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COSTS AND CO$_2$ EMISSIONS REDUCTION BENEFITS OF POTENTIAL PHASE 3 FUEL CONSUMPTION STANDARDS FOR INDIA'S PASSENGER VEHICLES

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EXECUTIVE SUMMARY

India's transportation sector is expected to expand rapidly due to rising incomes and increasing urbanization, and the government is keen to electrify transportation to reduce greenhouse gas emissions. India has set a national goal of 30% battery electric vehicle (BEV) sales by 2030 and fleet-average carbon dioxide (CO_2) emission standards are effective in supporting the adoption of BEVs in passenger car fleets. This study evaluates how prospective phase 3 fuel consumption standards for the passenger car segment in India could help meet the 30% target. We evaluated CO_2-reducing internal combustion engine vehicle (ICEV) technologies and compared the direct manufacturing costs (DMC) of BEVs with the DMCs of improved ICEVs for a variety of vehicle classes. The results can guide regulators to propose phase 3 fuel consumption standards for passenger cars.

We undertook cost and efficiency analyses and used the results to generate cost curves that elucidate the incremental cost for the industry to comply with a given set of more stringent CO_2 standards. We looked at two compliance strategies, one in which ICEV technology is used until no further reduction in CO_2 emissions is possible and the reduction limit for a new CO_2 emission level can only be met with a significant shift in production to BEVs, and a second in which the shift from ICEV to BEV is earlier and happens at an optimal transition point that minimizes compliance costs. This second strategy does not, however, consider potential market barriers such as infrastructure availability and customer acceptance of BEVs. We also analyzed the impact of super credits on compliance costs under both strategies.

Figure ES1 shows the potential fleet-average CO_2 emission standards for passenger cars using various CO_2-reducing technology and BEV sales percentages. There are no super credits assigned to BEVs in the figure; the sales of BEVs are absolute numbers. As illustrated, 30% BEV penetration is possible at a fleet-average target of 90 gCO_2/km. This implies manufacturers could meet this standard solely by adopting 30% BEVs in their fleets and zero percent ICEV improvement on the other end. With that 30% BEV market share, remaining ICEVs could still undergo small improvements. But in this scenario, there are no certain CO_2 reductions through ICEV technologies by 2030. The dotted horizontal line in Figure ES1 represents 30% BEV penetration and shows that this is possible with standards in the range of 75–90 gCO_2/km, depending on the expectation of ICEV technology improvement by 2030.

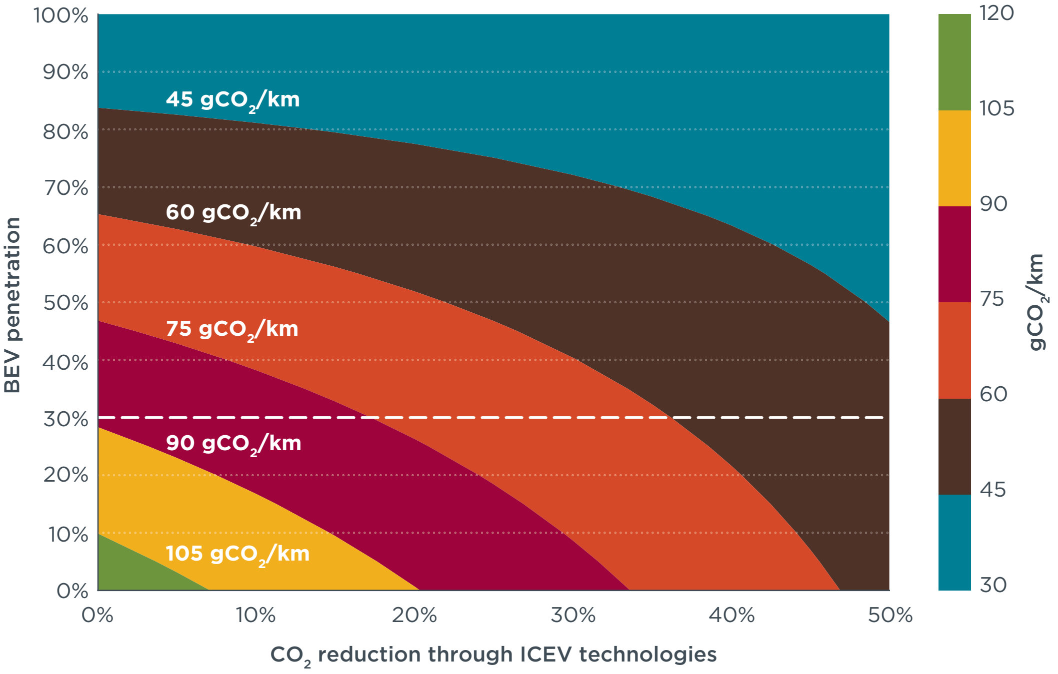

Figure ES1. Possible passenger car fleet-average CO_2 emission standards for India, in gCO_2/km, that could be achieved through improved ICEV technologies and/or BEVs with no super credits.

Regarding the impact of super credits granted to BEVs, without super credits, the shift to BEVs would likely be delayed because BEVs would remain more expensive in the near-term. At the fleet level, CO_2 reductions of 20%–34% are possible through ICEV improvements to achieve targets of 75–90 gCO_2/km by 2030. Rapidly declining battery prices will likely make electric vehicles cheaper for all segments after 2030. Until then, super credits can boost BEV sales. Such credits need to be phased out by 2030, though, to meet the 30% BEV national goal. Our analysis shows that with a super credit factor of 3, BEVs have a lower compliance cost than baseline ICEV technologies in the entry and midsize multi-purpose vehicle segments, and in the compact and midsize sport utility vehicle segments. Also, in all the diesel segments the BEVs were found to have lower compliance costs than baseline ICEV technologies. At the vehicle level, compressed natural gas (CNG) vehicles offer CO_2 reductions at lower compliance cost through 2030 even with super credits for BEVs. (Still, while not taken into account in this study, CNG, which is mostly methane, has a higher global warming potential than CO_2 and the CO_2 reductions at the vehicle level would be reduced or offset entirely by the high climate impact of even relatively small amounts of CNG leaking into the atmosphere.)

Although super credits are helpful in incentivizing BEVs, their use inflates the actual number of BEVs sold, and manufacturers do not need to reduce the ICEV CO_2 emissions as much as they would have to without super credits. This is because the super credits allow them to meet fleet-average CO_2 targets with a relatively small number of BEVs. Given that the real-world CO_2 emissions of ICEVs are about 1.4 times higher than New European Driving Cycle type-approval values, the fleet-average real-world CO_2 emissions of India's fleet would be expected to be significantly higher than the standard suggests with the use of super credits. An effective way to prevent this would be to launch phase 3 targets earlier, in 2027, and then gradually reduce the super credits by 1 until they are phased out in 2030.

The analysis did not take into account either new technological developments or future optimization of existing technologies through product redesigns that take advantage of evolving knowledge. As a result, the cost curves presented are conservative estimates; actual costs are likely to be lower.

TABLE OF CONTENTS

ABBREVIATIONS

BEV	Battery electric vehicle
CDPF	Catalyzed diesel particulate filter
DCT	Dual-clutch transmission
DMC	Direct manufacturing cost
DOC	Diesel oxidation catalyst
DVVT	Discrete variable valve timing
EGR	Exhaust gas recirculation
GDI	Gasoline direct injection
GST	Goods and services tax
ICEV	Internal combustion engine vehicle
ICM	Indirect cost multiplier
LNT	Lean NO_x traps
MPV	Multi-purpose vehicle
SDPF	SCR catalyzed diesel particulate filter
SUV	Sport utility vehicle
VCR	Variable compression ratio
VVL	Variable valve lift
VVT	Variable valve timing

INTRODUCTION

As a member of the EV30@30 campaign, India has a goal of 30% electrification in the passenger car segment by 2030 (Kant et al., 2021). Stringent fleet-average fuel consumption targets can support achievement of battery electric vehicle (BEV) sales targets.[1] India has implemented fuel consumption regulations for passenger cars in two phases. The first was in effect from 2017 to March 31, 2022; the second started on April 1, 2022 and will last until the next phase of standards is implemented. However, the relative leniency of these targets compared to the existing performance of the fleet has thus far meant that incremental carbon dioxide (CO_2) emissions reductions in internal combustion engine vehicles (ICEVs) have been sufficient and the penetration of BEVs remains small. More stringent targets in the future could help support the wider adoption of BEVs and reduce the country's dependence on imported oil.

The technology required to meet more stringent fleet-average targets and the associated costs in India have not been adequately studied. To help, this paper evaluates potential technology pathways and the incremental costs using the approach developed by the International Council on Clean Transportation (ICCT) for the European Union's CO_2 emission standards (Meszler et al., 2012). Although standards in India are presented in terms of fuel consumption, many of the steps leading to the development of the cost curves in this paper were performed in terms of CO_2 emissions. Thus, the discussion and the charts are based on CO_2 rather than fuel consumption; the two metrics are directly proportional and references to fuel consumption and CO_2 emissions are used interchangeably. Using CO_2 emissions reduction does not affect the accuracy of the cost curves presented here.

We evaluate the potential of several engine and vehicle technology packages and also highlight the impact of various electrification scenarios. For ICEVs, technologies are typically developed to increase combustion efficiency; things like gasoline direct injection make the vehicle more energy efficient and automatically reduce CO_2 emissions. CO_2 emissions are the largest source of greenhouse gas emissions from car tailpipes. Incremental technologies were used to derive cost curves for individual passenger car segments. Those costs were then weighted by sales to derive the cost curves for India's entire car fleet. Cost curves help answer three critical questions for future policy:

1. How much would it cost car manufacturers to comply with more stringent fleet-average CO_2 standards in 2030?
2. How does the cost-effectiveness of using ICEV technologies to comply with CO_2 standards compare with the cost-effectiveness of using BEVs across different vehicle segments?
3. How do the super credits presently given to BEVs impact compliance costs, and would the standards be more effective at reducing emissions if those credits are phased out gradually?

This paper focuses on both adopted technologies and prospective technologies that could be adopted by the mass market. Some advanced technologies are already in production vehicles in the United States, Japan, and Europe, and there is an established supplier base. It should, therefore, be feasible for Indian manufacturers to also develop those technologies. The primary CO_2 technology cost data used in this analysis is from the European cost curves in Meszler et al. (2016), which came from FEV Inc.'s simulation modeling and teardown cost estimation work for the ICCT. These data were scaled to Indian vehicles and used to generate CO_2 cost curves for nine diesel vehicle

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[1] The passenger car segment covers vehicles that carry passengers and their luggage; they have no more than nine seats, including the driver's seat, and of gross vehicle weight not exceeding 3,500 kg.

classes: B, C, D, E, compact, midsize, and large sport utility vehicle (SUV), and midsize and large multi-purpose vehicle (MPV). For gasoline vehicles, we generated curves for those same nine classes and an additional A class.

Compliance cost curves are based on the direct manufacturing costs (DMCs) of the technologies that a manufacturer would incur. We used learning factors and high-volume production to estimate these costs. These are not estimates of the retail-level costs; those would be higher because of additional costs added to the DMC like depreciation and amortization, selling and general and administrative expenses, research and development, manufacturer profit, and dealer markups. The developed incremental compliance costs also do not include off-cycle credits for either ICEV or electric vehicle technology.

