling and electrical water pumps cannot be used. Following the U.S. Environmental Protection Agency (EPA, 2016), we consider the reduction of engine friction for two-wheeler engines as a two-stage process. The first stage incorporates modification of the principal dimensions of the engine components, which accounts for a 4% improvement in fuel consumption; the second stage integrates the coating of the components and accounts for another 4% benefit, for a total of 8% improvement in fuel consumption as compared to the base engine (Sukumaran & Joseph, 2013).

(2) Lubricating oil additives

A common oil sump used for both the engine and the lubricated (wet) clutch in motorcycles makes it important to balance the properties of the oil for both engine efficiency and clutch performance. However, scooters that run on 4-stroke engines and a CVT do not have wet clutches. But, because of the location of the engine in a scooter, less draft air reaches the engine for cooling (Posada et al., 2011). As a result, the oil in both a motorcycle and a scooter needs to have lower volatility at higher temperature, higher shear stability, better anti-wear performance, and good gear pitting toughness. Moreover, engine oils contain friction modifiers such as molybdenum compounds, and these decrease the clutch capacity in wet-clutch systems (Iyer, 2012). In on-board diagnostics (OBD-II) norms, catalyst deterioration detection is slated to be implemented by April 2023. One of the industry's challenges is to develop additives to avoid gear pitting (Infineum International Limited, 2019). Currently, phosphorus is an additive chemical component in lubricating oil. The use of phosphorus in lubricating oil poisons the three-way catalyst system, and if phosphorus levels are lowered in the future, there will be a need for a standardized gear pitting test. In this paper, a fuel economy improvement of 3% is considered to result from blending low-viscosity base oil with additives (Marcella & Michlberger, 2016).

(3) Cam phasing, also known as variable valve timing (VVT)

VVT is widely used in gasoline engines. The system rotates the camshaft to improve engine operation. Maximum benefits are achieved with both intake and exhaust VVT, but most of the benefit can be obtained with intake VVT only. Rotating the camshaft to reduce valve overlap at low engine speeds simultaneously increases torque and reduces fuel consumption; increasing valve overlap at high engine speeds increases engine power (Taki et al., 2009). VVT also provides an internal gas recirculation mechanism, which can be used to reduce NO_x emissions. Intake VVT can reduce fuel consumption by 3% and dual VVT by 4.5% (Kramer & Phlips, 2002).

TRANSMISSION TECHNOLOGIES

For two-wheelers, transmission is one domain where there has not been much technology improvement. In India, motorcyclists generally prefer the control offered by a manual transmission. However, scooters fitted with continuously variable transmission (CVT) have gained wide acceptance. Table 3 shows the difference in fuel consumption of a motorcycle and a scooter from the same manufacturer and with the same engine displacement but different transmissions ((Ramachandra et al., 2016).

Table 3. Comparison of fuel consumption levels with different transmission systems.

Vehicle type	Small motorcycle	Scooter
Engine	4-stroke, single-cylinder, 109.2 cc gasoline engine	4-stroke, single-cylinder, 109.2 cc gasoline engine
Power and torque	6.2 kW @ 7,500 rpm 9.1 Nm @ 5,000 rpm	5.8 kW @ 7,500 rpm 8.9 Nm @ 5,500 rpm
Transmission	Manual, 4 speed	CVT
Declared fuel economy (km/liter)	69	49.5
Fuel consumption (liters/100 km)	1.5	2.0
CO_2 emissions (g/km)	34.4	48.9

As the table shows, the commonly used rubber-belt CVT, even though it operates at the maximum power point by automatically varying the speed, has 28% lower efficiency than a 4-speed manual (Zhu et al., 2010)[1]. Improved transmission is a major avenue for fuel efficiency improvement in a two-wheeler. The key technologies discussed in this study are 5- or 6-speed manual transmission, dual-clutch transmission, improved CVT, and automated manual transmission (AMT).

(1) 5- or 6-speed manual transmission

The ratio spread of a 4-speed transmission is small, and the engine must operate at more revolutions per minute (RPM) to meet vehicle speed requirements. This means that the engine operates at higher brake specific fuel consumption (BSFC) points, which increases fuel consumption (Durack, 2016). The Class 1 test cycle does not require operation at high speeds, and therefore a 4-speed gearbox is sufficient. However, the speed range of the Class 2-1 test cycle is high, and in that case there are benefits from a 5- or 6-speed transmission. The engine will also operate in lower BSFC zones, and that will improve fuel efficiency. The power requirements of a small motorcycle are lower than for a large motorcycle, so a 5-speed gearbox will suffice as opposed to a 6-speed. The fuel efficiency benefit of a 5-speed transmission over a 4-speed is considered as 7% for our analysis (Trattner et al., 2015); for a 6-speed transmission over a 5-speed, the benefit is considered as 6%.

(2) Dual-clutch transmission

A dual-clutch transmission (DCT) combines the operating simplicity of an automatic transmission with the efficiency of a manual transmission. A conventional DCT connects the transmission with the engine via two driveshafts. The shift points are predetermined and operated using a mechatronic module that includes sensors and an electronic control unit (ECU). This enables precise and smooth gear shifts with no torque drop. For vehicles needing less power, a dry-type dual clutch is sufficient, but higher-powered vehicles require a clutch system that is submerged in oil and is known as a “wet” dual clutch. The fuel consumption benefit of adopting a dual-clutch transmission for a two-wheeler is 7% over the baseline 5-speed manual transmission (Meszler et al., 2016). A DCT has been designed that is as compact as a manual transmission (Watanabe et al., 2011).

(3) Improved CVT

The gearless scooters currently on the market use a variator-based mechanism to give the effect of changing the gears. This variator-based design uses a balance of belt tension and spring force. Additionally, a CVT is incapable of responding to varying load conditions, as the only control variable is engine speed. Researchers all over the world have sought to improve CVT performance in scooters. One readily applicable means of doing so is the installation of an electronic clutch (e-clutch) (ACMA, 2016). An electromechanical actuator–based CVT is capable of operating at all engine speeds, which optimizes powertrain performance. The efficiency improvement due to such an actuator could be ~12% (Grzegozek et al., 2017).

Another way to improve CVT efficiency is with the use of a chain-and-sprocket transmission drive, with only 1 to 4% loss in transmitted power. By contrast, the belt drive of a conventional CVT has 9 to 15% loss (TVS, 2019), which in turn leads to a power loss of 20 to 25% during transfer to the rear wheel. Switching from a belt drive to a chain-and-sprocket drive could improve CVT efficiency by an additional 12% (Henning, 2020).

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[1] The difference in fuel efficiency between a CVT and a small motorcycle is estimated from Table 3 as $1 - \left(\frac{49.5}{69}\right) = 28.2\%$.

(4) Automated manual transmission (AMT)

Another option for two-wheelers is the use of a semi-automatic gearbox and optimized gear selection via AMT. With a fully electronic control system, AMT can be adopted in scooters, where it can provide the benefits of automation and improved fuel economy (Shinde et al., 2015). Because we found no cost estimation for this technology in the literature, this study does not incorporate the benefit of AMT in the fuel consumption reduction potential for the two-wheeler fleet.

VEHICLE TECHNOLOGIES

(1) Start-stop technology

An integrated starter-generator (ISG) is currently used in some motorcycles and scooters. This is a simple technology that allows for the shutoff of the engine during idling and its restart once the driver wants to accelerate again. Shutting off the engine lowers fuel consumption and emissions for a given trip. The fuel economy benefit of idle start-stop in the World Motorcycle Test Cycle (WMTC) drive cycle for a two-wheeler is 5.8%, and there is an 8% benefit for advanced start-stop systems that also include coasting (Heinzmann et al., 2013). This technology is immensely helpful in the congested traffic conditions of urban areas, where there are frequent stops. It integrates the starter and generator functionality, and an ECU is used for control. In generator mode, it regulates the output voltage to drive the vehicle and at the same time charges the battery. Different kinds of sensors, including battery state of charge (SoC), brake pressure, and neutral gear sensors, are used.

The advanced start-stop system provides additional fuel economy benefits by using features such as idle coasting and start-stop coasting. In this, the engine is disengaged from the transmission and turned off during coasting. Advanced start-stop uses the same hardware as that of engine start-stop and provides the additional functionality by modifying the engine management system (EMS). However, the vehicle should have an automatic transmission system available for the advanced functionality to work efficiently. Electronic clutch (e-clutch) is one such automatic technology that can be used for two-wheelers (Arens et al., 2016). In a vehicle with e-clutch control, an electronic actuator replaces the physical clutch pedal as the mechanism that disengages the engine before gear change. With the help of sensors, the actuator understands when the driver wants to switch gears and, through electronic or hydraulic means, performs the task. EMS has more control of a vehicle and can switch off the vehicle in other instances such as coasting. This in turn reduces fuel consumption. The fuel efficiency benefit of an e-clutch can be realized in combination with advanced start-stop or hybridization technology.

(2) Low-rolling-resistance tires

Vehicle rolling resistance is influenced by vehicle weight and the coefficient of friction between the tires and a given road. The tire rolling resistance coefficient (RRC), measured in kg/tonne, is a function of hysteresis and varies with the tire material, tire width, and inflation pressure. However, compounds added to the tire to lower RRC may affect its grip and durability. Current motorcycle and scooter tires have an RRC of ~20 (Durack, 2016). In passenger cars over the past decade, RRC has dropped substantially and is now between 8 and 9. This shows the potential for two-wheelers to improve RRC. Takayanagi et al. (2017) showed that there is a fuel consumption benefit of ~2.3% for a reduction of 15% rolling resistance of a small motorcycle tire (e.g., from 20 to 17 RRC). Moreover, with current advancements in nanomaterials, it is reasonable to set a target of 25 to 30% reduction of RRC for two-wheelers, which would yield a fuel consumption benefit of ~4 to 5%.

(3) Low-drag brake calipers

Most of India's motorcycles and scooters use disc brake systems. Relative to standard calipers, low-drag caliper designs retract the piston farther from the rotor after each application of the brake. This leads to less disc pad contact with the rotor when the brakes are not applied and reduces the rolling resistance. Under normal driving conditions, a low-drag caliper should account for 0.5% improvement in fuel consumption reduction (United States Environmental Protection Agency, 2016).

(4) Mild hybridization

Hybridization technology is an amalgamation of electric power and an internal combustion engine. The hybrid powertrain can be placed in the same slot on the chassis as it is in conventional ICE models, and the electric drive system draws power from a battery (Hoekstra, 2019). The well-to-wheel analysis of both parallel hybrid and series hybrid models shows ~10% reduction in fuel consumption with minimal change to the vehicle ecosystem. In the parallel hybrid mode, both the electric motor and internal combustion engine power the vehicle individually or together. In the series hybrid mode, the vehicle is primarily driven by the electric motor, and the battery pack provides the energy to drive the vehicle; the engine of the vehicle charges the battery whenever required. The penetration of hybrid two-wheelers could contribute substantially to the electrification of on-road transport in India by 2030 (Dhawan et al., 2017). For large motorcycles, the fuel consumption benefit is estimated to be the same as that for a passenger car, 9% (Lutsey et al., 2017). For a small motorcycle and scooter, a benefit of 11.2% was obtained from an SAE paper (Ramachandra et al., 2016).

(5) Electrification

At present, India uses the energy consumption approach to attribute CO_2 emissions to electric vehicles. The electric energy consumption of battery electric vehicles (in kWh/100 km) is converted to gasoline equivalent in terms of liters/100 km using an energy conversion factor specified in the compliance proposal (Rokadiya et al., 2019). The energy consumption of an E2W uses the factor 0.1028 to convert to gasoline equivalent fuel consumption. The CO_2 emission factor for an E2W uses the factor 23.715 to convert to g/km.

ADVANCED ENGINE TECHNOLOGIES

(1) High compression ratio

Whereas passenger vehicles currently have compression ratios of 11:1 to 12:1, the compression ratios of the air-cooled engines in two-wheelers are still below 10:1. Since the advent of BS VI, four-stroke two-wheeler engines use a three-way catalyst (TWC), which requires a stoichiometric mixture setting and lambda control in part load conditions. This is to guarantee effective exhaust gas aftertreatment. A high compression ratio can also substantially reduce the fuel consumption in part load conditions. However, both thermal stress and exhaust temperature increase with higher compression ratios, and the engine requires improved cooling of the exhaust port and exhaust system (Trattner et al., 2015). Switching from air cooling to water cooling at a higher compression ratio will improve efficiency in part load conditions by ~1.5% and in wide-open throttle operation by 4.5%.