Most global standards define electric vehicles to include BEVs, plug-in hybrid electric vehicles (PHEVs), and fuel cell electric vehicles (FCEVs). However, due to cost and complexity, PHEVs are not ideal for mass market segments in India; for FCEVs, the costs are far more uncertain due to their lack of market maturity in India and the projected time frame for high-volume production by multiple manufacturers with competitive suppliers is years behind that of BEVs and PHEVs (Ohnsman, 2021). Therefore, BEVs are the only electric vehicles to which this paper refers.

METHODOLOGY, DATA, AND ASSUMPTIONS

Determining the cost-effectiveness of ICEV technologies that reduce CO_2 emissions requires in-depth knowledge. When supporting the development of European Union (EU) 2025–2030 CO_2 emission standards, ICCT adopted the approach to technology impact and cost estimation used by the U.S. Environmental Protection Agency (EPA) in developing U.S. 2021–2025 light-duty vehicle fuel efficiency standards. This approach estimates the fuel-saving impacts of various vehicle technologies through detailed vehicle simulation modeling. Associated costs are calculated based on detailed teardown analysis. Vehicle simulation modeling is the best approach to determine the CO_2 benefits of technology on vehicle operation. The method considers interactions among the vehicle components and subsystems required to drive the vehicle over a standardized test cycle.

Here we built upon prior ICCT analyses for passenger cars in the European Union (Meszler et al., 2016) and China (Yang & Cui, 2020). In these studies, the primary CO_2 saving potential and ICEV technology costs were derived from simulation modeling and cost estimates from a component cost analysis performed by FEV Inc. (Blanco-Rodriguez, 2015). Analyzing new vehicle technologies other than those considered by FEV would require additional simulation modeling work and teardown cost studies that are beyond the scope of this study.

Conducting a teardown cost study involves figuratively disassembling a car into its parts, down to the level of individual nuts and bolts, estimating the manufacturing costs associated with each separate piece, and then aggregating those costs. The net incremental cost of the vehicle technology is determined by the teardown cost estimate minus the price of replaced components, if any, determined through similar teardown studies. This approach is similar to the method employed by auto manufacturers and it results in objective, consistent, transparent, and reproducible impact estimates.

This study derives India-specific fuel efficiency cost curves which are representative of technology costs for an average car manufacturer in India. Evaluating the conditions under which the given cost values are valid for a specific car manufacturer is a significant challenge. Costs of vehicle components are highly dependent on workforce costs, original equipment manufacturer's margins, dealership margins, research and development expenditures, and production volumes. Moreover, fluctuating currency and inflation rates also make cost values less transparent and comparable. So while our approach is not specific to any single manufacturer, it allows for a reliable picture of average costs across manufacturers.

The curve development process in this paper uses fuel efficiency impact data developed in the European Union, with appropriate adjustment, in conjunction with cost data explicitly designed for India and comparable cost data for the European Union. Figure 1 illustrates the process of technology and cost adoption for India. The automotive market is global. To minimize costs, manufacturers typically deploy new technologies on vehicle architectures that can be used for the worldwide market. Moreover, most manufacturers in India have a worldwide presence and are likely to carry newly developed technologies across regions. Technologies needed to meet EU 2025–2030 passenger car standards can also be used to meet CO_2 standards in the Indian market because many European car manufacturers and suppliers have a manufacturing base in India.

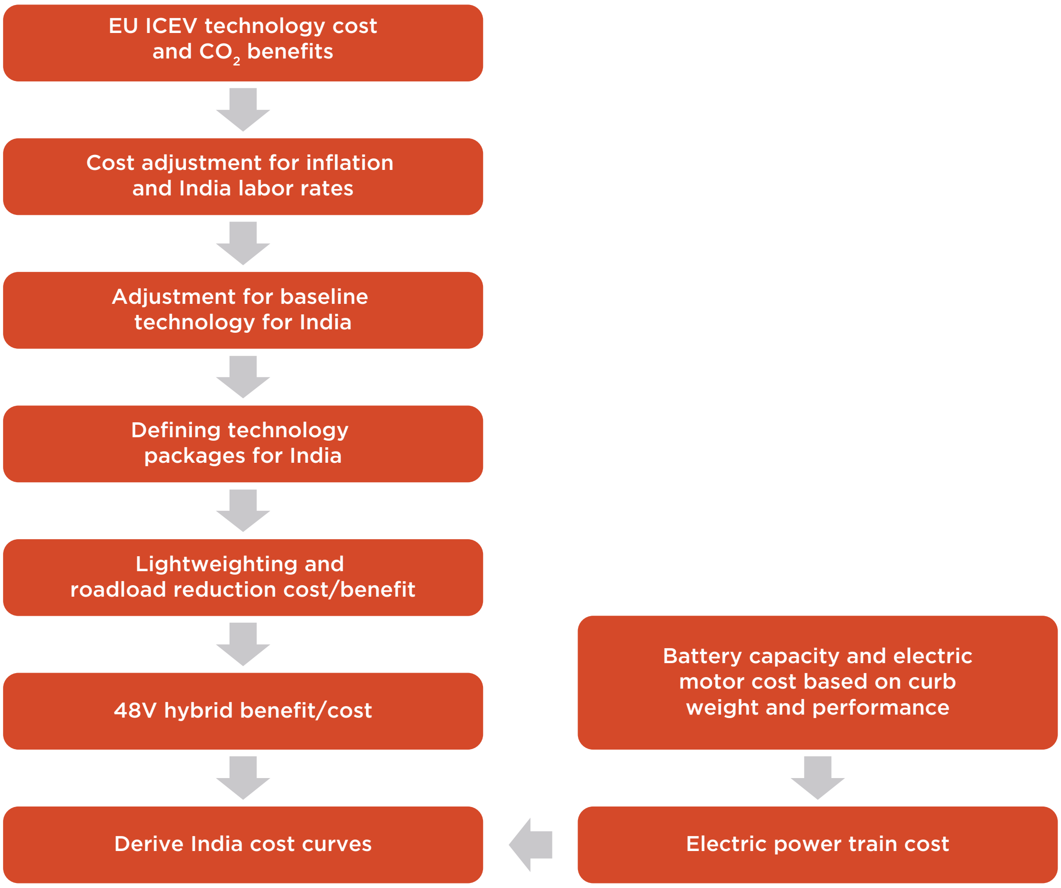

Figure 1. Overview of the India technology cost curve calculations used in this analysis.

In both India and Europe, vehicle segments for passenger cars do not have any formal characterization and instead are based on vehicle cost and customer preference. In particular, the boundaries between the C, D, and E segments are largely based on price and equipment used in the vehicle. In India, to reduce road congestion, the national government decided to give tax benefits to cars that are less than 4 m in length and are powered by gasoline engines less than 1,200 cc and diesel engines less than 1,500 cc. This led to four vehicle segments not seen in Europe: A and B class passenger cars, compact SUVs, and entry MPVs.

The goods and services tax for sub-4 m cars is 28% with an additional 1%–3% cess, much less than the 15%–20% cess for vehicles that are longer than 4 m.[2] The cess rate reduction has been so lucrative for carmakers that sub-4 m vehicles are now sold even in the SUV and MPV segments as compact SUVs and entry MPVs. Our analysis assumed 2021 sales shares of vehicle segments throughout the evaluation period until 2030. Table 1 lists the different segments and representative vehicles used in this study.

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[2] A cess is an additional tax levied by the government on existing taxes to raise funds for specific purposes.

Table 1. Vehicle segments used in the analysis; the equivalent European vehicle class is used for cost scaling

Vehicle segment in India	Equivalent European class	Market share (%)	Representative vehicles in India
Mini hatchbacks	A	17.2	Maruti Alto 800, S-Presso
Hatchbacks	B	34.9	Hyundai i20, Maruti Suzuki Swift,
Compact & small sedans	C	3.4	Maruti Suzuki Dzire, Hyundai Aura, Hyundai Verna, Honda City, Maruti Ciaz
Midsize luxury sedans	D	0.4	BMW 3-series, Skoda Octavia, Hyundai Elantra
Executive sedans	E	0.03	Skoda Superb, Audi A6, BMW 5-Series, Mercedes Benz E-class
Compact SUV	C	22.0	Tata Nexon, Mahindra CUV300, Maruti Brezza
Midsize SUV	D	12.7	Mahindra Scorpio, Tata Safari, Toyota Fortuner
Large SUV	E	1.1	Toyota Land Cruiser LC300, Mercedes Maybach GLS600, Range Rover Sport
Entry MPV	C	5.7	Maruti Ertiga, Honda BR-V
Midsize MPV	D	1.4	Toyota Innova Crysta, Mahindra Marazzo, Toyota Vellfire,
Large MPV	E	0.1	KIA Carnival, Mercedes-Benz V-Class

India's vehicle fleet differs from Europe's mainly in that it has much lower average engine power and fewer cylinders are used in baseline power trains. To account for the differences between the two markets, we adjusted baseline costs for India's power trains and scaled technology cost data to reflect power trains in India. Such adjustments included adapting data to vehicle classes that are unique to India.

DATA SOURCES

ICEV technologies

Because the FEV Inc. cost data focused primarily on engine technologies, we supplemented it with lightweight vehicle design cost data from Ricardo (Hill et al., 2016) and updated data on 48V mild hybrids from AVL and Schaeffler (Dornoff et al., 2022). Indirect cost estimates and annual cost reductions due to learning were taken from U.S. EPA rulemaking documents (EPA & Department of Transportation, 2012).

To approximately estimate the cost of vehicle manufacturing, data has to be available at least for the cost of main components like the vehicle body, power train, and energy storage system. But costs are held by most companies as business secrets and are not widely available. Therefore, the rough estimates used in this analysis for vehicle subsystem costs such as drivetrain, chassis, vehicle body, and their equipment were taken from scientific studies (Fries et al., 2017). Data on India's passenger car sales and curb weight for fiscal year (FY) 2020–21 was obtained from Segment Y.[3] The retail prices of vehicles were taken from commercial websites like CarWale (2021) and CarDekho (2021) to reflect vehicle ex-showroom prices in New Delhi, India for 2021.[4]

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[3] Segment Y Automotive Intelligence focuses on automotive markets in Asia. Data was purchased from Segment Y for FY 2020–21 for this analysis.

[4] A vehicle's ex-showroom price is the amount a customer pays without road tax, additional registration, or insurance charges. It is generally advertised by manufacturers and includes the vehicle dealer's margin, GST, and ex-factory cost of the vehicle.

Table 2. Data sources used to develop cost curves; DMC estimates are for high-volume annual production of 250,000 cars

Parameters	Cost and CO_2 benefits	Description
ICEV technology packages	Blanco-Rodriguez (2015) EPA & Department of Transportation (2012)	Teardown analysis conducted by FEV Inc. for ICEV technologies in power train and transmission. Learning and indirect cost factors taken from U.S. EPA study.
48V hybrids	AVL, Schaeffler Eckenfels et al. (2018) Melaika et al., 2019)	Cost analysis of P0, P1, and P2 conducted by AVL. CO_2 benefits considered from the Schaeffler study.
Lightweighting	Hill et al. (2016)	Costs for 10% mass reduction in small, medium, and large cars.
Electric vehicles	UBS (2017) BNEF (2021)	Costs of electric components are from UBS teardown of electric vehicles in the United States. Battery pack prices were estimated from global cell prices published by Bloomberg. Non-power train costs were calculated from the ex-showroom prices of vehicles.
CNG	Fries et al. (2017)	CNG tank cost in Euros/kg.