In combination with an exhaust gas recirculation system, further reduction of fuel consumption can be achieved, primarily by de-throttling the engine. Hence, using exhaust gas recirculation along with high compression ratios reduces NO_x emissions as well as fuel consumption. An increase of compression ratio from 8:1 to 11:1 improves overall engine efficiency and results in ~6% lower fuel consumption on the WMTC. In part load, the compression ratio is not limited by knocking and therefore an increase is feasible from the thermodynamic point of view. Currently, the engines of most two-wheelers are being designed on the basis of the quality of fuel available, and the availability of octane 91 fuel in the BS VI era will help manufacturers to design engines for higher compression ratios.

(2) Variable valve lift

Variable valve lift (VVL) changes the intake and/or exhaust valve lift dynamically during its operation. The VVL mechanism controls power output from idling to maximum by continuously varying the valve lift, thereby enabling higher power output relative to conventional engines. Adding VVL to VVT can reduce fuel consumption by 3% (Isato et al., 2009).

(3) Atkinson cycle

In an internal combustion system, the Atkinson cycle is implemented by early or late intake valve closing; this leads to recirculation of the gas into the cylinder through the intake valve and increases the expansion stroke to extract more energy from the combustion process. However, the Atkinson cycle leads to reduced power density in a naturally aspirated engine. This can be compensated for either by combining it with intake boosting (turbocharging), also known as the Miller cycle, or by using wide-range cam phasing to switch from the Atkinson cycle to the Otto cycle for peak power. Because two-wheelers use single-cylinder engines, turbocharging is not feasible, unless there is an adequate arrangement (such as a buffer tank) for continuous exhaust flow. Such an arrangement will inevitably increase the complexity of the system. Hence, turbocharging and adoption of the Miller cycle is not considered in this study. The primary benefits of the Atkinson cycle come from a higher compression ratio and lower peak pressure and temperature, resulting in lower knock tendency. In the Atkinson cycle, an increased expansion stroke is realized by an alternative crank train. In this study, the Atkinson cycle is considered to yield ~7% improvement in fuel consumption reduction for two-wheelers (Pertl et al., 2015).

(4) Gasoline direct injection

Gasoline direct injection (GDI) uses a pressurized fuel injection system with a common rail and injects the fuel directly into the combustion chamber. High-pressure injection ensures that the fuel gets finely atomized and the air-fuel mixing happens directly in the chamber. This allows for higher engine compression and lower fuel consumption. The direct injection of fuel also contributes to in-cylinder cooling, which helps in increasing compression because it reduces the tendency to knock. In this paper, the benefit of a direct injection system along with turbocharging on a 4-stroke motorcycle engine is considered to be up to 7% as compared to the stoichiometric operation of a baseline engine in the European ECE40 drive cycle (Cathcart et al., 2004). However, turbocharging is difficult to implement for a single-cylinder engine because there is not a steady flow of exhaust for the turbocharger to use. The benefit of GDI alone is estimated to be 2% (EPA & DOT, 2012).

(5) Exhaust gas recirculation

In exhaust gas recirculation (EGR), a portion of the inert exhaust gas is extracted from the exhaust manifold and recirculated back into the intake system in order to slow down combustion and reduce combustion temperature. This reduces NO_x, reduces knock effects, and improves fuel efficiency in gasoline engines through its de-throttling benefits. The rerouting of exhaust gas into the combustion chamber can also be achieved by intake and exhaust cam phasing, known as internal EGR. When the rerouting of exhaust gas is done by piping it from the exhaust manifold to the inlet manifold externally, it is called external EGR (Xiao et al., 2018). Our literature review shows that an EGR system can reduce both fuel consumption and NO_x without deterioration of combustion stability (Takasu et al., 2008). In this study, external EGR is presumed to be used together with GDI and the Atkinson cycle with higher compression ratios, yielding a fuel efficiency improvement of 7%.

COST ESTIMATION AND CO_2 REDUCTION OF THE FUEL EFFICIENCY TECHNOLOGIES

The next step is to estimate how much it would cost a two-wheeler manufacturer to adopt these technologies. Our estimates were derived using the incremental costs of manufacturing major technologies for European Union Class B four-wheeler passenger vehicles. Below, we provide detailed information on the characteristics of the scaling done for two-wheelers and the costs of each technology.

COST ESTIMATION APPROACH

This cost assessment is necessarily indirect because technology costs are not in the public domain. A recent press release by Hero MotoCorp, a top-selling manufacturer in the two-wheeler market, mentioned the price hike in BS VI models as compared to the BS IV market. BS VI models cost 10 to 15% more than the BS IV equivalent models (Hero MotoCorp Limited, 2020). The technology assessment presented in this study is a projection based on the technologies that are currently available or are under development. The sources of information are:

(1) CO_2 reduction technologies for EU market Class B passenger cars (Meszler et al., 2016)

(2) Technology and cost assessment for U.S. market light-duty vehicles (Lutsey et al., 2017)

(3) Mid-term evaluation of greenhouse gas emission standards for U.S. market light-duty vehicles (United States Environmental Protection Agency, 2016)

The necessary scaling adjustments were made using a scaling factor for the technology components, an EU factor for the conversion of labor cost from western Europe to eastern Europe, an inflation factor, and currency conversion. We assume that the labor costs of eastern Europe are comparable to those in India (Tanning & Tanning, 2012). All of the cost estimates of DMCs reflect the cost of materials, 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 (R&D), 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 three representative segments of two-wheelers for 2020 in India used the following formula:

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

where

DMC_i refers to the direct manufacturing cost of a technology for a two-wheeler

$PV\ cost_i$ refers to the direct manufacturing cost of the technology in a passenger car

$scaling\ factor_i$ refers to the scaling factor used for the technology under the assumptions described below

EU factor refers to the adjustment factor used to convert labor cost to the eastern EU market

Inflation factor refers to the adjustment factor used to convert 2015 cost to 2020 cost

Currency conversion to INR refers to the factor used to express the DMC as INR 2020

SCALING ASSUMPTIONS FOR TWO-WHEELERS

The scaling of components for each technology was based on the component hardware. Table 4 summarizes the cost-influencing parameter and scaling factor for each technology. Cost estimates for the three representative segments of two-wheelers in this study were executed with the corresponding scaling methodologies.

Table 4. Scaling estimation for two-wheeler technology.

Type of technology	Specific technology	Cost-influencing parameter	Scaling parameter
Engine technology	Engine friction reduction	Roller bearings at camshafts, oil pump, additional manufacturing for split cooling	Scaled by number of cylinders
	Lubricating oil	Improvement in engine machining to accommodate lighter oil and/or low-friction additives	No additional cost compared to baseline oil
	Cam phasing	Camshaft, cylinder head	Scaled by number of cylinders
Transmission technology	5- or 6-speed manual transmission	Clutch housing, wheel set, bearings, shift elements, actuation, assembly, and end-of-line test	Scaled by torque ratio
	Dual-clutch transmission	Dual dry/wet clutch, mechatronics control module	Scaled by torque ratio
	Improved CVT	Precision manufacturing of gearbox, bearings	Scaled by torque ratio
	Electronic clutch	Position sensor, electrohydraulic actuator	Scaled by torque ratio
Vehicle technology	Start-stop	Battery, alternator, sensors, starter, EMS	All components scaled by engine power; sensors remain nonvariable
	Low-rolling-resistance tires and low-drag brake calipers	Tire pressure, design of sidewall, depth of tread of tire	Depends on the chosen value of RRC and the passenger vehicle cost of low-rolling-resistance tires, which is also assumed for the two-wheeler; the cost of low-drag brakes is also assumed similar to passenger vehicle cost
	Mild hybridization	AGM battery, BSG, electronics, EMS, flywheel	All components scaled by motor power; sensors remain nonvariable
	Electrification	Battery pack cost, thermal management, power distribution module, DC converter	Scaled by electrical energy consumption, including range
Advanced engine technology	High compression ratio	Engine cooling, exhaust temperature, bore dimensions	Scaled by engine power
	Variable valve lift	Camshaft, actuators, mountings, cylinder head cover	Scaled by number of cylinders
	Atkinson cycle	Connecting rod design, mechanical actuation	Scaled by number of cylinders
	Gasoline direct injection	Needle valve, turbocharging, opening and closing of the injector via solenoids/piezoelectric components	Scaled by number of cylinders
	Exhaust gas recirculation	EGR cooler, valve, pipes, assembly	Scaled by number of cylinders

For the engine cost estimation, the cost structure of a standard 4-cylinder gasoline four-wheeler was used as the reference for the base engine. The main engine parts of a motorcycle, such as the crank, can be scaled by the number of cylinders and engine power, and the camshaft can be scaled by the number of cylinders. For the engine's electronic components, the ECU depends on the number of cylinders and the sensors but remains independent of engine power.

The cost of friction is disaggregated in two ways, namely the coating of the components and the cooling, roller-bearing components; the cost estimation is equally factored for these two. Although low-friction lubricating oil is a key fuel economy enabler for a two-wheeler, there is no additional cost for low-viscosity oil as compared with the baseline oil. We referenced the cost from the four-wheeler to estimate the same for a two-wheeler to accommodate low-friction additives and low-rolling-resistance tires.

To estimate the cost of transmission technologies—5-speed versus 6-speed transmission and dual-clutch transmission in the three representative segments of two-wheelers—we considered the torque ratio of a two-wheeler against that of a passenger car. We estimated the cost of improved CVT and the electronic clutch after consultation with a tier-1 supplier in the two-wheeler market in India.

The components of a start-stop system are scaled with respect to engine power. The system considered here is a conventional starter capable of meeting the requirement of multiple starts after the engine is shut off for a short duration in traffic. Like battery and brake pressure sensors, the sensors present in the start-stop system remain the same even when the engine power is different. For advanced start-stop, an additional engine management system would be needed. For the mild hybrid technology that combines the starter and alternator into a belt-driven starter-generator with a tensioner for the belt, the scaling was similar to that of start-stop, except that we assumed no alternator in a mild hybrid model.

The cost estimation of high compression ratio is scaled by engine power in this study. The capacity of the engine to compress the fuel mixture varies depending on its maximum power, and with the use of a knock sensor, an appropriate value of compression ratio for a two-wheeler can be obtained.

The number of actuators needed to move cam lobes in a VVL system depends on the number of cylinders in the engine. As a result, the scaling parameter assumed in estimating the cost of advanced engine technologies (e.g., variable valve timing, direct injection, Atkinson cycle) is the number of cylinders in a two-wheeler engine as compared to a passenger car.

Table 5 summarizes the DMCs of various fuel consumption reduction technologies for the three representative models of a two-wheeler and the corresponding CO_2 reduction benefits. The values in the table are a figurative representation of the assumptions used, and the technologies are listed in increasing order of DMC.

Table 5. Summary of fuel consumption reduction and direct manufacturing costs for three representative segments of two-wheelers in India for 2020.