Electric vehicles

ICCT published an assessment of electric vehicle costs in the 2020–2030 time frame in the United States (Lutsey & Nicholas, 2019) that used costs for different electric vehicle components from the UBS Evidence Lab study (2017). For this India analysis, we took those manufacturing costs for electric elements such as the electric drive module, power electronics, and thermal management and scaled them to match the lower propulsion power ratings in India. The DMCs of components not part of the power train of BEVs for India were derived from conventional ICEV prices in 2021 using an indirect cost multiplier of 1.6 (Meszler et al., 2016) and an ICEV drivetrain cost factor of 0.24 (Fries et al., 2017). We used global battery pack prices from BNEF (2021). Note that the DMC of standard vehicle models does not include depreciation and amortization, research and development, selling, general, and administrative expenses, automaker profit, or dealer markups.

INFLATION AND LABOR RATES

Cost estimates by FEV Inc. were for 2015, and the devaluation of money over time (inflation) was taken into account. Table 3 shows the inflation rates used in this analysis. Additionally, labor cost adjustments for India were made based on an ICCT analysis of the impact of labor costs in Western and Eastern Europe on ICEV technologies (Kolwich, 2013). The factor used in the analysis is 0.81. We assumed Eastern Europe's labor costs are comparable to India's.

Table 3. Inflation rates in Europe used for this analysis

Year	Inflation (%)
2015	1.0
2016	0.9
2017	1.5
2018	2.0
2019	2.2
2020	1.6
2021	2.7

Source: World Bank Group (2021)

LEARNING FACTORS

DMCs for a given evaluation year are a function of base-year DMC and an associated annual cost reduction due to learning, called a learning factor. In this analysis, the cost estimates for the technology packages are for future years. Therefore, it is necessary to extrapolate costs until 2030. We accomplished this using the annual learning factors listed in Table 4. We used low and moderate learning factors for mature technologies and high learning factors for new technologies.

Table 4. Learning factors used for 2016–2030

Technologies	Annual learning (%)
Low-friction lubricant, engine friction reduction	0
GDI, cooled EGR, low resistance tire	2
Aerodynamic, 6-speed manual transmission	2
Cooled HP/cooled low pressure EGR	2
VVT, aftertreatment upgrade from LNT + CDPF to DOC + SDPF	2
Downsizing	3
Advanced micro hybrid, P0, P1, P2	6

Source: Meszler et al. (2016)

DIRECT MANUFACTURING COST FORMULA

The DMC does not include indirect costs such as research and development, corporate operations, dealer support, marketing, or taxes. The DMCs for vehicles in India were calculated as follows.

India ICEV technology DMC = Europe ICEV technology DMC × Inflation factor × India labor cost rates x Currency conversion to INR x learning factor.

Where,

- India ICEV technology DMC refers to the DMC of technology in India
- Europe ICEV technology DMC refers to the DMC of the technology in a passenger car in Europe
- The inflation factor refers to the adjustment factor used to convert 2015 costs to 2021 costs
- India labor cost rates refer to the adjustment to convert labor costs to the Indian market
- Currency conversion to INR refers to the factor used to express the Europe DMC cost as INR 2021.

INDIRECT COST MULTIPLIER

We applied indirect cost multipliers (ICMs) to DMC data to estimate ex-showroom costs, not including road tax or insurance costs. We used ICMs for back-calculating the BEV DMC from the ex-showroom price and later calculating the DMC of non-power train components such as body-in-white, chassis, and other equipment (Fries et al., 2017). These costs for components other than the power train, combined with battery and electric motor costs, formed the total DMC of the BEV. ICMs vary based on many factors such as vehicle segment and overall business strategy of manufacturers. Unlike their smaller counterparts, larger manufacturers can benefit from economies of scale that lower their indirect costs per unit. Manufacturers that invest heavily in R&D for new technologies or to improve current ones might have higher indirect costs. In this study, we used a constant ICM factor of 1.6 for all segments.

ASSUMPTIONS FOR ALL VEHICLES

Baseline vehicles in India are lighter than European vehicles by about 15%–20%. As a result, lightweighting of more than 10% was not considered in the cost analysis. Also, the Indian standard test cycle has a maximum test speed of 90 km/hr. At this speed, the effect of aerodynamic improvements on fuel consumption is limited. Hence, only a modest aerodynamic improvement of 10% was considered.

Although this study's cost curves are based on extensive vehicle simulation modeling and detailed bottom-up cost assessments, a limitation of this approach is that the conventional vehicle technologies used are based on 2015 information and do not include any technology improvements or cost reductions since 2015, beyond annual learning factors. Also, the curves we developed do not account for the effects of any potential regulatory structure that might discount the value of any particular CO_2 reduction technology, in whole or part.

In developing cost curves, we assumed that market shares of fuels and vehicle segments will not change. In particular, we assumed that the market shares of gasoline, diesel, and CNG vehicles would remain constant over time. Note, too, that all CO_2 emission reduction technology was evaluated on a constant-performance basis, which means if the installation of a technology affects performance, the engine size was adjusted to maintain the same performance in terms of acceleration and top speed. CO_2 emissions reduction costs for reduced-performance vehicles would be lower than depicted in the presented cost curves.

COST CURVE GENERATION

In India, fuel consumption standards for passenger cars are set at the manufacturer fleet level. Individual vehicles do not have to meet a particular CO_2 emissions target. That means ICEVs and BEVs can be variously combined to adjust compliance costs. We first calculated the level of CO_2 emissions reduction that could be achieved through gradual ICEV technology improvement in the coming years and then analyzed CO_2 compliance costs using the cost-beneficial penetration of BEVs. Independent cost curves were developed for each vehicle segment listed in Table 1. Individual vehicle class estimates were later sales-weighted to determine overall fleet CO_2 levels using FY 2020–21 sales data.

COMPLIANCE COST

We ordered CO_2 emission reduction technologies by their cost-effectiveness in terms of cost-to-benefit ratio, then grouped them into technology packages. Some packages include technologies that address the same issues (for example, low-rolling-resistance tires and aerodynamic improvements both impact a vehicle's road load); we grouped some technologies as a package even though manufacturers could choose to use individual technologies alone.

Constructing a compliance cost is conceptually simple. The "ICEV technology exhaustion strategy" depicts a scenario in which all fuel consumption reductions result from ICEV technology upgrades. We identified the CO_2 emissions of, and technology applied to, the baseline fleet, which is the zero-cost baseline. We combined baseline data with CO_2 emissions and cost estimates to produce a series of cost data points; the points were then subjected to regression analysis and from that a generalized CO_2 cost curve was estimated. The cost of ICEV technology is typically represented by an exponential curve. Once the ICEV technology was exhausted, then BEV market penetration served to extend the ICEV technology cost curve to lower CO_2 levels. When developing these cost curves, not all of the ICEV technology options detailed below were taken into account. Only the most cost-effective technology packages were chosen, in other words, those with lower costs than others for comparable fuel-savings potential. The technology packages available to different segments might also differ.

In the second strategy, the "cost-beneficial BEV strategy," the level of CO_2 emissions reduction is achieved by increasing the market penetration of BEVs when the marginal cost per gram of CO_2 reduction is lower than progressively more expensive ICEV technology. This strategy represents a scenario in which expanding BEV market penetration is an option for meeting fuel consumption targets. That BEVs' marginal costs can be lower than the marginal costs of incremental ICEV technology does not imply that BEVs are less expensive to purchase than alternative ICEV technology, but rather that the cost per unit CO_2 reduction is lower. In this analysis, upstream CO_2 emissions from electricity generation were considered for BEVs; these vehicles still offer significant CO_2 reductions over which to spread costs.

The transition to BEVs is expected only after the per-gram cost of incrementally ranked ICEV technology packages exceeds the per-gram cost of BEVs. At that point, it is assumed that BEVs will enter the market while the ICEVs in the fleet will continue to be sold with the cost-effective technology. CO_2 reduction benefits can be realized by increasing the market penetration of BEVs, as this is the lowest cost compliance strategy. The cost curve analysis below gives the optimum integration of BEVs under this strategy for lowest compliance cost. Figure 2 shows the methodology adopted for the compliance cost estimation.

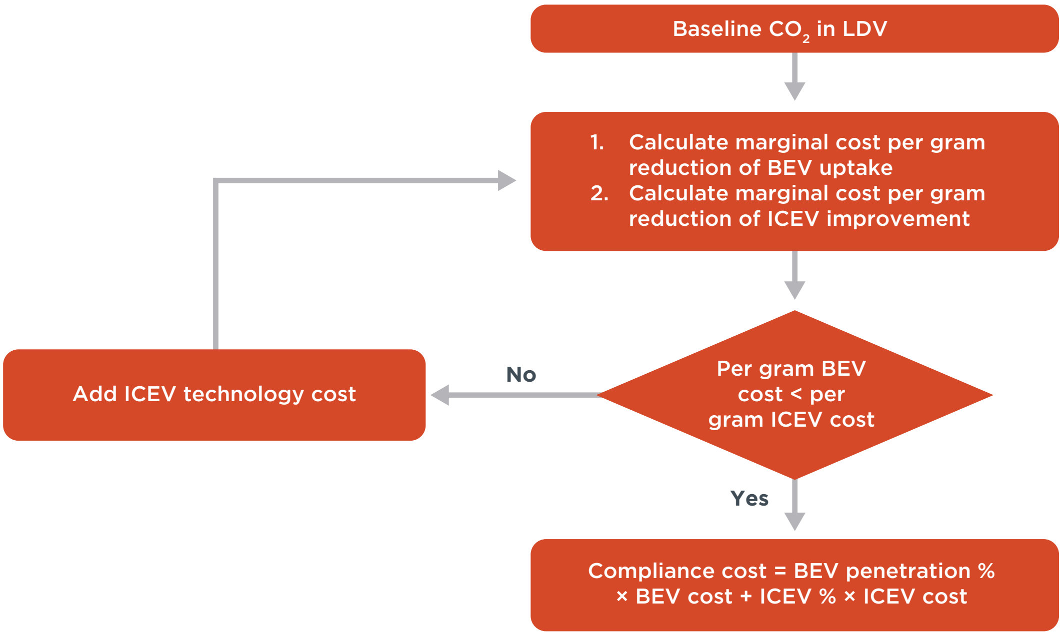

Figure 2. The process to calculate the compliance cost of passenger cars for the cost-beneficial BEV strategy.

INDIA BASELINE SPECIFICATIONS

This study used India's 2021 vehicle fleet as the baseline for developing cost curves. To reflect differences between India's and the European Union's baseline fleets, we compared the two and applied adjustments derived from the FEV Inc. teardown analysis to the baseline estimate. Table 5 provides an overview of the baseline vehicle characteristics for India's 2021 fleet along with European vehicle data for 2015. Baseline vehicles were selected to reasonably reflect the average Indian market of that year using Segment Y data. For each vehicle class, the technologies listed in Table 5, Table 6, and Table 7 reflect the mainstream technology of the fleet. The following evaluation process considers the penetration of some advanced technologies that have a larger market share today but were not mainstream technologies in 2021.

Because of insufficient valve technology information for the 2021 fleet, we assumed baseline fleet technology to be similar to Europe's. We expect the mainstream valve technology of some vehicle classes in the 2021 fleet to be lower than what we assumed in our analysis; this results in a slightly underestimated cost for valvetrain technology.

The 2015 FEV Inc. study was based on 2014 EU vehicles, four different classes of gasoline vehicles and six different classes of diesel vehicles. We used both gasoline and diesel vehicle characteristics associated with the 2015 FEV Inc. modeling in this study. In India, the SUV and MPV segments are further divided into entry-level or compact, midsize, and large segments. These divisions do not exist for EU vehicles and thus were not modeled by the FEV Inc. study; to compensate, we used equivalent C, D, and E class vehicle technology packages for these SUVs and MPVs. Each indicated class in India is mapped onto one of the FEV Inc. classes based on the similarity of engine specifications.

The passenger car market is expected to be dynamic; vehicle class market shares change over time. In this study, fleetwide cost curves were calculated by the market share of each type in 2021. Because of the challenge inherent in predicting minor market share changes and to avoid introducing more uncertainties into the fleetwide estimation, we assumed that the market shares of fuels and vehicle segments would remain the same until 2030.

Table 5. Baseline gasoline vehicle characteristics of India's 2021 fleet using Segment Y data; EU data is for 2015

Parameters	India	A	B	C	D	E	E-MPV	M-MPV	C-SUV	M-SUV	L-SUV
	EU	B	B	C	D	E	C	D	C	D	E
Market share	India	14.9%	33.8%	2%	0.3%	0.03%	4.51%	0.0%	14.48%	5.7%	0.2%
Displacement (l)	India	1	1.2	1.4	2.0	2	1.3	2.7	1.2	1.5	2.5
	EU	1.3	1.3	1.8	2.4	3	1.8	2.4	1.8	2.4	3
Engine configuration	India	I3	I4	I4	I4	I4	I4	I4	I4	I4	I4
	EU	I4	I4	I4	V6	V6	I4	V6	I4	V6	V6
Injection system	India	MPFI	MPFI	MPFI	MPFI	MPFI	MPFI	MPFI	MPFI	MPFI	MPFI
	EU	MPFI	MPFI	MPFI	MPFI	MPFI	MPFI	MPFI	MPFI	MPFI	MPFI
Turbocharged	India	No	No	No	No	No	No	No	No	No	No
	EU	No	No	No	No	No	No	No	No	No	No
Rated engine output (kW)	India	39	61	84	154	170	69	122	75	93	209
	EU	65	65	95	135	180	95	135	95	135	180
Valve technology	India	DVVT	DVVT	DVVT	DVVT	DVVT	DVVT	DVVT	DVVT	DVVT	DVVT
	EU	DVVT	DVVT	DVVT	DVVT	DVVT	DVVT	DVVT	DVVT	DVVT	DVVT
Transmission	India	M5	M5	M5	A8	A8	M5	M6	M5	M6	A8
	EU	M5	M5	M5	A8	A8	M5	A8	M5	A8	A8
Curb weight (kg) +150 kg	India	974	1,137	1,353	1,800	1,965	1,226	2,105	1,265	1,456	2,268
Mass in running order (kg)	EU	1,150	1,150	1,345	1,578	1,800	1,345	1,578	1,345	1,578	1,800
Idle-off technology	India	No	No	No	No	No	No	No	No	No	No
	EU	No	No	No	No	No	No	No	No	No	No
CO$_2$ emissions (g/km)	India	109	112	129	165	161	127	218	138	146	203
	EU	139	139	170	183	214	170	183	170	183	214

Table 6. Baseline diesel vehicle characteristics of India's 2021 fleet using Segment Y data; EU data is for 2015

Diesel	India	B	C	D	E	M-MPV	L-MPV	C-SUV	M-SUV	L-SUV
	EU	B	C	D	E	D	E	C	D	E
Market share	India	0.2%	1.4%	0.1%	0.0%	1.4%	0.1%	6.6%	7.0%	0.9%
Displacement (l)	India	1.5	1.5	1.8	2.1	2.4	2.2	1.5	1.8	2.4
	EU	1.4	1.6	2.0	3.0	1.6	2.0	1.6	2.0	3.0
Engine configuration	India	I3	I4	I4	I4	I4	I4	I4	I4	I4
	EU	I3	I4	I4	I6	I4	I4	I4	I4	I6
Injection system	India	DI	DI	DI	DI	DI	DI	DI	DI	DI
	EU	DI	DI	DI	DI	DI	DI	DI	DI	DI
Turbocharged	India	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	EU	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Rated engine output (kW)	India	70	85	128	151	110	145	71	99	145
	EU	60	80	110	150	80	110	80	110	150
Valve technology	India	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed
	EU	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed
Transmission	India	M5	M6	M6	A8	M6	A8	M6	M6	A8
	EU	M5	M6	M6	A8	M6	M6	M6	M6	A8
Curb weight (kg) +150 kg	India	1,330	1,501	1,837	2,002	2,119	2,482	1,616	1,756	2,372
Mass in running order (kg)	EU	1,224	1,434	1,625	1,838	1,434	1,625	1,434	1,625	1,838
Idle-off technology	India	No	No	No	No	No	No	No	No	No
	EU	No	No	No	No	No	No	No	No	No
CO$_2$ emissions (g/km)	India	108	111	132	141	173	188	135	145	191
	EU	104	115	122	152	115	122	115	122	152

Table 7. Baseline CNG vehicle characteristics of India's 2021 fleet using Segment Y data; EU data is for 2015 and engine characteristics are those of gasoline vehicles

CNG	India	A	B	E-MPV	C-SUV
	EU	B	B	C	C
Market share	India	3.2%	0.9%	1.2%	0.9%
Displacement (l)	India	1.0	1.2	1.3	1.2
	EU	1.3	1.3	1.8	1.8
Engine configuration	India	I3	I4	I4	I4
	EU	I4	I4	I4	I4
Injection system	India	MPFI	MPFI	MPFI	MPFI
	EU	MPFI	MPFI	MPFI	MPFI
Turbocharged	India	No	No	No	No
	EU	No	No	No	No
Rated engine output (kW)	India	36	46	68	46
	EU	65	65	95	95
Valve technology	India	DVVT	DVVT	DVVT	DVVT
	EU	DVVT	DVVT	DVVT	DVVT
Transmission	India	M5	M5	M5	M5
	EU	M5	M5	M5	M5
Curb weight (kg)	India	1,069	1,159	1,469	1,275
Mass in running order (kg)	EU	1,150	1,150	1,345	1,345
Idle-off technology	India	No	No	No	No
	EU	No	No	No	No
CO_2 emissions (g/km)	India	87	89	105	114
	EU	139	139	170	170

TECHNOLOGY PACKAGES

This section describes the ICEV technologies and scaling parameters used to adjust the costs for Indian vehicles. The study by Meszler et al. (2016) described the co-benefits and other market drivers (e.g., emission standards) that spur the adoption of CO_2 reduction technologies. Co-benefits include improved performance, handling, and braking, reduced noise, enhanced safety, and increased durability. Here we used the same performance-based adjustments as Meszler et al. (2016) but did not account for the other co-benefits; as a result, the applied estimates of the costs of various technologies are conservative. Costs depend on engine power and other technical parameters for some technologies; we adjusted costs based on the engine power and displacement.

ICE TECHNOLOGIES

Engine: The cost of each engine technology package is based on the incremental cost of the technology package in the study by Meszler et al. (2016). We adjusted the incremental engine technology cost to account for the differences in engine size and power in the baseline engine of Indian cars. To map engine technologies to EPA technologies, which were used to identify the learning factors and estimate the costs for future years, we disaggregated engine downsizing costs into three components: direct-injection, turbocharging, and downsizing.

Transmission: The cost of transmissions comes from the 2015 FEV Inc. study. The E class, large SUV, and large MPV have baseline engines with automatic transmissions (AT). We assumed it would be cost effective to convert ATs to dual-clutch transmissions (DCT).

Exhaust gas recirculation (EGR) technology: We adjusted the cost of EGR by vehicle power based on the EGR cost/power relationship derived from FEV Inc. data.

Turbocharger technology: Because we accounted for turbocharger changes due to downsizing as part of engine costs, we estimated the cost of turbocharging technology as the incremental cost of advanced turbo technology relative to single-stage wastegate turbo. The single-stage variable geometry turbo cost was estimated at a fixed price, the same as in the FEV Inc. estimates. The two-stage wastegate turbo cost was adjusted by vehicle power, with the cost relation derived from FEV Inc. data.

Valvetrain technology: The costs of dual variable valve timing (DVVT) and dual variable valve lift (DVVL) vary with cylinder number and were, therefore, adjusted to the cylinder count for Indian vehicles. We also accounted for the penetration of fixed valves (no camshaft phasing) in the baseline of each class to more precisely evaluate the incremental costs of moving from baseline technology to advanced technologies. While implementing higher efficiency combustion processes is possible with DVVT and DVVL at no additional cost, there are indirect costs because of reduced power output. For example, turbocharged engine output can be maintained with the Miller cycle by increasing boost pressure.

Variable compression ratio (VCR) technology: VCR costs are based on the two-stage cylinder connecting rod concept, not the more complicated system implemented by Nissan on the 2018 Infinity QX50. VCR costs vary with cylinder count and specific torque.

Friction-reduction technology: Friction-reduction costs are disaggregated into two components, internal engine and cooling system friction reduction. Both are fixed costs for a given cylinder count engine. This is consistent with the FEV Inc. estimates.

Start-stop: The FEV Inc. estimates for start-stop are different for vehicles with manual transmissions (MT) and AT. For India, we adjusted start-stop costs for engine power based on the cost/power relationship derived from FEV Inc. data. The 12-volt (V) advanced start-stop is treated as a fixed cost in addition to a regular start-stop. Advanced start-stop costs were included in 7-speed DCT and DCT-10 transmissions based on FEV Inc. data.

Hybrid vehicle technology: Different architectures have different CO_2-saving potentials and different costs. We used the most suitable architectures for the required CO_2 reductions in this analysis. Mild hybrid electric vehicles (MHEVs) provide larger CO_2 emissions reductions than conventional ICEVs. Currently, most mild hybrid systems consist of a belt-driven starter generator (P0 configuration) and a 48V lithium-ion battery. A recent ICCT paper estimated the CO_2 reduction potential of P0 MHEV systems to be around 6% over a stop-start system on the New European Driving Cycle test cycle (Dornoff et al., 2022).

Different from the 48V technology, a strong or full hybrid electric vehicle (HEV) is built with larger capacity and higher voltage batteries and motors, which allows the use of a dedicated hybrid engine designed for higher efficiency in a narrow operating range. However, we considered only a 48V P2 mild hybrid configuration for this analysis, as it has the lowest cost per percent efficiency improvement.

Compressed natural gas (CNG): In spark-ignition engines, CNG is used as an alternative fuel for CO_2 reduction. CNG has a higher octane number and knocking resistance than gasoline, and that allows CNG-specific engines to have higher compression ratios and thus higher indicated efficiencies (Hill et al., 2016). If the engine is properly tuned, CNG could be used instead of gasoline with few modifications. A CO_2 emissions reduction of 17%–20% is possible through CNG powered vehicles.