Type	Technology	Direct manufacturing cost (2020 INR)	Fuel consumption and CO_2 reduction benefits
Small motorcycle	Low-friction lubricant	203	2.8%
	Low-rolling-resistance tires, low-drag brakes	405	2.3%
	High compression ratio	772	6.0%
	Engine friction reduction stage 1	1,300	4.0%
	Engine friction reduction stage 2	1,300	4.0%
	5-speed manual transmission vs. 4-speed manual transmission	2,575	7.7%
	Idle start-stop	3,253	5.8%
	Advanced start-stop, with e-clutch	3,707	8.0%
	Mild hybridization	6,549	11.2%
Large motorcycle	Low-friction lubricant	203	2.8%
	Low-rolling-resistance tires, low-drag brakes	405	2.3%
	Intake cam phasing	625	3.0%
	Exhaust cam phasing	1,131	1.5%
	Engine friction reduction stage 1	1,300	2.2%
	Engine friction reduction stage 2	1,300	2.2%
	High compression ratio	1,603	6.0%
	Idle start-stop	3,845	5.5%
	Variable valve lift	4,548	3.0%
	Advanced start-stop	5,342	8.0%
	6-speed manual transmission vs. 5-speed manual transmission	7,439	6.2%
	GDI + EGR + Atkinson cycle	11,461	7.0%
	Mild hybridization	13,604	9.0%
	DCT	14,089	11.6%
Scooter	Low-friction lubricant	203	2.8%
	Low-rolling-resistance tires, low-drag brakes	405	2.3%
	High compression ratio	661	6.0%
	Advanced start-stop with modification in CVT	3,693	8.0%
	Engine friction reduction stage 1	1,300	4.0%
	Engine friction reduction stage 2	1,300	4.0%
	Idle start-stop	3,174	5.8%
	Mild hybridization	5,606	11.2%
	Improved CVT	7,500	12.0%

The technology progression and the consequent reduction of CO_2 emissions in a small motorcycle, a large motorcycle, and a scooter are shown in Figures 1 to 3. The individual benefits of each technology are multiplicatively compounded so that the benefits of adding the technologies on top of one other are accounted for. It can be seen that a reduction of CO_2 emissions by more than 10% is possible in a small motorcycle with a DMC of less than INR 5,000, and that a 5-speed manual transmission provides a good pathway to further CO_2 reduction. Although the limit on the maximum speed of a Class 1 motorcycle in the WMTC cycle, 50 km/hour, restricts the usefulness of a 5-speed transmission, idle start-stop can be adopted for Class 1 motorcycles. The premium variants of most BS VI motorcycles are adopting idle start-stop, and the standard variants are sold without it. Similarly, a high compression ratio provides satisfactory fuel consumption reduction, provided the production tolerance of a manufacturer can accommodate this technology. In other words, the leeway between the prototype and the actual product should be in the acceptable range for the adoption of the technology. Also, increasing the compression ratio beyond 10.5:1 should be accompanied by liquid cooling to prevent a decrease in engine longevity.

There are many more technology options for a large motorcycle than for a small motorcycle. Most of the high-performance motorcycles in the ASEAN market already adopt features with fuel efficiency benefits, such as cam phasing (ASEAN Secretariat, 2019). Also, EGR could be used in a large motorcycle to improve fuel efficiency. For scooters and for the minority of small and large motorcycles that use CVTs, the fuel consumption benefit achieved through an improved CVT is a great opportunity. Mild hybridization of these representative segments is also shown in the technology progression. Until the expected transition to purely electric vehicles, hybrids can provide an incremental technology pathway to reduce fuel consumption.

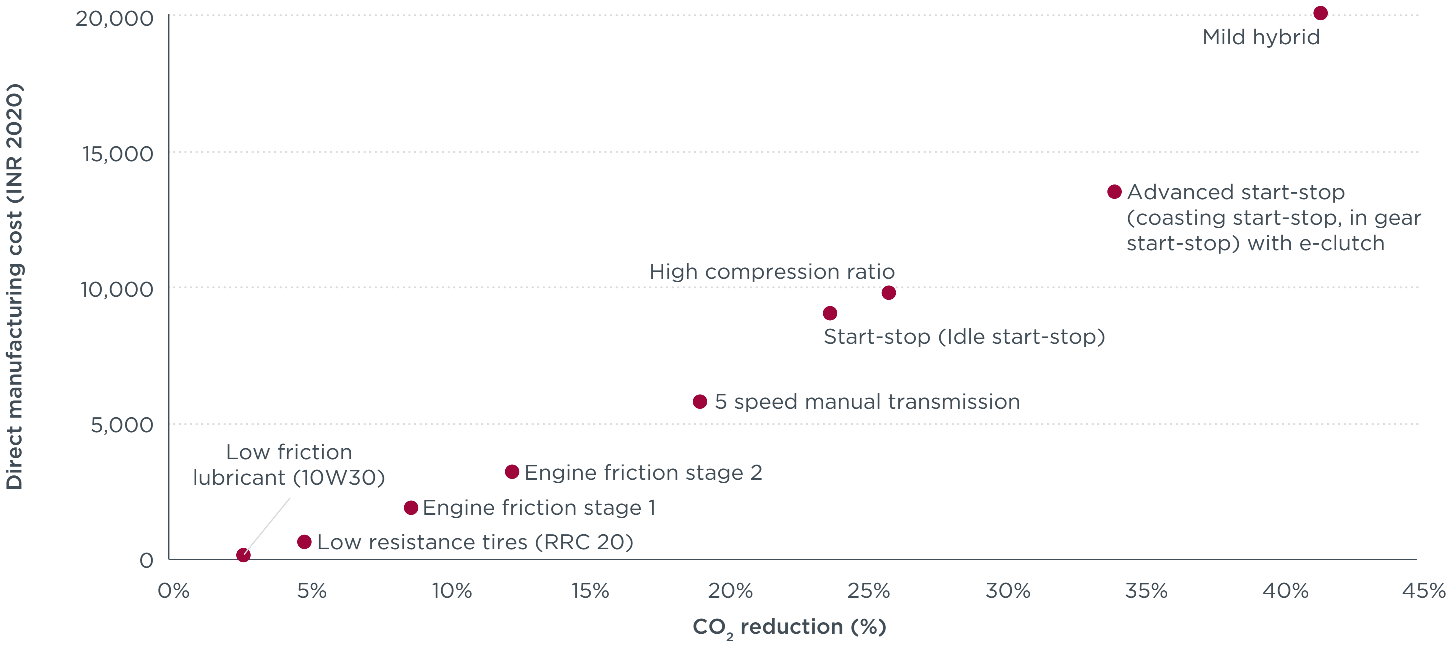

Figure 1. Lowest-cost efficiency technology progression for CO_2 reduction in a small motorcycle.

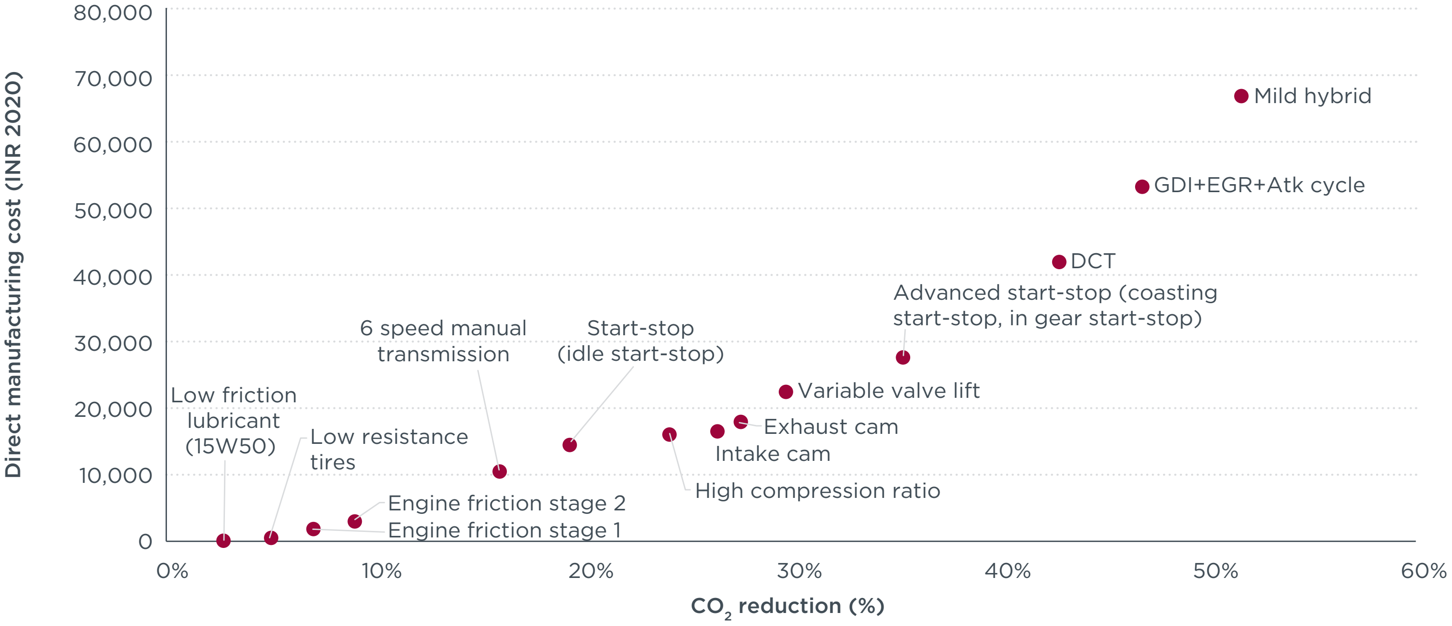

Figure 2. Lowest-cost efficiency technology progression for CO_2 reduction in a large motorcycle.

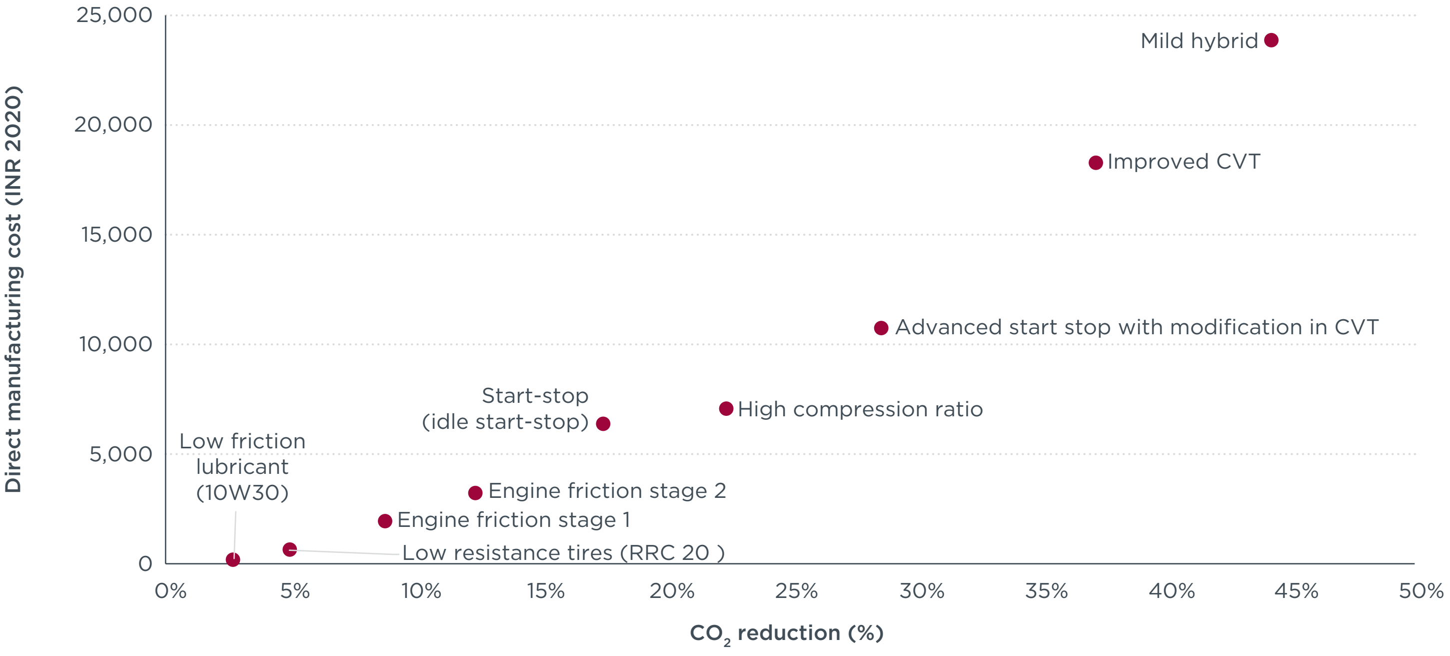

Figure 3. Lowest-cost efficiency technology progression for CO_2 reduction in a scooter.

TECHNOLOGY PACKAGES

We created five ICE technology packages each for the small motorcycle segment and the scooter segment—plus a sixth package representing the fully electric version—and eight ICE technology packages for large motorcycles. These packages cover a wide range of fuel consumption and reflect a baseline of the two-wheeler fleet in FY 2017–18. We find that the ICE technology packages can reduce fuel consumption (and hence CO_2 emissions) by up to 42% in a small motorcycle, 52% in a large motorcycle, and 44% in a scooter. The technology packages, their incremental costs, and their CO_2 reduction benefits are shown in Tables 6 to 8. The packages have been arranged in increasing order of cost-to-benefit ratio. The package costs were obtained by adding the DMC of each technology in the package, and the CO_2 reductions are calculated cumulatively.

Table 6. Technology packages, CO_2 reduction, and cost in year 2025 for a small motorcycle.

Package	Technologies	CO_2 emissions reduction (%)	Cumulative cost (2020 INR)
	Baseline (4-speed MT, air-cooled, EFI, BS VI)	0	0
Tech PK1	Low-friction lubricant, low-rolling-resistance tires, low-drag brakes, engine friction stage 1	8.8	1,907
Tech PK2	Low-friction lubricant, low-rolling-resistance tires, low-drag brakes, engine friction stage 1, engine friction stage 2, 5-speed MT	19.2	5,782
Tech PK3	Low-friction lubricant, low-rolling-resistance tires, low-drag brakes, engine friction stage 1, engine friction stage 2, 5-speed MT, start-stop (idle), high compression ratio	26.0	9,806
Tech PK4	Low-friction lubricant, low-rolling-resistance tires, low-drag brakes, engine friction stage 1, engine friction stage 2, 5-speed MT, start-stop (idle), high compression ratio, advanced start-stop (coasting/in-gear) with e-clutch	34.2	13,514
Tech PK5	Low-friction lubricant, low-rolling-resistance tires, low-drag brakes, engine friction stage 1, engine friction stage 2, 5-speed MT, start-stop (idle), high compression ratio, advanced start-stop (coasting/in-gear) with e-clutch, mild hybrid	41.5	20,063
Tech PK6	Electric motorcycle	76.9	27,148

Table 7. Technology packages, CO_2 reduction, and cost in year 2025 for a large motorcycle.

Packages	Technologies	CO_2 emissions reduction (%)	Cumulative cost (2020 INR)
	Baseline (5-speed MT, air-cooled, EFI, BS VI)	0	0
Tech PK1	Low-friction lubricant, low-rolling-resistance tires, low-drag brakes, engine friction stage 1	7.0	1,907
Tech PK2	Low-friction lubricant, low-rolling-resistance tires, low-drag brakes, engine friction stage 1, engine friction stage 2, 6-speed MT	16.0	10,646
Tech PK3	Low-friction lubricant, low-rolling-resistance tires, low-drag brakes, engine friction stage 1, engine friction stage 2, 6-speed MT, start-stop, high compression ratio	24.2	16,094
Tech PK4	Low-friction lubricant, low-rolling-resistance tires, low-drag brakes, engine friction stage 1, engine friction stage 2, 6-speed MT, start-stop, high compression ratio, intake cam phasing, exhaust cam phasing, VVL	29.2	22,397
Tech PK5	Low-friction lubricant, low-rolling-resistance tires, low-drag brakes, engine friction stage 1, engine friction stage 2, 6-speed MT, start-stop, high compression ratio, intake cam phasing, exhaust cam phasing, VVL, advanced start-stop (coasting/in-gear)	35.4	27,738
Tech PK6	Low-friction lubricant, low-rolling-resistance tires, low-drag brakes, engine friction stage 1, engine friction stage 2, start-stop, high compression ratio, intake cam phasing, exhaust cam phasing, VVL, advanced start-stop, DCT	42.8	41,827
Tech PK7	Low-friction lubricant, low-rolling-resistance tires, low-drag brakes, engine friction stage 1, engine friction stage 2, start-stop, high compression ratio, intake cam phasing, exhaust cam phasing, VVL, advanced start-stop, DCT, GDI, EGR, Atkinson cycle	46.9	53,289
Tech PK8	Low-friction lubricant, low-rolling-resistance tires, low-drag brakes, engine friction stage 1, engine friction stage 2, start-stop, high compression ratio, intake cam phasing, exhaust cam phasing, VVL, advanced start-stop, DCT, GDI, EGR, Atkinson cycle, mild hybrid	51.6	66,893

Table 8. Technology packages, CO_2 reduction, and cost in year 2025 for a scooter.

Package	Technologies	CO_2 emissions reduction (%)	Cumulative cost (2020 INR)
	Baseline (CVT, fan-cooled, EFI, BS VI)	0	0
Tech PK1	Low-friction lubricant, low-rolling-resistance tires, low-drag brakes, engine friction stage 1	8.8	1,907
Tech PK2	Low-friction lubricant, low-rolling-resistance tires, low-drag brakes, engine friction stage 1, engine friction stage 2, start-stop (idle), high compression ratio	22.5	7,042
Tech PK3	Low-friction lubricant, low-rolling-resistance tires, low-drag brakes, engine friction stage 1, engine friction stage 2, start-stop (idle), high compression ratio, advanced start-stop with modification in CVT	28.7	10,735
Tech PK4	Low-friction lubricant, low-rolling-resistance tires, low-drag brakes, engine friction stage 1, engine friction stage 2, start-stop (idle), high compression ratio, advanced start-stop, improved CVT	37.2	18,235
Tech PK5	Low-friction lubricant, low-rolling-resistance tires, low-drag brakes, engine friction stage 1, engine friction stage 2, start-stop (idle), high compression ratio, advanced start-stop, improved CVT, mild hybrid	44.3	23,841
Tech PK6	Electric scooter	78.4	23,639

ELECTRIC VEHICLE PENETRATION IN THE TWO-WHEELER MARKET AND ITS IMPACT ON FLEET AVERAGE CO_2 EMISSIONS

Whereas ICE technology costs generally form an upwardly sloping exponential curve, E2W costs are generally constant for a given vehicle class and battery capacity in a given year. Still, the battery capacity can vary depending on the E2W's range. In a forthcoming ICCT publication, the 10-year total cost of ownership for a short-range E2W was calculated, and this was our reference for the electric model. For this paper, the battery capacity for the E2W models is 3.46 kWh for a small motorcycle and 2.9 kWh for a scooter. The range of an EV model was not specifically stated in a manufacturer specification sheet or in user reviews. Hence, the real-world range for the EV small motorcycle and scooter was assumed from the "ride mode" of the vehicle (Karkera, 2020). The real-world fuel efficiency in kWh/km is estimated for both small motorcycles and scooters from the battery capacity and the real-world range. The battery pack sizes for the short-range models for these segments are obtained from the real-world fuel efficiency. Short-range values of 100 km for a small motorcycle and 75 km for a scooter were chosen on the basis of their typical usage (proportion of highway versus city rides). Because the two-wheeler market in India does not have any electrified models of large motorcycles currently, this study does not take into consideration the E2W model of a large motorcycle.

The cost estimation of the E2W is done such that the DMC of an ICE package can be compared with that of an EV package. The DMC of an EV package is assumed to reflect the E2W vehicle powertrain cost, which consists of components such as the battery, thermal management, power distribution model, inverter, electric drive module, converter, control module, cable, and charging cord. The DMC cost corresponds to the incremental cost of the E2W as compared to the ICE model of the two-wheeler. The cost involved for vehicle assembly and the indirect costs of R&D and depreciation are not considered in this comparison.

As discussed earlier, we accounted for an E2W as both a non–zero-emission vehicle and a zero-emission vehicle. The non–zero-emission value was calculated using the energy consumption approach mentioned above regarding electrification technology. The E2W package cost, which has a CO_2 emission level of *A* g/km, was obtained using the following formula:

$$\textit{E2W package cost for A g/km of } CO_2 = \left(\frac{\textit{E2W cost}}{\textit{Baseline } CO_2 - \textit{E2W } CO_2} \right) \times \frac{A}{\textit{multiplier factor}}$$

where

E2W cost refers to the incremental DMC cost in an evaluation year

A g refers to the CO_2 emission level

multiplier factor refers to the value of the multiplier chosen

Baseline CO_2 refers to the weighted average CO_2 of the two-wheeler fleet in FY 2017–18

E2W CO_2 refers to the non-zero CO_2 emissions of the E2W corresponding to energy consumption (this is set to zero when considering the E2W as a zero-emission vehicle)

The multiplier factor considered in this study is 1.5. A multiplier of 1.5 means that every E2W vehicle sold is counted as one and a half vehicles for the purpose of a manufacturer's fleetwide CO_2 emissions calculation. This spreads the cost of an E2W vehicle over one and a half vehicles.

Table 9 compares the CO_2 emissions and incremental costs of technology packages of the ICE representative segments considered in this study. The non-zero emissions of an E2W small motorcycle and scooter are also listed, as is the weighted average CO_2 emissions of the two-wheeler fleet in FY 2017–18. (The impact of zero-emission accounting for an E2W vehicle is discussed below.) The technology package incremental costs for the E2Ws shown in the table do not account for the use of a multiplier. The cost of the packages in 2025 was obtained by adding the incremental cost of each of the technologies in the package. For the cost evaluation in 2030, learning factor adjustments were used. The introduction of a new technology and a mature technology to the two-wheeler segment incurred learning factor adjustments of -2% and -1%, respectively, such that the incremental costs for a technology package in 2030 are lower than in 2025.

Table 9. Comparison of CO_2 emissions and incremental costs for the representative segments of two-wheelers in India with selected ICE technology packages, compared with those for an E2W small motorcycle and scooter.

Vehicle type	CO_2 emissions (g/km)	Package cost in 2025 (INR 2020) compared with baseline	Package cost in 2030 (INR 2020) compared with baseline
Weighted average of two-wheeler fleet in India in 2017–18	41.2	—	—
ICE small motorcycle (baseline)	35.3	—	—
ICE small motorcycle with Tech PK4	23.2	13,514	13,244
ICE small motorcycle with Tech PK5	20.6	20,063	19,661
E2W small motorcycle	8.4	27,148	11,041
ICE large motorcycle (baseline)	58.1	—	—
ICE large motorcycle with Tech PK7	30.9	53,289	50,677
ICE large motorcycle with Tech PK8	28.1	66,893	63,614
ICE scooter (baseline)	45.2	—	—
ICE scooter with Tech PK4	28.4	18,235	17,341
ICE scooter with Tech PK5	25.2	23,841	22,672
E2W scooter	10.1	23,639	8,676

TECHNOLOGY COST CURVES AND COMPLIANCE COST OF E2W AND ICE TECHNOLOGY IN THE TWO-WHEELER MARKET

Unless there is a requirement that each vehicle meet a particular fuel efficiency level, not all ICE technologies need to be exhausted before introducing E2W vehicles into the fleet. This means that there are multiple ways in which ICE and E2W cost curve data can be integrated to examine compliance cost.

In this study, CO_2 compliance cost is analyzed using two strategies: (1) ICE technology exhaustion and (2) cost-beneficial penetration of E2Ws. The first strategy identifies the level of CO_2 reduction that can be achieved through gradual ICE technology improvement in the coming years.[2] The transition to E2Ws is expected to take place only after all the possible ICE technology packages have been exhausted. At that point, it is assumed that E2Ws will enter the market while these ICE vehicles continue to be sold with the maximum technology. The second strategy reflects the CO_2 reduction that can be realized by increasing the market penetration of E2Ws when the DMC, including multipliers, is less than that of the ICE technology. In this strategy, it is assumed that no E2W vehicles will be sold until cost parity with the ICE technology, including multipliers, is attained. The cost curve analysis below gives the optimum integration of E2W vehicles under the two strategies, and Figure 4 shows the methodology adopted for the compliance cost estimation.

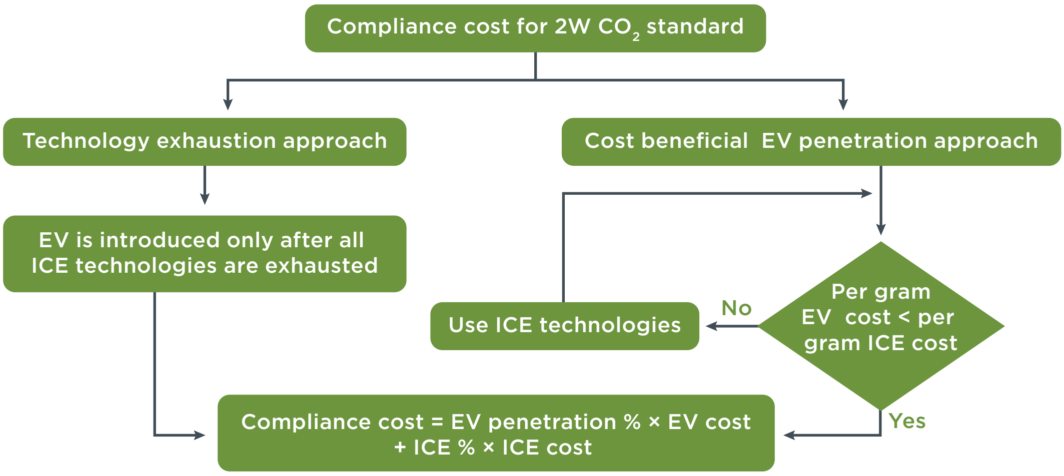

Figure 4. The methodology adopted for the compliance cost estimation.