Table 8. Scaling approach used in this study for different technologies

Technology type	Specific technology	Cost influencing parameter	Cost scaling parameter
Engine	Engine friction reduction	Roller bearings at camshafts, oil pump, additional manufacturing for split cooling	Cylinder number
	Lubricating oil	Improvement in engine machining to accommodate lighter oil and/or low-friction additives	None
	Cam phasing	Cam phaser, position sensor, control valve, oil supply	None for all inline engines
	Variable compression ratio	Push rods, pistons, valves, actuators, assembly	Cylinder number, engine power per cylinder
	Variable valve lift	Camshaft, actuators, mountings, cylinder head cover	Cylinder number
	Gasoline direct injection	Needle valve, solenoids/ piezoelectric components, controls	Cylinder number
	Exhaust gas recirculation	EGR cooler, valve, pipes, assembly	Engine power
	Turbocharging	Turbine and compression wheels, bearings, wastegate and actuator, housings, oil supply, assembly, tubes	Engine power
Transmission	6-speed manual transmission	Clutch, clutch housing, wheel set, bearings, shift elements, actuation, assembly, end-of-line test	None
	Dual-clutch transmission	Dual dry/wet clutch, mechatronics control module	None
Vehicle	Start-stop	Battery, alternator, sensors, starter, engine management system	Engine power (for all components except sensors)
	Low-rolling-resistance tires	Tire pressure, design of sidewall, tread compound, depth of tire	Vehicle weight

Mass reduction: Ricardo's study (Hill et al., 2016) used separate estimates for the cost of mass reduction for all vehicle classes. Because Indian vehicles are already lighter than European vehicles, a conservative target of 10% mass reduction was assumed for all vehicle classes. These estimates were not developed for individual components or systems but rather based on combinations or groups of other parts where it is possible to reduce mass.

Road load estimates: Aerodynamic improvements were also assumed to be modest, 10%, as the India test cycle limits the maximum vehicle speed to 90 km/hr. B and C class vehicle improvements include underbody covers, air dams, wheel spoilers, and aerodynamic improvements that can be incorporated into the vehicle outer body during the design stage. These improvements are generally plastic add-ons or changes that would have been otherwise done for vehicle styling. However, advanced technologies (e.g., active grille shutters) though costly, can be used for premium vehicles or large MPVs and SUVs. Low-rolling-resistance tires are generally less durable than regular tires. Our analysis assumed that the 10% benefit of low-rolling-resistance tires will have an average durability of 160,000 km.

BATTERY ELECTRIC VEHICLES

Presently, BEVs in India are built on vehicle bodies adapted from existing ICEV architecture. It is the simplest, quickest way to build a BEV, and the process does not require significant development of the vehicle body. All BEV costs analyzed in this study are based on such adapted vehicle architectures. However, over the next decade, most manufacturers are expected to transition to dedicated BEV platforms (these are essentially vehicles with a flat underbody, chassis systems, and a battery pack that allows for maximum design flexibility). Such dedicated platforms are costly and time-consuming to develop, but once manufacturers have purpose-built BEV platforms, designing new vehicles from them is relatively simple and inexpensive.

We assumed BEV battery costs would drop by 7% annually from 2018–2030 (Slowik et al., 2022), but the precise cell and pack costs differ by battery pack size. Additionally, in adjusting Indian vehicle prices in each vehicle class, all costs were adjusted down for lower India-based manufacturing and indirect costs. Overall, this approach ensures best available engineering costs that most accurately represent the average price in each Indian vehicle class.

We assumed the evaluated BEVs to have ranges of 300 km, due to the high levels of congestion and the largely urban driving both common in India. BEV efficiency was assumed to improve 1% annually, because of vehicle-level improvements (e.g., aerodynamics, tires, and mass reduction, as assessed above), and incremental improvements in electric power train components. Better efficiency leads to a reduced battery pack size for a given vehicle class and range over time.

The battery capacity of a BEV depends on its range and curb weight (Jung et al., 2018). Similarly, the electric motor's power depends on its 0–100 km/hr performance and vehicle curb weight (Mruzek et al., 2016). We collected data on battery capacity, curb weight, 0–100 km/hr performance, and electric motor power available for different BEVs (Electric Vehicle Database, n.d.). Later, we used multiple regression to calculate battery capacity for different curb weights and the 300 km range for the vehicle classes in Table 1.[5] We also calculated electric motor power for different curb weights and 0–100 km/hr performance using multiple regression. The weight of each battery is an additional weight over the curb weight of a vehicle body. We assumed a specific energy of 241 Wh/kg to calculate battery weights. A BEV's curb weight will change according to the different battery capacities required for different vehicle classes. Although battery chemistry and specific energy might vary for different vehicle classes (and thus change the battery weight), we assumed a constant specific energy to

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[5] Multiple regression is a statistical technique for examining the relationship between a single dependent variable and several independent variables. It uses known independent variables to predict the value of dependent variables.

determine battery weight in this analysis. Table 9 (gasoline) and Table 10 (diesel) list the curb weight, performance, battery capacity, and electric motor size for different vehicle segments based on multiple regression.

Table 9. Vehicle attributes for different gasoline vehicle segments estimated using multiple regression analysis of data collected from commercial websites

Vehicle class	Range (km)	EV curb weight (kg)	0–100 km/hr performance (s)	Battery capacity (kWh)	Electric motor (kW)
A	300	973	14	37	30
B	300	1,127	12	38	57
C	300	1,326	9	43	116
D	300	1,716	8	56	217
E	300	1,859	7	62	276
E-MPV	300	1,241	9	33	55
M-MPV	300	1,898	8	54	179
C-SUV	300	1,275	9	34	59
M-SUV	300	1,444	8	39	127
L-SUV	300	2,161	7	62	258

Table 10. Vehicle attributes for different diesel vehicle segments using multiple regression analysis of data collected from commercial websites

Vehicle class	Range (km)	EV curb weight (kg)	0–100 kmph performance (s)	Battery capacity (kWh)	Electric motor (kW)
B	300	1,322	11	38	47
C	300	1,474	9	43	122
D	300	1,771	8	52	193
E	300	1,917	7	57	241
M-MPV	300	2,021	10	60	178
L-MPV	300	2,343	9	70	253
C-SUV	300	1,575	11	46	85
M-SUV	300	1,699	10	50	130
L-SUV	300	2,245	9	67	239

Although we used representative ICEV costs in 2021 to calculate the non-power train DMCs for BEVs, prices might vary as compared to actual the DMCs of BEVs. The significant difference is the battery pack cost, which we assumed decreases significantly from 2021 to 2030 (BNEF, 2021). We also assumed that factors such as raw material prices and energy costs do not significantly impact battery costs. The range of a BEV decides the battery pack size. That, in turn, significantly impacts vehicle manufacturing costs. Though not analyzed in this study, BEVs with shorter ranges are expected to have lower prices than conventionally powered cars.

While BEVs have no tailpipe emissions, CO_2 is produced and emitted when the electricity used to charge them is generated at power stations. India's phase 2 fuel consumption standards treat BEVs with upstream emissions. This study assumed that such treatment will continue through at least 2030. Therefore, we calculated and applied upstream CO_2 emissions to all BEVs.

OFF-CYCLE CO_2 REDUCTION CREDITS

While off-cycle technologies do not perform during a standardized test cycle, they nonetheless reduce CO_2 emissions in real-world conditions. India's fuel consumption standards currently regard start-stop, regenerative braking, tire pressure monitoring system (TPMS), and 6-speed transmission as off-cycle technologies. As vehicles' on-cycle efficiency increases, the real benefits of these off-cycle technologies will decrease, because the absolute benefit of the constant-percentage reduction will shrink. This is perhaps easiest to understand when considering that as the conversion efficiency of fuel energy increases, the amount of fuel input energy required to perform whatever function the off-cycle technology is displacing decreases (Meszler et al., 2016). Therefore, as CO_2 standards become more stringent, it will take progressively more off-cycle technology to generate a constant 9 g/km credit (the maximum off-cycle credit a manufacturer can avail).

Although this analysis did not consider the impact of off-cycle credits in compliance costs, start-stop, regenerative braking, and 6-speed transmission were all considered as a technology package in the compliance cost analysis. A prior study on the India market (Deo et al., 2022) showed that low-GWP refrigerants offer the lowest cost per gram of CO_2 emissions reduction compared to existing off-cycle credit technologies. Refrigerants are not currently offered any off-cycle credits, but future regulations could include them.

RESULTS

While our compliance cost estimates are a combination of two compliance strategies, ICEV exhaustion and cost-beneficial BEV penetration, manufacturers will usually follow the lowest incremental cost to meeting CO_2 emissions targets. The addition of any technology increases a vehicle's total cost. Therefore, manufacturers implement technologies judiciously. India is a price-sensitive market; most passenger cars sold are below 10 lakhs. Currently, the retail price of a BEV with 300 km driving range is higher than 10 lakhs and thus beyond the reach of most mass-market customers. ICEV technologies are the more affordable short-term solution for CO_2 reduction until the BEV prices drop. CNG engines are also a comparatively cheaper option for A and B class passenger cars, entry MPVs, and compact SUVs. However, because of natural gas leakage across the supply chain and the greenhouse gas emissions that result, CNG cars do not offer lower life-cycle greenhouse gas emissions than gasoline or diesel vehicles (Bieker, 2021).

Table 11 shows that CO_2 emissions reductions of up to 35% are possible through cost-competitive ICEV technologies across all segments of gasoline cars; the same CO_2 reduction potential is up to 20% for diesel and more than 40% for CNG. The table also shows how super credits help lower the compliance cost of BEVs and make early adoption of BEVs possible in segments that are cost effective. Currently, the phase 2 fleet-average CO_2 standards offer a super credit factor of 3 for BEVs. This means that every BEV sold is counted as three cars when it comes to manufacturers compliance with CO_2 standards; spreading the cost over three cars lowers the compliance cost of BEVs compared to improved ICEVs. In the short term, super credits can act as a catalyst for greater market penetration of BEVs. Increased BEV sales is expected to reduce battery and overall vehicle costs. At the same time, super credits undermine the intended environmental benefits of CO_2 standards, because they exceed real-world emission reductions. Thus, super credits are not conducive with realizing maximum long-term emissions reductions.

Table 11. Percentage of CO_2 reductions possible through ICEV technologies until BEV compliance costs are lower for manufacturers in 2030; an electric range of 300 km was considered for all cars

Segment	Class	Gasoline		Diesel		CNG	
		without super credit	with super credit	without super credit	with super credit	without super credit	with super credit
Passenger car	**A class**	24%	13%	—	—	50%	28%
	B class	29%	17%	10%	0%	46%	35%
	C class	34%	19%	20%	9%	—	—
	D class	10%	0%	0%	0%	—	—
MPV	**Entry MPV**	27%	11%	—	—	40%	29%
	Midsize MPV	35%	21%	19%	6%	—	—
SUV	**Compact SUV**	29%	13%	19%	9%	41%	28%
	Midsize SUV	27%	12%	16%	3%	—	—

With a super credit factor of 3 for BEVs, the CO_2 reduction possible through cost-competitive ICEV technologies ranges from 13%–19% for A, B, and C class gasoline vehicles. For the diesel versions of the entry-level MPV and compact SUV, BEVs are already the cheaper compliance option. The midsize MPV can have 21% CO_2 reductions through ICEV technologies before switching to the electric option. For CO_2 reductions above these levels, BEVs become cheaper than continuing to add more ICEV technology. Continuing battery cost reductions will almost certainly make BEVs more cost effective after 2030. For class D, E, midsize and large MPVs, and SUVs, BEVs are always the lower cost compliance path, although these are premium class vehicles and customers value comfort more than technology. Customers who consider a 300 km BEV range inadequate might prefer PHEVs instead. However, in real-world use, PHEVs only show 25%–31% lower life-cycle greenhouse gas emissions than gasoline cars (Bieker, 2021).