Figure 5 shows the cost curve plot of a small motorcycle for the year 2025. The horizontal axis represents the CO_2 level in g/km. The left vertical axis represents the compliance cost for achieving a particular CO_2 reduction percentage; the right vertical axis shows the percentage of E2W penetration that can be incorporated in the two-wheeler fleet to achieve the particular CO_2 level. The analysis starts from the baseline CO_2 level of the small motorcycle for FY 2017–18 on the horizontal axis. Recall that this study does not take fuel injection technology into consideration in any of the packages. Manufacturers have reported that the increase in fuel efficiency due to the adoption of fuel injection is 10% to 13% (Singh, 2019). In this study, the ICE technology packages can achieve CO_2 reductions up to 42% for a small motorcycle.

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[2] For CO_2 level of A g/km, the corresponding CO_2 reduction percentage needed

$$= \left(\frac{\text{Fleet average } CO_2 \frac{gm}{km} \text{ of baseline} - A}{\text{Fleet average } CO_2 \frac{gm}{km} \text{ of baseline}} \right) \times 100 .$$

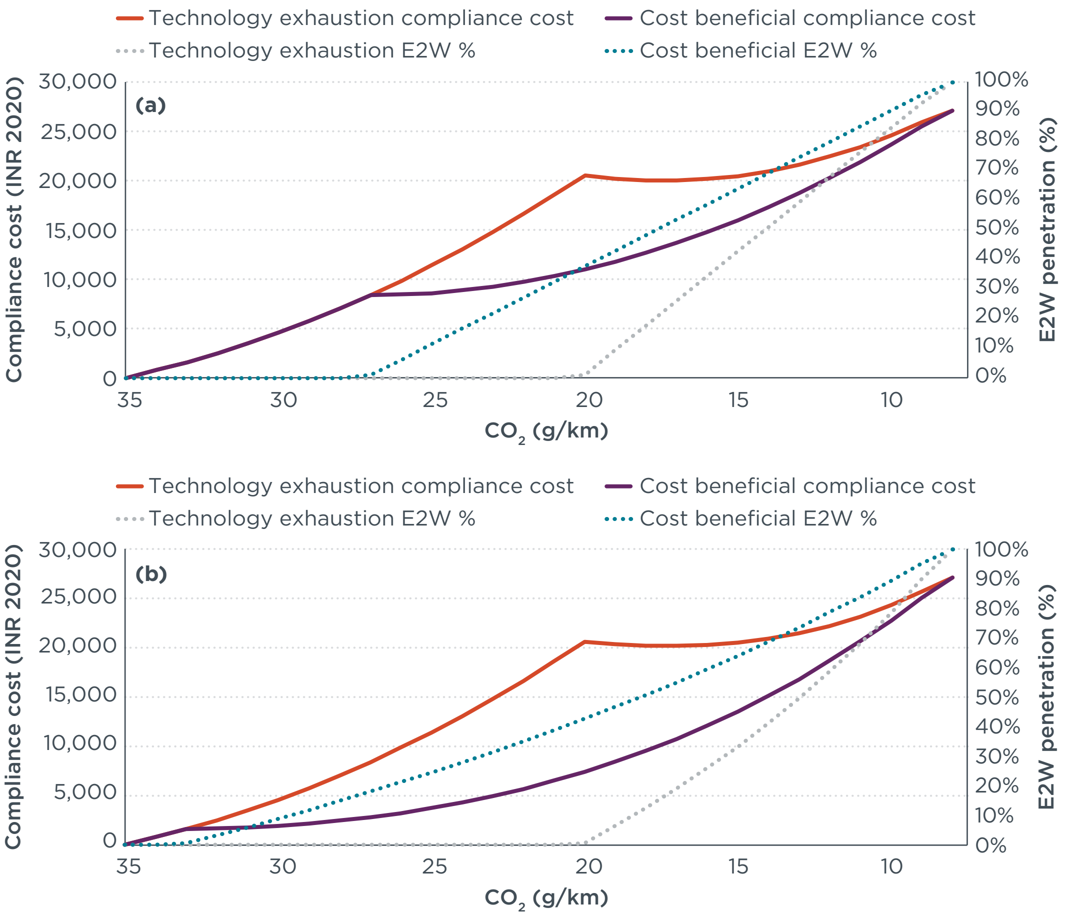

Figure 5. Compliance cost in 2025 for a small motorcycle, ICE and E2W packages (a) and for the same with the E2W granted a multiplier of 1.5 (b).

Figure 5 shows the cost beneficial penetration of E2W motorcycles happens beyond the CO_2 level of 27 gCO_2/km. In the case of maximum exhaustion of ICE technologies, ICE motorcycles remain the only ones in the market up to 20 gCO_2/km, and then beyond 20 gCO_2/km, E2W penetration starts. The effect of the multiplier on the E2W penetration percentage is shown in the (b) portion of the figure. For E2Ws with a multiplier of 1.5, the cost parity of an E2W motorcycle is achieved at a CO_2 level of 33 gCO_2/km and the cost-beneficial E2W penetration starts from there.

To estimate costs for the year 2030, we included a learning factor for easily adopted or new technologies for ICE technology packages, and assumed that the cost of the components and battery for the E2W package would fall by 2030 primarily due to lower battery cost. The compliance cost curves for a small motorcycle in 2030 are shown in Figure 6.

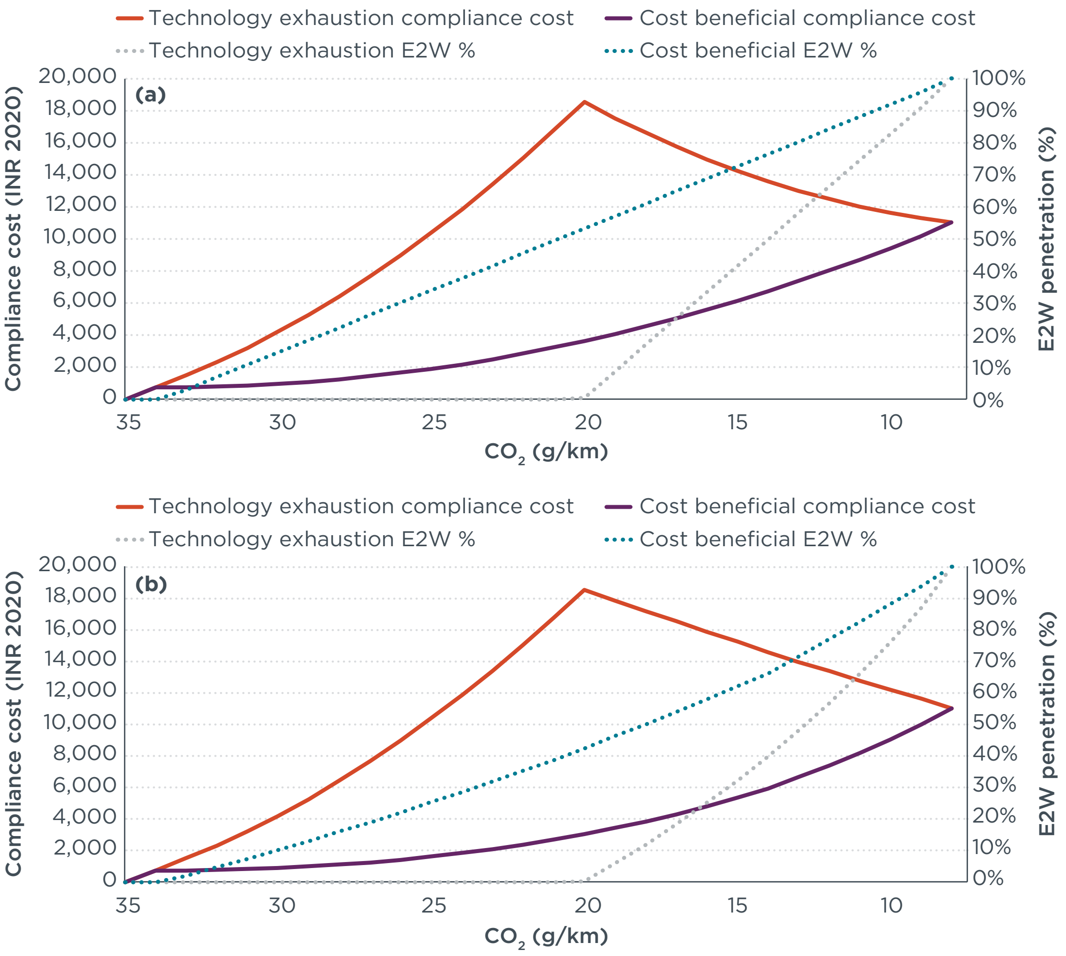

Figure 6. Compliance cost in 2030 for a small motorcycle, ICE and E2W packages (a) and for the same with the E2W granted a multiplier of 1.5 (b).

As shown in the figure, upfront cost parity for E2W motorcycles occurs at a CO_2 level lower than 34 gCO_2/km. For achieving the CO_2 level of 25 gCO_2/km, the cost-beneficial E2W penetration ensures a compliance cost of less than INR 2,000, without multiplier. The cost curve shows that for achieving same CO_2 level of 25 gCO_2/km, the approach of ICE technology exhaustion costs more than INR 10,000 for compliance.

The compliance cost curves for a scooter for 2025 are shown in Figure 7. In this segment, even without any multiplier, there is cost-beneficial EV penetration when the CO_2 level is 38 gCO_2/km. Figure 7a shows that up to the 38 gCO_2/km of CO_2 level, both the technology exhaustion and the cost-beneficial E2W penetration approaches follow the same pathway, which means that up to 38 gCO_2/km, the ICE technology packages for a scooter can provide the CO_2 reduction at the same compliance cost as E2W penetration. Tech package PK2 would be sufficient to achieve this CO_2 level. Beyond 38 gCO_2/km, there is cost parity for the E2W package and it is possible to expect cost-beneficial penetration of E2W to the fleet. The maximum reduction of CO_2 possible from the ICE packages is 44% (26 gCO_2/km), and the same reduction is possible with E2W penetration in the fleet. However, if there is no stringent requirement to achieve this reduction, there would not be any possibility of cost-beneficial penetration of E2W models into the fleet. With multiplier 1.5, E2W scooters could achieve cost parity in 2025 at a CO_2 level of 44 gCO_2/km.