Figure 3 shows the compliance costs for India's passenger car fleet without any super credits for BEVs. In this figure, the ICEV exhaustion strategy is generally represented as an upwardly sloping power curve and the BEVs are added only when all the ICEV technologies have been exhausted. At the fleet level, a maximum 45% CO_2 emissions reduction can come from ICEV technologies. Beyond that, BEVs become more cost-effective than continued ICEV improvements in the ICEV exhaustion strategy. The BEV penetration in the cost curve extends the ICEV technology cost curve to lower levels of CO_2 than would otherwise be possible. The thickest line represents the cost-beneficial BEV penetration strategy where BEVs are introduced early when the per-gram cost for CO_2 reduction is lower than it is through ICEV technologies; in this pathway, up to 25% CO_2 reduction is possible through ICEV technologies; increased BEV penetration then provides the lowest cost to manufacturers. At the 25% ICEV technology level, most of engine technologies described above would be required along with P2 hybrid technology. The class-specific compliance cost curves for different vehicle classes for both gasoline and diesel ICEVs are presented in Appendix B.

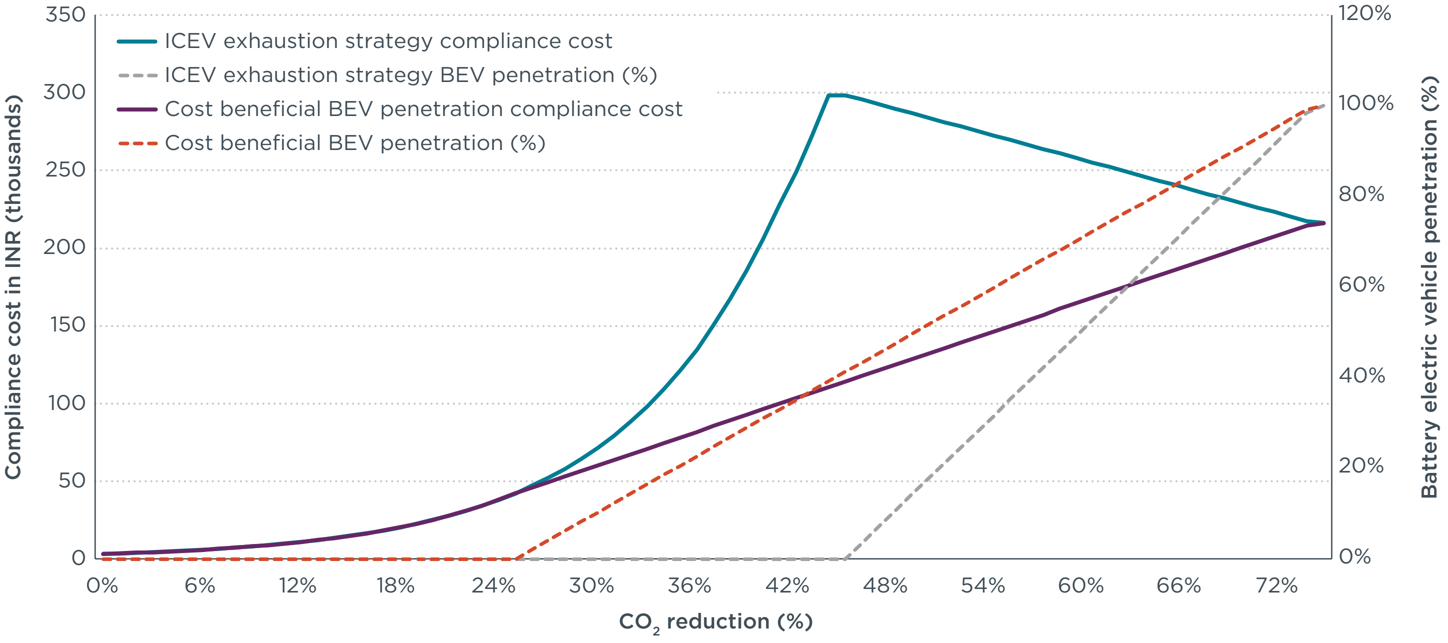

Figure 3. DMC curves for reducing the fleet-average CO_2 emissions of passenger cars in 2030 versus the lowest cost of full deployment of ICEV technology prior to the transition to BEVs with no super credits.

Early adoption of BEVs through the cost-beneficial BEV penetration strategy was estimated to reduce the compliance cost by approximately ₹250,000 at the fleet level. However, ICEV technologies remain competitive throughout the fleet as compared to BEVs without any super credits. 25% of CO_2 reduction in ICEVs can be achieved through incremental improvements in engine technologies, friction reduction, downsizing, and hybridization combined with vehicle-level improvements like aerodynamic and weight reduction. These technologies together would increase the DMC of the vehicle by ₹50,000.

Figure 4 shows the compliance cost of the passenger car fleet with a super credit factor of 3 for BEVs. Super credits help lower the compliance cost of BEVs; their early adoption would reduce the overall compliance cost by approximately ₹25,000 at the fleet level. This means that at a fleet level, 15% of CO_2 reduction is possible with ₹25,000 DMC increase. Technologies like aerodynamic improvements, friction reduction, and P0 hybrids would be sufficient to meet the 15% CO_2 reduction before BEVs become cost effective.

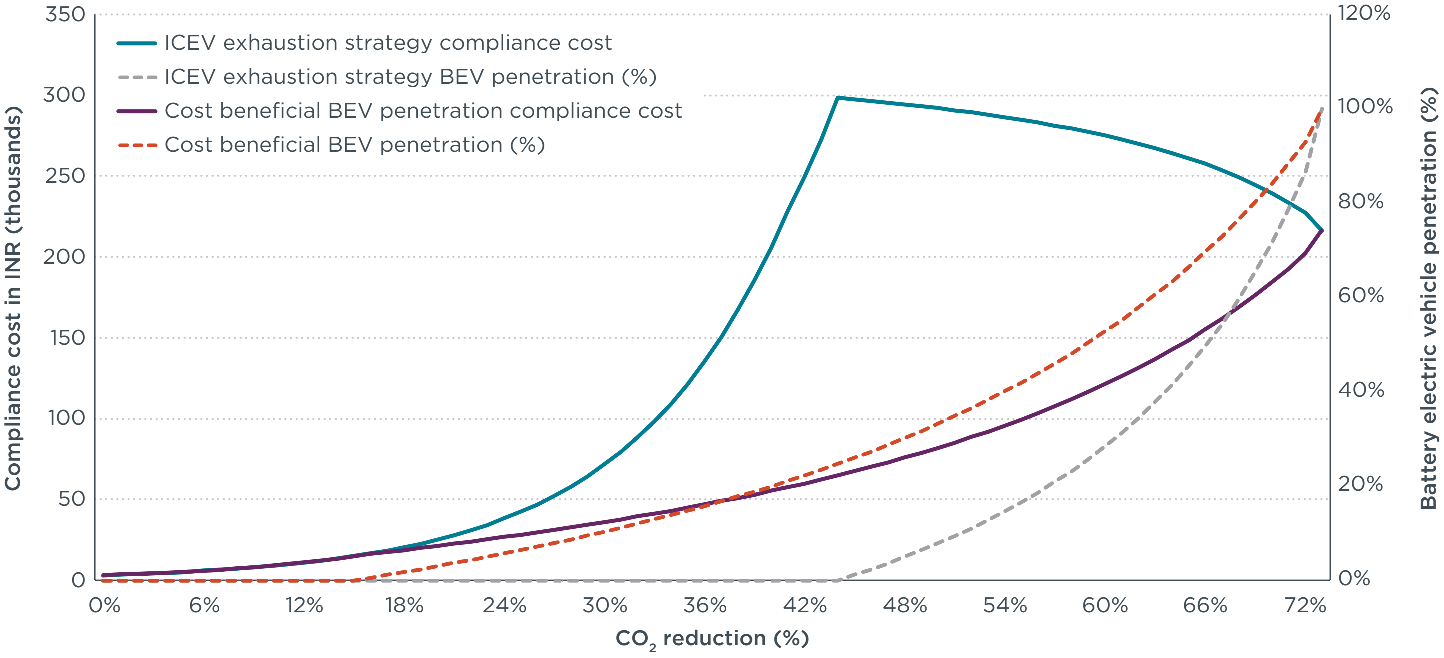

Figure 4. DMC curves for reducing the fleet average CO_2 emissions of passenger cars in 2030 versus the lowest cost of full deployment of ICE technology prior to the transition to EVs with a super credit factor of 3.

For any particular level of fleet-average gCO_2/km that would be set, manufacturers can comply by adopting various ICEV technologies, increasing the market share of BEVs, or a combination of the two. To help identify feasible and cost-effective levels for a possible standard, we assumed that the primary market composition in terms of the share of vehicle segments and ICEV fuel mix will remain the same in India. Based on that, the sales-weighted gCO_2/km of an ICEV and BEV are estimated.

Figure 5 shows the possible values of fleet-average CO_2 emission standards for different ICEV technologies and BEV percentages. For example, if a fleet-average CO_2 target is set at 90 gCO_2/km, the compliance curve spans from 0% BEVs on one end, meaning that manufacturers could meet this standard solely by improving the fuel economy of the ICEVs by 20%, to 30% BEVs on the other end, which means this amount of BEV market share could meet the target without any improvements to the ICEVs. Because Indian manufacturers are likely to choose a combination of ICEVs and BEVs, different manufacturers will apply different technology combinations, and average costs for individual manufacturers will vary. How this is reflected in manufacturers' decision-making will depend on policy, the market environment, and company development strategy.

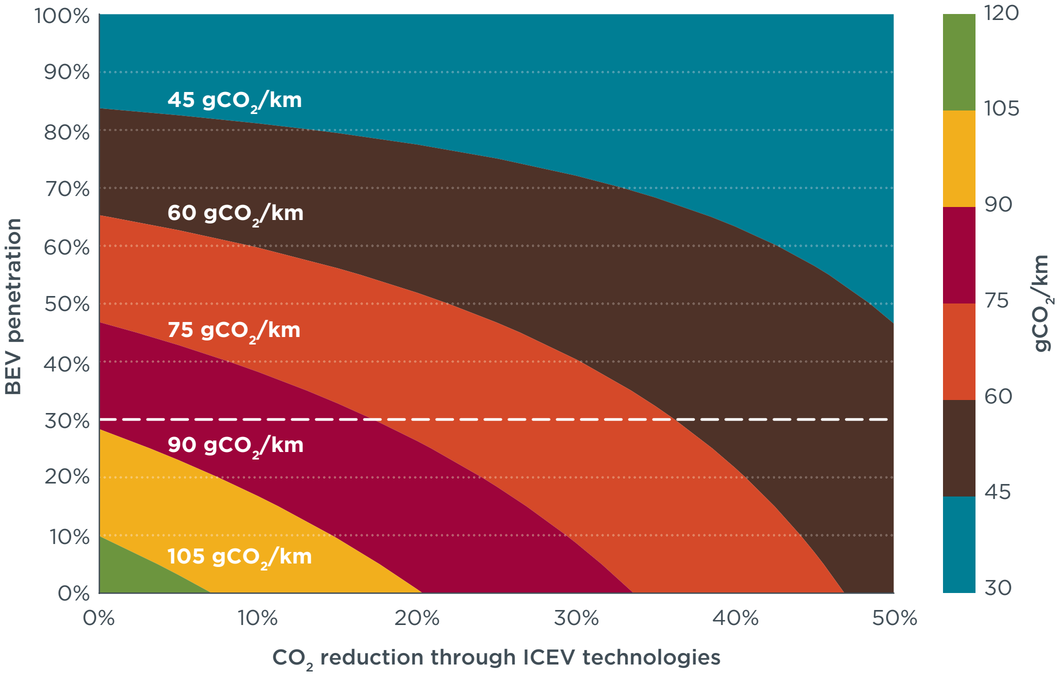

Figure 5. New passenger car fleet-average gCO_2/km that could be achieved by choosing ICEV efficiency improvement and BEVs. Note that the baseline fleet-average CO_2 is 113 gCO_2/km and there are no super credits for BEVs.