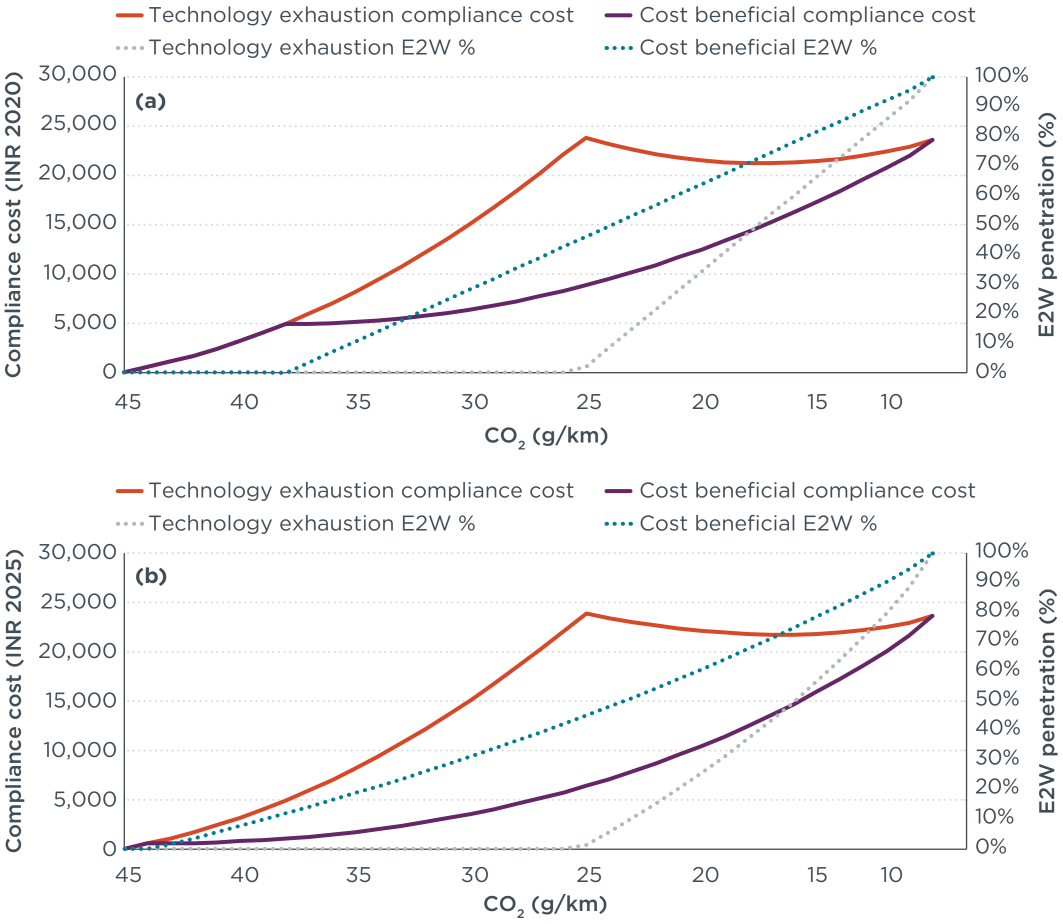

Figure 7. Compliance cost at 2025 for a scooter, ICE and E2W (a) and for the same vehicles with the E2W granted a multiplier of 1.5 (b).

The same methodology used for plotting the compliance cost curves for 2030 for a small motorcycle was used to plot the compliance cost curves for 2030 for a scooter, shown in Figure 8. The cost-beneficial E2W penetration of a scooter is achieved beyond CO$_2$ level 44 gCO$_2$/km. (Figure 8a). By setting a tight standard of less than 22 gCO$_2$/km in 2030, cost-beneficial E2W penetration in the two-wheeler fleet ensures compliance cost less than INR 5,000. The same target of 22 gCO$_2$/km achieved by ICE technology exhaustion costs more than INR 15,000. The effect of adopting multipliers of 1.5 is shown in Figure 8b. The compliance cost curve of a large motorcycle is shown in Figure 9. The technology exhaustion cost curves are plotted for 2025 and 2030. We have not estimated E2W potential or costs for this segment.

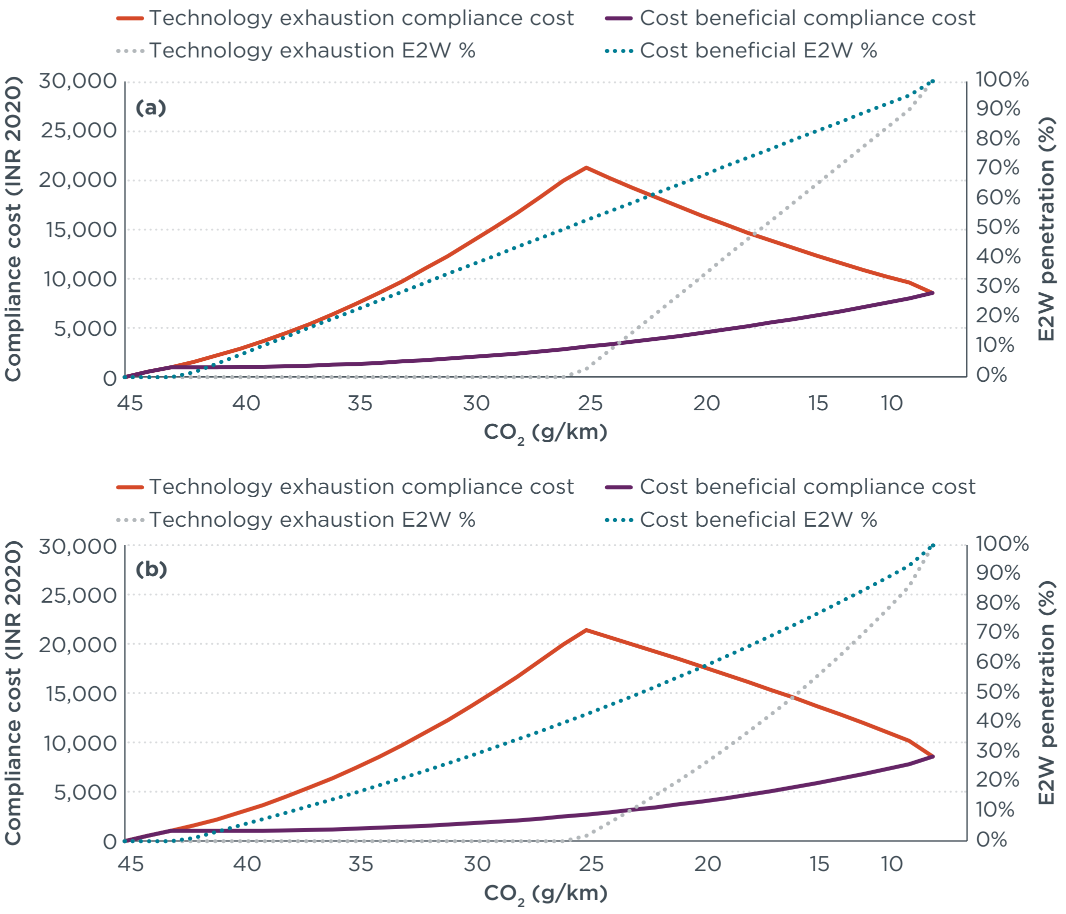

Figure 8. Compliance cost at 2030 for a scooter, ICE and E2W packages (a), and for the same with the E2W granted a multiplier of 1.5 (b).

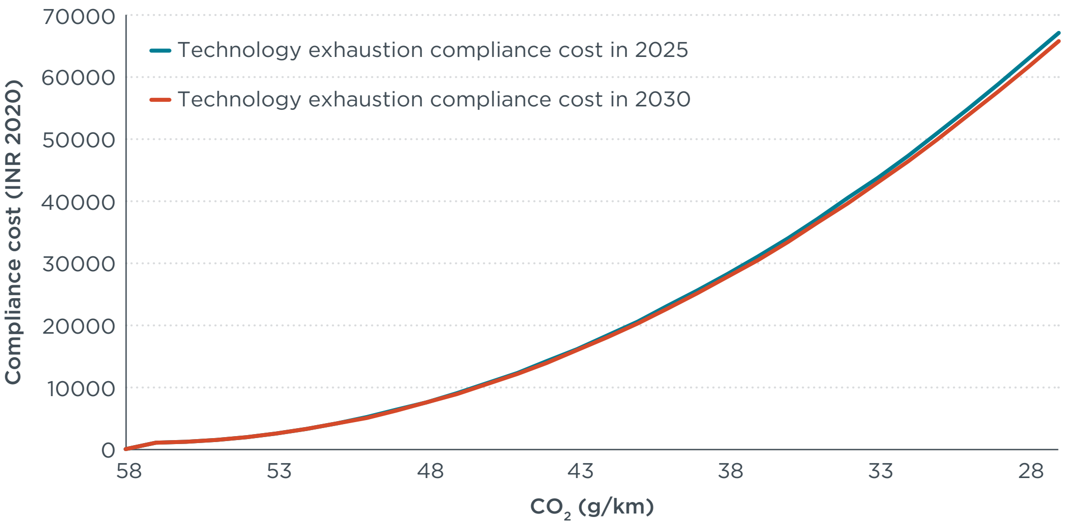

Figure 9. Compliance cost for a large motorcycle, ICE packages, in 2025 and 2030.

IMPACT OF ZERO-EMISSION ACCOUNTING ON FLEET AVERAGE CO_2 EMISSIONS

In the preceding discussion, the emissions from an E2W vehicle were considered in such a way that the E2W package corresponded to a particular battery capacity and a particular range and had a non-zero CO_2 emission level. That is the energy consumption approach of converting an E2W vehicle into its gasoline equivalent. We can also examine the implications for fleet average CO_2 emissions using E2W penetration by accounting for the emissions of an E2W vehicle as zero. The difference is that the E2W percentage penetration required to achieve a particular CO_2 level is less for zero-emission accounting. This means that the regulatory mechanism is reaching that particular CO_2 level with fewer E2W vehicles in the fleet. The actual environmental benefit of CO_2 reduction is not achieved with zero-emission accounting as compared to non–zero-emission accounting.

The E2W penetration percentage curves in Figures 5 to 8 show that even with 100% E2W penetration, the fleet average CO_2 level has a non-zero value. For a small motorcycle, the gasoline equivalent gCO2/km is 8.2 and for a scooter it is 9.8 gCO_2/km. In terms of CO_2 percentage, the fleet average is reduced to 77% for a small motorcycle and 78% for a scooter, as shown in the E2W penetration percentage curves of motorcycle and scooter.[3] With zero-emission accounting, the CO_2 percentage would have come down 100%.[4] The difference with zero-emission accounting is that to reach the same non-zero value of fleet average CO_2, 100% E2W penetration is not necessary and a lower E2W penetration percentage can achieve it. Tables 10 and 11 show the reduction of E2W percentage by zero-emission accounting for a small motorcycle and a scooter for 2025 and 2030.

Table 10. Comparison of E2W penetration percentage for non–zero-emission and zero-emission accounting for an E2W motorcycle.

Vehicle type	Gasoline equivalent gCO_2/km	E2W penetration % for non–zero-emission accounting	E2W penetration % for zero-emission accounting
E2W motorcycle for 2025	8.2	100	75
E2W motorcycle for 2030	7.9	100	54

Table 11. Comparison of E2W penetration percentage for non–zero-emission and zero-emission accounting for an E2W scooter.

Vehicle type	Gasoline equivalent gCO_2/km	E2W penetration % for non–zero-emission accounting	E2W penetration % for zero-emission accounting
E2W scooter for 2025	9.8	100	77
E2W scooter for 2030	9.5	100	76

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[3] *Gasoline equivalent gCO_2/km of E2W motorcycle or scooter in non–zero emission = real world electrical energy consumption in kWh/100km × electrical energy consumption factor* 0.1028 × *gasoline equivalent factor* 23.7135. In 2025, for an E2W motorcycle real world electrical energy consumption is 3.35 kWh/100 km and gasoline equivalent gCO_2/km is 3.35 × 0.1028 × 23.7135 = 8.2 *gCO_2/km*. In 2030, for an E2W motorcycle real world electrical energy consumption is 3.24 kWh/100 km and gasoline equivalent gCO_2/km is 3.24 × 0.1028 × 23.7135 = 7.9 *gCO_2/km*. In 2025,for an E2W scooter real world electrical energy consumption is 4.00 kWh/100 km and gasoline equivalent gCO_2/km is 4.00 × 0.1028 × 23.7135 = 9.8 *gCO_2/km*. In 2030, for an E2W scooter real world electrical energy consumption is 3.88 kWh/100 km and gasoline equivalent gCO_2/km is 3.88 × 0.1028 × 23.7135 = 9.5 *gCO_2/km*.

[4] *Gasoline equivalent gCO_2/km of E2W motorcycle or scooter in zero emission* = 0

PAYBACK EVALUATION OF TECHNOLOGY PACKAGES

Consumer payback period refers to the number of years required for operational savings to recover the initial investment in a vehicle technology—that is, to recover the cost of the purchase. The average kilometers driven per year is assumed to be 10,000 km. Our analysis considers real-world fuel consumption, which is assumed to be 20% higher than the certified value. The fuel price is the existing retail price in Delhi (Petroleum Planning & Analysis Cell, 2020). The energy consumption charge or tariff for electric vehicles was based on the tariff schedule for FY 2019–20 for the distribution company in Delhi (*Tariff Order FY 2019-20*, 2019). Table 12 shows the costs of various vehicle technology packages for a small motorcycle, along with the associated vehicle tax, insurance, and fuel savings. The payback period of E2W vehicle package PK6 was estimated without battery replacement cost or maintenance cost. The cumulative operational savings are calculated as the sum of vehicle technology, vehicle tax, and fuel savings in a year. The consumer payback occurs when these cumulative operating costs shift from negative, reflecting a net outflow of cash, to positive, reflecting net savings. As can be seen, technology package PK4 takes up to 6 years to get to payback, and the hybrid technology in PK5 takes 8 years for net savings. Meanwhile, the initial package PK1 could take only 4 years to pay back. The E2W motorcycle is technology package PK6, and the incremental technology cost without the adoption of any multiplier gives a payback period of 4 years. This means that the purchase of an E2W motorcycle in 2020 would bring cost benefits before 2025.

Table 12. Technology package payback periods (years) in 2025 for a small motorcycle.

Technology package	Year of ownership	Vehicle technology (INR 2020)	Vehicle tax (INR 2020)	Insurance (INR 2020)	Fuel savings (INR 2020)	Cumulative operational savings (INR 2020)
Tech PK1	1	–2,861	–609	–24	1,199	–2,295
	2			–22	1,152	–1,165
	3			–20	1,108	–76
	4			–17	1,106	973
Tech PK2	1	–8,673	–1,846	–72	2,618	–7,972
	2			–67	2,517	–5,522
	3			–59	2,421	–3,161
	4			–50	2,328	–883
	5			–42	2,238	1,313
Tech PK3	1	–14,710	–3,130	–122	3,880	–14,081
	2			–114	3,731	–10,464
	3			–101	3,588	–6,977
	4			–85	3,450	–3,613
	5			–72	3,317	–368
	6			–57	3,189	2,764
Tech PK4	1	–20,271	–4,314	–168	4,661	–20,092
	2			–157	4,482	–15,767
	3			–139	4,309	–11,597
	4			–117	4,144	–7,570
	5			–99	3,984	–3,685
	6			–79	3,831	67

Technology package	Year of ownership	Vehicle technology (INR 2020)	Vehicle tax (INR 2020)	Insurance (INR 2020)	Fuel savings (INR 2020)	Cumulative operational savings (INR 2020)
Tech PK5	1	–30,094	–6,404	–249	5,667	–31,081
	2			–233	5,449	–25,865
	3			–206	5,239	–20,832
	4			–174	5,038	–15,968
	5			–147	4,844	–11,272
	6			–117	4,658	–6,731
	7			–102	4,478	–2,355
	8			–88	4,306	1,863
Tech PK6	1	–40,722	0	–185	11,816	–29,092
	2			–231	11,361	–17,962
	3			–204	10,924	–7,242
	4			–172	10,504	3,090

The payback periods for the technology packages for a large motorcycle are shown in Table 13. Technology package PK1 gives payback within 3 years; depending on the technology package chosen (PK2, PK3, or PK4), up to 30% CO_2 reduction is possible with payback within 7 years. PK5 gives payback within 8 years, but the incremental cost of DMC of PK5 is less than INR 30,000 and this can achieve 35% CO_2 reduction from the baseline CO_2 level of a large motorcycle.

Table 13. Technology package payback periods (years) in 2025 for a large motorcycle.

Technology package	Year of ownership	Vehicle technology (INR 2020)	Vehicle tax (INR 2020)	Insurance (INR 2020)	Fuel savings (INR 2020)	Cumulative operational savings (INR 2020)
Tech PK1	1	–2,861	–609	–23	1,590	–1,903
	2			–21	1,529	–395
	3			–17	1,470	1,058
Tech PK2	1	–15,969	–3,398	–127	3,629	–15,865
	2			–114	3,489	–12,490
	3			–97	3,355	–9,233
	4			–79	3,226	–6,085
	5			–64	3,102	–3,048
	6			–49	2,983	–114
	7			–41	2,868	2,713
Tech PK3	1	–24,141	–5,137	–192	5,741	–23,729
	2			–173	5,520	–18,381
	3			–147	5,308	–13,220
	4			–119	5,104	–8,236
	5			–97	4,908	–3,425
	6			–74	4,719	1,220
Tech PK4	1	–33,595	–7,149	–267	6,973	–34,038
	2			–241	6,705	–27,574
	3			–205	6,447	–21,332
	4			–166	6,199	–15,299
	5			–135	5,961	–9,473
	6			–103	5,731	–3,845
	7			–87	5,511	1,579

Technology package	Year of ownership	Vehicle technology (INR 2020)	Vehicle tax (INR 2020)	Insurance (INR 2020)	Fuel savings (INR 2020)	Cumulative operational savings (INR 2020)
Tech PK5	1	−41,608	−8,854	−331	8,222	−42,570
	2			−298	7,905	−34,963
	3			−254	7,601	−27,615
	4			−206	7,309	−20,511
	5			−167	7,028	−13,651
	6			−128	6,758	−7,021
	7			−108	6,498	−631
	8			−89	6,248	5,528
Tech PK6	1	−62,741	−13,351	−499	9,886	−66,704
	2			−450	9,506	−57,648
	3			−382	9,140	−48,890
	4			−310	8,789	−40,411
	5			−253	8,451	−32,213
	6			−193	8,126	−24,280
	7			−162	7,813	−16,629
	8			−134	7,513	−9,250
	9			−107	7,224	−2,133
	10			−103	6,946	4,710
Tech PK7	1	−79,933	−17,010	−636	10,775	−86,804
	2			−573	10,360	−77,017
	3			−487	9,962	−67,542
	4			−395	9,579	−58,358
	5			−322	9,210	−49,469
	6			−246	8,856	−40,859
	7			−207	8,515	−32,551
	8			−170	8,188	−24,533
	9			−137	7,873	−16,797
	10			−131	7,570	−9,358
	11			−126	7,279	−2,205
	12			−121	6,999	4,673
Tech PK8	1	−1,00,340	−21,352	−809	11,129	−1,11,372
	2			−740	10,701	−1,01,412
	3			−639	10,289	−91,761
	4			−525	9,894	−82,393
	5			−434	9,513	−73,314
	6			−337	9,147	−64,504
	7			−287	8,795	−55,996
	8			−240	8,457	−47,779
	9			−195	8,132	−39,843
	10			−191	7,819	−32,214
	11			−186	7,518	−24,882
	12			−181	7,229	−17,834

Table 14 shows the technology packages and payback periods for a scooter.

Even though hybrid technology adoption may take 7 years to pay back, technology packages PK1 and PK2 could pay back after 3 and 4 years of ownership, respectively. PK3 can give payback within 5 years, and the CO_2 reduction benefit corresponding to PK3 is 29%. PK6 is the incremental technology of an E2W scooter without any multiplier, and the payback period is 3 years. Similar to an electric motorcycle, purchase of an E2W scooter in 2020 could give cost benefits before 2025.

Table 14. Technology package payback periods (years) in 2025 for a scooter.

Technology package	Year of ownership	Vehicle technology (INR 2020)	Vehicle tax (INR 2020)	Insurance (INR 2020)	Fuel savings (INR 2020)	Cumulative operational savings (INR 2020)
Tech PK1	1	−2,861	−609	−23	1,539	−1,954
	2			−22	1,480	−497
	3			−20	1,423	906
Tech PK2	1	−10,562	−2,248	−84	3,933	−8,961
	2			−82	3,782	−5,260
	3			−72	3,637	−1,696
	4			−61	3,497	1,740
Tech PK3	1	−16,102	−3,426	−128	5,020	−14,637
	2			−115	4,827	−9,926
	3			−98	4,641	−5,383
	4			−80	4,462	−1,000
	5			−65	4,291	3,226
Tech PK4	1	−27,352	−5,820	−217	6,519	−26,871
	2			−196	6,268	−20,800
	3			−167	6,027	−14,940
	4			−135	5,795	−9,280
	5			−110	5,572	−3,818
	6			−84	5,358	1,456
Tech PK5	1	−35,761	−7,610	−284	7,750	−35,906
	2			−256	7,452	−28,711
	3			−218	7,165	−21,764
	4			−177	6,889	−15,051
	5			−144	6,624	−8,570
	6			−110	6,370	−2,311
	7			−93	6,125	3,721
Tech PK6	1	−41,087	0	−180	15,686	−25,580
	2			−156	15,083	−10,653
	3			−133	14,503	3,717

The technology package costs can also be looked at through the perspective of discounted cash flow, which is spread over the lifetime of a vehicle. That is, the present-day net value of a technology package can be estimated by forecasting the future cash flow and applying a discount rate over the lifetime of the vehicle. Essentially, this estimation accounts for the time value of money. For this study, the discount rate is 4% and the vehicle lifetime is assumed to be 12 years (Bansal & Bandivadekar, 2013). Table 15 shows the net present value for the technology packages for the three representative segments of two-wheelers in 2025 and 2030.

Table 15. Net present value for technology packages for the three representative segments of two-wheelers in 2025 and 2030.

Technology package	Net present value in 2025 (INR 2020)			Net present value in 2030 (INR 2020)		
	Small motorcycle	Large motorcycle	Scooter	Small motorcycle	Large motorcycle	Scooter
Tech PK1	8,076	11,920	11,396	8,112	11,957	11,433
Tech PK2	14,572	15,343	25,021	14,682	15,545	25,155
Tech PK3	19,247	25,687	28,750	19,435	25,991	28,953
Tech PK4	19,825	25,825	29,236	20,082	26,248	29,581
Tech PK5	17,201	27,939	30,680	17,583	28,461	31,130
Tech PK6	73,072	17,616	1,16,879	97,396	18,404	1,40,148
Tech PK7	—	4,673	—	—	5,678	—
Tech PK8	—	–17,834	—	—	–16,570	—

CONCLUSION

This study examined fuel consumption reduction technologies that are applicable for the two-wheeler market in India. We analyzed the cost-effective adoption of these technologies and their benefits in reducing fuel consumption. We found that even the most fuel-efficient segment of the two-wheeler fleet, small motorcycles, has the potential to further reduce fuel consumption up to 42% using ICE technologies alone. Additionally, in small motorcycles, fuel consumption reductions of up to 26% are paid back within 6 years of ownership, and fuel consumption reductions of up to 42% are paid back within 8 years. The payback period for an E2W small motorcycle package is just 4 years, and the net present value estimated for the E2W motorcycle package is more than four times of the net present value estimated for the maximum ICE technology package.

Large motorcycles, the least fuel-efficient segment of the two-wheeler fleet, can improve fuel efficiency with additional ICE technology packages (up to eight packages including mild hybridization). As much as 7% fuel consumption reduction can be achieved and paid back within 3 years for a large motorcycle, and 30% CO_2 emissions reduction from the baseline of FY 2017–18 is possible with additional technologies that pay back within 7 years.

With respect to scooters, their comparatively high baseline fuel consumption presents big opportunities to add efficiency-improving technologies. In the scooter segment, as much as a 29% reduction in fuel consumption can be paid back within 5 years of ownership, and a 37% fuel consumption reduction can be achieved with a payback period of 6 years. The payback of the E2W scooter package (3 years) is faster than that of the E2W small motorcycle package (4 years).

Having analyzed the cost-effective penetration of E2W vehicles in the two-wheeler fleet in 2025 and 2030, we conclude that the three important aspects influencing E2W penetration are (1) the chosen standard for fleet average CO_2 emissions; (2) the accounting method for estimating the CO_2 emissions of an E2W; and (3) the type of multiplier used in calculating E2W compliance with the standard. The chosen standard for fleet average gCO_2/km can be achieved either by fully exhausting ICE technologies or by E2W penetration. The sales-weighted compliance cost for a particular level of gCO_2/km shows that for both small motorcycles and scooters, E2W penetration can be done cost beneficially as compared to exhausting ICE technologies. The CO_2 emissions from an E2W motorcycle/scooter can be accounted as zero or gasoline equivalent gCO_2/km. For zero gCO_2/km, the E2W penetration percentage required to achieve a particular level of gCO_2/km is less than that required for a non-zero gCO_2/km. The use of a multiplier reduces the cost per gCO_2/km for an E2W motorcycle/scooter to meet a given standard. For a small motorcycle with a standard beyond 27 gCO_2/km, the cost per gCO_2/km reduction estimated for the year 2025 shows it is cost effective to use an E2W motorcycle and no multiplier is needed. For a scooter beyond 38 gCO_2/km, the cost per gCO_2/km reduction estimated for the year 2025 shows it is cost effective to use an E2W scooter without a multiplier.