Increasing BEV penetration will reduce the incremental cost to comply with future fuel consumption targets in 2030. However, challenges remain in securing the supply chain, consumer awareness of this relatively new technology, and setting up adequate charging infrastructure. Government and industry must act collectively to help remove these barriers for BEVs to replace conventional ICEVs rapidly. In the meantime, before BEVs become fully mainstream in the passenger car segment, many cost-effective ICEV technologies could reduce CO_2 emissions and fuel use.

CONCLUSION AND POLICY IMPLICATIONS

This paper presented a set of fleet-average CO_2 targets for passenger cars in India by primarily considering improvements in ICEV technologies until BEV introduction becomes more cost-effective from a CO_2 emissions reduction standpoint. Based on the cost curves we derived, it is possible to estimate compliance costs for a range of possible fleet-average CO_2 targets that could be set in 2030.

Increased BEV market share is expected to result in lower technology costs and lower CO_2 emissions. While BEVs are more expensive than ICEVs in the near term, it is reasonable to assume that manufacturers will meet lower CO_2 targets by exhausting less expensive ICEV technologies to the greatest extent possible before switching to BEVs. Manufacturers usually follow a common parts strategy where the same component is used in as many vehicles as possible. If the number of BEVs increases substantially, the cost per vehicle could drop. At the same time, the cost for the remaining ICE cars might increase because fewer of those parts are in use in production.

According to the estimates from this analysis, a fleet-average target not lower than 90 gCO_2/km for passenger cars in 2030 would be needed for 30% BEV penetration. Improving ICEVs at the fleet level by 20% or having BEV penetration of 30% can attain the 2030 targets of 90 gCO_2/km, but for most of the vehicle segments, BEVs will still be expensive from compliance cost point of view. The estimated additional DMC cost over 2021 at a fleet level for attaining the CO_2 target in 2030 is approximately ₹50,000 ($666) per vehicle. With the existing super credit factor of 3, the compliance cost to meet 90 gCO_2/km can be halved.

Indeed, we estimated that if BEVs are incentivized by super credits, their compliance cost could be lower than gasoline ICEV technologies in segments like entry MPVs and SUVs as well as midsize SUVs and MPVs. In all diesel segments, BEVs were estimated to have lower compliance costs than baseline ICEV technologies. Only CNG engines are estimated to have lower compliance cost compared to BEVs even with super credits, but when taking the 20-year global warming potential of CNG vehicles into account, these vehicles offer no significant climate benefits.

Implementing phase 3 targets in 2027 and then gradually reducing super credits by 1 until they are phased out in 2030 would incentivize manufacturers to produce BEVs in each passenger car segment and simultaneously help India achieve its target of 30% BEVs in 2030. Super credits help incentivize BEVs and will help BEVs penetrate all Indian passenger car segments. However, gradually phasing them out (because they over-credit the number of BEVs sold), would reduce the over-crediting over time and help ensure that manufacturers deploy more BEVs so that India can meet its 30% BEV target by 2030.

Additionally, low-GWP refrigerant offers the lowest cost per gram of CO_2 emissions reduction compared to existing off-cycle credit technologies and should be added to the list of off-cycle technologies (Deo et al, 2022). As CO_2 standards become more stringent, it will take progressively more off-cycle technologies to generate a constant 9 g/km credit.

The cost curves presented in this paper can be used to generate additional estimates. It is critical to recognize that the cost curves only apply to the average vehicle market. Individual manufacturer costs vary, as does the mix of technologies used by each manufacturer. Cost estimates are based on the assumption of high mass production, and future technological design changes are not taken into account. This means that any potential technological transformation to improve efficiency and reduce associated costs is not reflected in cost curves. This more conservative approach is referred to as the “should cost” estimate by FEV Inc., because it is based on what the cost of already existing technology should be if it is produced in large quantities with no design changes to reflect current knowledge. This is distinct from a “could cost” valuation that considers what the cost of the technology could be for a new product if optimized over time.

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APPENDIX A. INDIA GASOLINE AND DIESEL TECHNOLOGY COSTS FOR 2030

Table A1. Gasoline cumulative technology costs and CO_2 for the A class passenger car in India for 2030

Package	A class	Cumulative CO_2 (%)
1	Start/Stop	5.0%
2	Downsizing to 0.8L, single stage turbocharging + GDI	19.0%
3	10% reduction in rolling resistance & Aerodynamics	20.6%
4	20% friction, variable oil pump, electric coolant pump	21.3%
5	DVVT+VVL	22.8%
6	Cooled low pressure EGR	24.7%
7	6 speed MT +10% mass reduction	26.9%
8	Advanced Micro hybrid (2.3 kW & 0.04 kWh)	29.4%
9	P0 hybrid (8 kW & 200Wh)	31.8%
10	P1 (8 kW & 200Wh)	33.2%
11	P2 coaxial (8 kW & 200Wh)	38.5%

Table A2. Gasoline cumulative technology costs and CO_2 for the B class passenger car in India for 2030

Package	B class	Cumulative CO_2 (%)
1	Start/Stop	5.0%
2	Downsizing to 0.8L, GDI + single stage turbocharging,	19.0%
3	10% reduction in rolling resistance & Aerodynamics	23.8%
4	6 speed MT +10% mass reduction	26.1%
5	20% friction, variable oil pump, electric coolant pump	26.8%
6	DVVT+VVL	28.2%
7	Cooled low pressure EGR	29.9%
8	7 speed DCT, advance start stop	32.4%
9	Advanced Micro hybrid (2.3 kW & 0.04 kWh)	34.7%
10	P0 hybrid (10 kW & 250Wh)	36.9%
11	P1 (10 kW & 250Wh)	38.2%
12	P2 coaxial (10 kW & 250Wh)	43.1%

Table A3. Gasoline cumulative technology costs and CO_2 for the C class passenger car in India for 2030

Package	C class	Cumulative CO_2 (%)
1	Start/Stop	5.0%
2	Downsizing to 1L, single stage turbocharging + GDI	21.1%
3	6 speed MT +10% mass reduction	25.1%
4	10% reduction in rolling resistance & Aerodynamics	29.6%
5	20% friction, variable oil pump,	30.8%
6	7 speed DCT + advanced start-stop	32.7%
7	2-stage, DVVT+VVL+Miller	35.7%
8	Two-step VCR, cooled low pressure EGR	36.0%
9	P0 hybrid (15 kW & 375Wh)	40.2%
10	P1 (15 kW & 375Wh)	41.4%
11	P2 coaxial (15 kW & 375Wh)	46.1%

Table A4. Gasoline cumulative technology costs and CO_2 for the D class passenger car in India for 2030

Package	D class	Cumulative CO_2 (%)
1	Start/Stop	5.0%
2	Downsizing to 1.4L+ GDI + 10 speed DCT	24.4%
3	10% weight and 10% coastdown reduction	28.0%
4	DVVT+VVL	29.4%
5	20% friction, variable oil pump,	30.2%
6	2-stage, miller	33.3%
7	Two-step VCR, cooled low pressure EGR	34.2%
8	P0 hybrid (20 kW & 500 Wh)	38.5%
9	P1 (20 kW & 500 Wh)	39.8%
10	P2 coaxial (20 kW & 500 Wh)	44.6%

Table A5. Gasoline cumulative technology costs and CO_2 for the E class passenger car in India for 2030

Package	E class	Cumulative CO_2 (%)
1	Start/Stop	5.0%
2	Downsizing 1.6L+ GDI + 10 speed DCT	23.6%
3	10% weight and 10% Coastdown reduction	27.9%
4	DVVT+VVL	29.1%
5	2-stage, 20% friction, variable oil pump,	32.0%
6	cooled LP, two-step VCR	33.7%
7	P0 hybrid (25 kW & 625 Wh)	38.0%
8	P1 (25 kW & 625Wh)	39.3%
9	P2 coaxial (25 kW & 625Wh)	44.1%

Table A6. Gasoline cumulative technology costs and CO_2 for the compact SUV in India for 2030

Package	Compact SUV	Cumulative CO_2 (%)
1	Start/Stop	6.1%
2	Downsizing to 1L, single stage turbocharging + GDI	21.9%
3	6 speed MT + 10% mass reduction	25.9%
4	10% reduction in rolling resistance & Aerodynamics	30.3%
5	20% friction, variable oil pump,	31.5%
6	7 speed DCT + advanced start-stop	33.5%
7	2-stage, DVVT+VVL+Miller	36.4%
8	Two-step VCR, cooled low pressure EGR	36.7%
9	Advanced Micro hybrid (2.3 kW & 0.04 kWh)	43.1%
10	P0 hybrid (10 kW & 250Wh)	45.0%
11	P1 (10 kW & 250Wh)	46.1%
12	P2 coaxial (10 kW & 250Wh)	50.4%

Table A7. Gasoline cumulative technology costs and CO_2 for the midsize SUV in India for 2030

Package	Midsize SUV	Cumulative CO_2 (%)
1	Start/Stop	5.0%
2	Downsizing to 1.4L+ GDI + 10 speed DCT + Advanced start-stop	24.4%
3	10% weight and 10% Coastdown reduction	28.0%
4	DVVT+VVL	29.4%
5	20% friction, variable oil pump,	30.2%
6	2-stage, miller	33.3%
7	cooled low pressure EGR, two-step VCR	34.2%
8	P0 hybrid (20 kW & 500 Wh)	38.5%
9	P1 (20 kW & 500 Wh)	43.8%
10	P2 coaxial (20 kW & 500 Wh)	44.6%

Table A8. Gasoline cumulative technology costs and CO_2 for the large SUV in India for 2030

Package	Large SUV	Cumulative CO_2 (%)
1	Start/Stop	9.0%
2	Downsizing to 1.6L+ GDI + 10 speed DCT + Advanced start-stop	27.8%
3	10% weight and 10% Coastdown reduction	31.8%
4	DVVT+VVL	33.0%
5	2-stage, 20% friction, variable oil pump,	35.7%
6	cooled low pressure EGR, two-step VCR	37.3%
7	P0 hybrid (25 kW & 625 Wh)	41.5%
8	P1 (25 kW & 625Wh)	42.6%
9	P2 coaxial (25 kW & 625Wh)	47.2%

Table A9. Gasoline cumulative technology costs and CO_2 for the entry MPV in India for 2030