Tables 16–19 summarize the compliance costs of technology improvement and electrification in of the two-wheeler fleet. ICE technology exhaustion as well as cost-beneficial E2W penetration for small motorcycle and scooter are shown below. The E2W penetration percentage estimated below assumes gasoline equivalent gCO_2/km for E2W motorcycle/scooter and compliance cost estimation assumes a multiplier of 1. For the large motorcycle, the compliance cost corresponding to the technology package PK2 has been assumed. Note, too, that the tables in the Appendix list the impact of technology improvement and electrification for various additional fuel consumption levels achieved by ICE technology exhaustion as well as cost beneficial E2W penetration.

Table 16. Compliance cost in 2025 for fleet average 25.3 gCO_2/km for two-wheeler fleet achieved by ICE technology exhaustion.

Vehicle type	segment share (%)	ICE share of segment (%)	EV share of segment (%)	ICE gCO_2/km	EV gCO_2/km	ICE share of market (%)	EV share of market (%)	Compliance cost (INR 2020)
small	60	100	0	21	8.2	60	0	18,589
scooter	30	100	0	26	9.8	30	0	22,069
large	10	100	0	49	–	10	0	6,346
fleet average	100	100	0	25.3		100		18,409

Table 17. Compliance cost in 2025 for fleet average 25.3 gCO_2/km for two-wheeler fleet achieved by cost beneficial E2W penetration.

Vehicle type	segment share (%)	ICE share of segment (%)	EV share of segment (%)	ICE gCO_2/km	EV gCO_2/km	ICE share of market (%)	EV share of market (%)	Compliance cost (INR 2020)
Small	60	68	32	27.2	8.2	41	19	10,118
Scooter	30	58	42	37.9	9.8	17	13	8,327
Large	10	100	0	49	–	10	0	6,346
Fleet average	100	68	32	25.3		100		9,203

Table 18. Compliance cost in 2030 for fleet average 20.5 gCO_2/km for two-wheeler fleet achieved by ICE technology exhaustion.

Vehicle type	segment share (%)	ICE share of segment (%)	EV share of segment (%)	ICE gCO_2/km	EV gCO_2/km	ICE share of market (%)	EV share of market (%)	Compliance cost (INR 2020)
Small	60	67	33	20	7.9	40	20	14,970
Scooter	30	66	34	25	9.5	20	10	16,388
Large	10	100	0	49	0.0	10	0	6,285
Fleet average	100	70	30	20.5		100		14,525

Table 19. Compliance cost in 2030 for fleet average 20.5 gCO_2/km for two-wheeler fleet achieved by cost beneficial E2W penetration.

Vehicle type	segment share (%)	ICE share of segment (%)	EV share of segment (%)	ICE gCO_2/km	EV gCO_2/km	ICE share of market (%)	EV share of market (%)	Compliance cost (INR 2020)
Small	60	31	69	33	7.9	18.8	41.2	5,577
Scooter	30	32	68	44	9.5	9.6	20.4	10,217
Large	10	100	0	49	–	10	0.0	6,285
Fleet average	100	38	62	20.5		100		7,024

There is great potential for fuel consumption reduction from India's two-wheeler fleet. While a transition to electric two-wheelers seems inevitable, there are opportunities in the interim to squeeze more efficiency from ICE pathways. A fleet average gCO_2/km of 25.3 for the two-wheeler fleet can be expected to get 32% E2W penetration in the new two-wheeler fleet in India. Setting a fleet average target of 20.5 gCO_2/km in 2030 could achieve fuel consumption reductions of 50% in the two-wheeler fleet and a cost-effective penetration of 62% E2Ws. Adoption of stringent fuel consumption standards will give a clearer signal to vehicle manufacturers in terms of how much longer to exploit the ICE pathway, and enable rapid transition to electrification of the two-wheeler fleet in India.

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APPENDIX. DETAILS OF COMPLIANCE COSTS FOR TWO-WHEELERS FOR VARIOUS FUEL CONSUMPTION REDUCTION

Table A1. Compliance cost in 2025 for fleet average 34.9 gCO_2/km for two-wheeler fleet achieved by ICE technology exhaustion.

Vehicle type	Segement share (%)	ICE share of segment (%)	EV share of segment (%)	ICE gCO_2/km	EV gCO_2/km	ICE share of market (%)	EV share of market (%)	Compliance cost (INR 2020)
Small	60	100	0	30	8.2	60		4,567
Scooter	30	100	0	40	9.8	30	0	3,164
Large	10	100	0	49	–	10	0	6,346
Fleet average	100	100	0	34.9		100		4,324

Table A2. Compliance cost in 2025 for fleet average 34.9 gCO_2/km for two-wheeler fleet achieved by by cost beneficial E2W penetration.

Vehicle type	Segement share (%)	ICE share of segment (%)	EV share of segment (%)	ICE gCO_2/km	EV gCO_2/km	ICE share of market (%)	EV share of market (%)	Compliance cost (INR 2020)
Small	60	100	0	30	8.2	60	0	4,567
Scooter	30	100	0	40	9.8	30	0	3,164
Large	10	100	0	49	-	10	0	6,346
Fleet average	100	100	0	34.9		100		4,324

Table A3. Compliance cost in 2025 for fleet average 30.7 gCO_2/km for two-wheeler fleet achieved by ICE technology exhaustion.

Vehicle type	Segement share (%)	ICE share of segment (%)	EV share of segment (%)	ICE gCO_2/km	EV gCO_2/km	ICE share of market (%)	EV share of market (%)	Compliance cost (INR 2020)
Small	60	100	0	26	8.2	60	0	9,855
Scooter	30	100	0	34	9.8	30	0	9,406
Large	10	100	0	49	-	10	0	6,346
Fleet average	100	100	0	30.7		100		9,369

Table A4. Compliance cost in 2025 for fleet average 30.7 gCO_2/km for two-wheeler fleet achieved by cost beneficial E2W penetration.

Vehicle type	Segement share (%)	ICE share of segment (%)	EV share of segment (%)	ICE gCO_2/km	EV gCO_2/km	ICE share of market (%)	EV share of market (%)	Compliance cost (INR 2020)
Small	60	94	6	27	8.2	56.5	3.5	8,183
Scooter	30	86	14	38	9.8	25.8	4.2	5,371
Large	10	100	0	49	-	10.0	0.0	6,346
Fleet average	100	92	8	30.7		100		7,156

Table A5. Compliance cost in 2025 for fleet average 28.3 gCO_2/km for two-wheeler fleet achieved by ICE technology exhaustion.

Vehicle type	Segement share (%)	ICE share of segment (%)	EV share of segment (%)	ICE gCO_2/km	EV gCO_2/km	ICE share of market (%)	EV share of market (%)	Compliance cost (INR 2020)
Small	60	100	0	24	8.2	60	0	13,065
Scooter	30	100	0	30	9.8	30	0	10,718
Large	10	100	0	49	-	10	0	6,346
Fleet average	100	100	0	28.3		100		11,689

Table A6. Compliance cost in 2025 for fleet average 28.3 gCO_2/km for two-wheeler fleet achieved by cost beneficial E2W penetration.

Vehicle type	Segement share (%)	ICE share of segment (%)	EV share of segment (%)	ICE gCO_2/km	EV gCO_2/km	ICE share of market (%)	EV share of market (%)	Compliance cost (INR 2020)
Small	60	83	17	27	8.2	50	10	8,641
Scooter	30	72	28	38	9.8	22	8	6,470
Large	10	100	0	49	-	10	0	6,346
Fleet average	100	81	19	28.3		100		7,760

Table A7. Compliance cost in 2025 for fleet average 26.5 gCO_2/km for two-wheeler fleet achieved by ICE technology exhaustion.

Vehicle type	Segement share (%)	ICE share of segment (%)	EV share of segment (%)	ICE gCO_2/km	EV gCO_2/km	ICE share of market (%)	EV share of market (%)	Compliance cost (INR 2020)
Small	60	100	0	22	8.2	60	0	16,653
Scooter	30	100	0	28	9.8	30	0	18,439
Large	10	100	0	49	–	10	0	6,346
Fleet average	100	100	0	26.5		100		16,158

Table A8. Compliance cost in 2025 for fleet average 26.5 gCO_2/km for two-wheeler fleet achieved by cost beneficial E2W penetration.

Vehicle type	Segement share (%)	ICE share of segment (%)	EV share of segment (%)	ICE gCO_2/km	EV gCO_2/km	ICE share of market (%)	EV share of market (%)	Compliance cost (INR 2020)
Small	60	73	27	27	8.2	44	16	9,521
Scooter	30	65	35	38	9.8	19	11	7,303
Large	10	100	0	49	-	10	0	6,346
Fleet average	100	73	27	26.5		100		8,538

Table A9. Compliance cost in 2025 for fleet average 24.4 gCO_2/km for two-wheeler fleet achieved by ICE technology exhaustion.

Vehicle type	Segement share (%)	ICE share of segment (%)	EV share of segment (%)	ICE gCO_2/km	EV gCO_2/km	ICE share of market (%)	EV share of market (%)	Compliance cost (INR 2020)
Small	60	99	1	20	8.2	59.4	0.6	20,568
Scooter	30	98	2	25	9.8	29.4	0.6	23,801
Large	10	100	0	49	-	10.0	0.0	6,346
Fleet average	100	99	1	24.4		100		20,116

Table A10. Compliance cost in 2025 for fleet average 24.4 gCO$_2$/km for two-wheeler fleet achieved by cost beneficial E2W penetration.

Vehicle type	Segment share (%)	ICE share of segment (%)	EV share of segment (%)	ICE gCO$_2$/km	EV gCO$_2$/km	ICE share of market (%)	EV share of market (%)	Compliance cost (INR 2020)
Small	60	62	38	27	8.2	37.4	22.6	10,821
Scooter	30	54	46	38	9.8	16.2	13.8	8,909
Large	10	100	0	49	-	10.0	0.0	6,346
Fleet average	100	63	37	24.4		100		9,800

Table A11. Compliance cost in 2025 for fleet average 23.5 gCO$_2$/km for two-wheeler fleet achieved by ICE technology exhaustion.

Vehicle type	Segment share (%)	ICE share of segment (%)	EV share of segment (%)	ICE gCO$_2$/km	EV gCO$_2$/km	ICE share of market (%)	EV share of market (%)	Compliance cost (INR 2020)
Small	60	91	9	20	8.2	54.4	5.6	20,217
Scooter	30	92	8	25	9.8	27.5	2.5	23,178
Large	10	100	0	49	–	10	0.0	6,346
Fleet average	100	92	8	23.5		100		19,718

Table A12. Compliance cost in 2025 for fleet average 23.5 gCO$_2$/km for two-wheeler fleet achieved by by cost beneficial E2W penetration.

Vehicle type	Segment share (%)	ICE share of segment (%)	EV share of segment (%)	ICE gCO$_2$/km	EV gCO$_2$/km	ICE share of market (%)	EV share of market (%)	Compliance cost (INR 2020)
Small	60	57	43	27	8.2	34.2	25.8	11,629
Scooter	30	51	49	38	9.8	15.2	14.8	9,540
Large	10	100	0	49	–	10.0	0.0	6,346
Fleet average	100	60	41	23.5		100		10,474

Table A13. Compliance cost in 2030 for fleet average 21.7 gCO$_2$/km for two-wheeler fleet achieved by by ICE technology exhaustion.

Vehicle type	Segment share (%)	ICE share of segment (%)	EV share of segment (%)	ICE gCO$_2$/km	EV gCO$_2$/km	ICE share of market (%)	EV share of market (%)	Compliance cost (INR 2020)
Small	60	75	25	20	7.9	44.9	15.1	15,757
Scooter	30	79	21	25	9.5	23.6	6.4	18,234
Large	10	100	0	49	–	10.0	0.0	6,285
Fleet average	100	79	21	21.7		100		15,553

Table A14. Compliance cost in 2030 for fleet average 21.7 gCO$_2$/km for two-wheeler fleet achieved by cost beneficial E2W penetration.

Vehicle type	Segment share (%)	ICE share of segment (%)	EV share of segment (%)	ICE gCO$_2$/km	EV gCO$_2$/km	ICE share of market (%)	EV share of market (%)	Compliance cost (INR 2020)
Small	60	35	65	33	7.9	21.1	38.9	5,045
Scooter	30	38	62	44	9.5	11.4	18.6	10,942
Large	10	100	0	49	–	10.0	0.0	6,285
Fleet average	100	42	58	21.7		100		6,938