Package	Entry MPV	Cumulative CO_2 (%)
1	Start/Stop	6.1%
2	Downsizing to 1L, single stage turbocharging	21.9%
3	6 speed MT + GDI +10% mass reduction	25.9%
4	10% reduction in rolling resistance & Aerodynamics	30.3%
5	20% friction, variable oil pump	31.5%
6	7 speed DCT + advanced start-stop	33.5%
7	2-stage, DVVT+VVL+Miller	36.4%
8	two-step VCR, cooled low pressure EGR	36.7%
9	Advanced Micro hybrid (2.3 kW & 0.04 kWh)	43.1%
10	P0 hybrid (10 kW & 250Wh)	45.0%
11	P1 (10 kW & 250Wh)	46.1%
12	P2 coaxial (10 kW & 250Wh)	50.4%

Table A10. Gasoline cumulative technology costs and CO_2 for the midsize MPV in India for 2030

Package	Midsize MPV	Cumulative CO_2 (%)
1	Start/Stop	5.0%
2	Downsizing to 1.4L+ GDI + 10 speed DCT + Advanced start stop	25.4%
3	10% weight and 10% Coastdown reduction	29.0%
4	Engine technologies	30.4%
5	20% friction, variable oil pump,	31.1%
6	2-stage, miller	34.2%
7	cooled low pressure EGR, two-step VCR	35.1%
8	P0 hybrid (20 kW & 500 Wh)	39.4%
9	P1 (20 kW & 500 Wh)	40.6%
10	P2 coaxial (20 kW & 500 Wh)	45.4%

Table A11. Diesel cumulative technology costs and CO_2 for the B class passenger car in India for 2030

Package	B class	Cumulative CO_2 (%)
1	Start/Stop	3.5%
2	Downsizing to 1.2L/Transmission 5MT->6MT, Aftertreatment LNT + CDPF -> DOC + SDPF	4.5%
3	10% weight and 10% Coastdown reduction	8.3%
4	Friction, resistance	8.4%
5	Cooled HP/cooled low pressure EGR	9.1%
6	VVT	9.9%
7	Advanced micro hybrid (2.3 kW & 0.04 kWh)	13.0%
8	P0 hybrid (10 kW & 250Wh)	15.9%
9	P1 (10 kW & 250Wh)	17.6%
10	P2 coaxial (10 kW & 250Wh)	24.2%

Table A12. Diesel cumulative technology costs and CO_2 for the C class passenger car in India for 2030

Package	C class	Cumulative CO_2 (%)
1	Start/Stop	3.6%
2	Downsizing to 1.4L/7 speed DCT + advanced start-stop	13.2%
3	10% weight and 10% Coastdown reduction	16.7%
4	Friction, resistance	17.5%
5	Cooled HP/cooled low pressure EGR + VCR	21.5%
6	VVT, Aftertreatment LNT + CDPF -> DOC + SDPF	22.2%
7	P0 hybrid (15 kW & 375Wh)	27.3%
8	P1 (15 kW & 375Wh)	28.8%
9	P2 coaxial (15 kW & 375Wh)	34.5%

Table A13. Diesel cumulative technology costs and CO_2 for the D class passenger car in India for 2030

Package	D class	Cumulative CO_2 (%)
1	Start/Stop	4.8%
2	Downsizing to 1.6L/10 speed DCT + Advanced start stop	5.0%
3	10% weight and 10% Coastdown reduction	10.6%
4	Friction, resistance	11.4%
5	VVT	11.9%
6	Cooled low pressure EGR + VCR	17.2%
7	P0 hybrid (20 kW & 500 Wh)	22.7%
8	P1 (20 kW & 500 Wh)	24.3%
9	P2 coaxial (20 kW & 500 Wh)	30.3%

Table A14. Diesel cumulative technology costs and CO_2 for the E class passenger car in India for 2030

Package	E class	Cumulative CO_2 (%)
1	Start/Stop	4.8%
2	Downsizing to 2.0L/10 speed DCT, double TC, advanced start stop	12.3%
3	10% weight and 10% Coastdown reduction	21.2%
4	Friction, resistance	21.4%
5	VVT	21.6%
6	Cooled low pressure EGR + VCR	26.5%
7	P0 hybrid (25 kW & 625 Wh)	31.4%
8	P1 (25 kW & 625Wh)	32.8%
9	P2 coaxial (25 kW & 625Wh)	38.1%

Table A15. Diesel cumulative technology costs and CO_2 for the compact SUV in India for 2030

Package	Compact SUV	Cumulative CO_2 (%)
1	Start/Stop	3.6%
2	Downsizing to 1.4L/7 speed DCT, advanced start stop	13.2%
3	10% weight and 10% Coastdown reduction	16.7%
4	Friction, resistance	17.5%
5	Cooled HP/cooled low pressure EGR + VCR	21.5%
6	VVT, Aftertreatment LNT + CDPF -> DOC + SDPF	22.2%
7	Advanced micro hybrid	24.8%
8	P0 hybrid (10 kW & 250Wh)	27.3%
9	P1 (10 kW & 250Wh)	28.8%
10	P2 coaxial (10 kW & 250Wh)	34.5%

Table A16. Diesel cumulative technology costs and CO_2 for the midsize SUV in India for 2030

Package	Midsize SUV	Cumulative CO_2 (%)
1	Start/Stop	4.8%
2	Downsizing to 1.6L/10 speed DCT, advanced start-stop	5.0%
3	10% weight and 10% coastdown reduction	10.6%
4	Friction, resistance	11.4%
5	VVT	11.9%
6	Cooled HP/cooled low pressure EGR + VCR	17.2%
7	P0 hybrid (15 kW & 375Wh)	22.7%
8	P1 (15 kW & 375Wh)	24.3%
9	P2 coaxial (15 kW & 375Wh)	30.3%

Table A17. Diesel cumulative technology costs and CO_2 for the large SUV in India for 2030

Package	Large SUV	Cumulative CO_2 (%)
1	Start/Stop	5.9%
2	Downsizing to 2.0L/10 speed DCT, Adv SS,	13.3%
3	10% weight and 10% Coastdown reduction	22.1%
4	Friction, resistance	22.3%
5	VVT	22.5%
6	Cooled low pressure EGR + VCR	27.4%
7	P0 hybrid (25 kW & 625 Wh)	32.1%
8	P1 (25 kW & 625Wh)	33.5%
9	P2 coaxial (25 kW & 625Wh)	38.8%

Table A18. Diesel cumulative technology costs and CO_2 for the midsize MPV in India for 2030

Package	Midsize MPV	Cumulative CO_2 (%)
1	Start/Stop	4.8%
2	Downsizing to 1.6L/7 speed DCT, Adv SS	5.0%
3	10% weight and 10% Coastdown reduction	10.6%
4	Friction, resistance	11.4%
5	VVT	11.9%
6	Aftertreatment + Cooled low pressure EGR + VCR	17.2%
7	P0 hybrid (15 kW & 375Wh)	22.7%
8	P1 (15 kW & 375Wh)	24.3%
9	P2 coaxial (15 kW & 375Wh)	30.3%

Table A19. Diesel cumulative technology costs and CO_2 for the large MPV in India for 2030

Package	Large MPV	Cumulative CO_2 (%)
1	Start/Stop	5.9%
2	Downsizing to 2.0L/10 speed DCT, Adv SS,	13.3%
3	10% weight and 10% Coastdown reduction	22.1%
4	Friction, resistance	22.3%
5	VVT	22.5%
6	Aftertreatment + Cooled low pressure EGR + VCR	27.4%
7	P0 hybrid (30 kW & 750 Wh)	32.1%
8	P1 (30 kW & 750Wh)	33.5%
9	P2 coaxial (30 kW & 750Wh)	38.8%

Table A20. CNG cumulative technology costs and CO_2 for the A class passenger car in India for 2030

Package	A class	Cumulative CO_2 (%)
1	CNG	19.6%
2	Start/Stop	23.6%
3	Downsizing to 0.8L, single stage turbocharging + GDI	34.9%
4	10% reduction in rolling resistance & Aerodynamics	36.2%
5	20% friction, var. oil pump, electric coolant pump	36.7%
6	DVVT+VVL	38.0%
7	Cooled low pressure EGR	39.5%
8	6 speed MT +10% mass reduction	41.3%
9	Advanced Micro hybrid (2.3 kW & 0.04 kWh)	43.3%
10	P0 hybrid (8 kW & 200Wh)	45.2%
11	P1 (8 kW & 200Wh)	46.3%
12	P2 coaxial (8 kW & 200Wh)	50.6%

Table A21. CNG cumulative technology costs and CO_2 for the B class passenger car in India for 2030

Package	B class	Cumulative CO_2 (%)
1	CNG	20.6%
2	Start/Stop	24.6%
3	Downsizing to 0.8L, GDI + single stage turbocharging,	35.7%
4	10% reduction in rolling resistance & aerodynamics	39.5%
5	6 speed MT +10% mass reduction	41.4%
6	20% friction, var. oil pump, electric coolant pump	41.9%
7	DVVT+VVL	43.0%
8	Cooled low pressure EGR	44.4%
9	7 speed DCT, advance start stop	46.4%
10	Advanced Micro hybrid (2.3 kW & 0.04 kWh)	48.2%
11	P0 hybrid (10 kW & 250Wh)	49.9%
12	P1 (10 kW & 250Wh)	50.9%
13	P2 coaxial (10 kW & 250Wh)	54.8%

Table A22. CNG cumulative technology costs and CO_2 for the compact SUV in India for 2030

Package	Compact SUV	Cumulative CO_2 (%)
1	CNG	17.5%
2	Start/Stop	21.6%
3	Downsizing to 1.0L, single stage turbocharging + GDI	34.9%
4	6 speed MT + 10% mass reduction	38.2%
5	10% reduction in rolling resistance & Aerodynamics	41.9%
6	20% friction, var. oil pump	42.9%
7	7 speed DCT + advanced start-stop	44.5%
8	2-stage, DVVT+VVL+Miller	47.0%
9	Two-step VCR, cooled low pressure EGR	47.2%
10	Advanced Micro hybrid (2.3 kW & 0.04 kWh)	49.0%
11	P0 hybrid (10 kW & 250Wh)	50.7%
12	P1 (10 kW & 250Wh)	51.7%
13	P2 coaxial (10 kW & 250Wh)	55.5%

Table A23. CNG cumulative technology costs and CO_2 for the entry MPV in India for 2030

Package	Entry MPV	Cumulative CO_2 (%)
1	CNG	17.5%
2	Start/Stop	21.6%
3	Downsizing to 1.0L, single stage turbocharging	34.9%
4	6 speed MT + GDI +10% mass reduction	38.2%
5	10% reduction in rolling resistance & Aerodynamics	41.9%
6	20% friction, var. oil pump	42.9%
7	7 speed DCT + advanced start-stop	44.5%
8	2-stage, DVVT+VVL+Miller	47.0%
9	two-step VCR, cooled low pressure EGR	47.2%
10	Advanced Micro hybrid (2.3 kW & 0.04 kWh)	49.0%
11	P0 hybrid (10 kW & 250Wh)	50.7%
12	P1 (10 kW & 250Wh)	51.7%
13	P2 coaxial (10 kW & 250Wh)	55.5%

APPENDIX B. COST CURVES FOR INDIA TECHNOLOGY COST IN 2030 BY SEGMENT

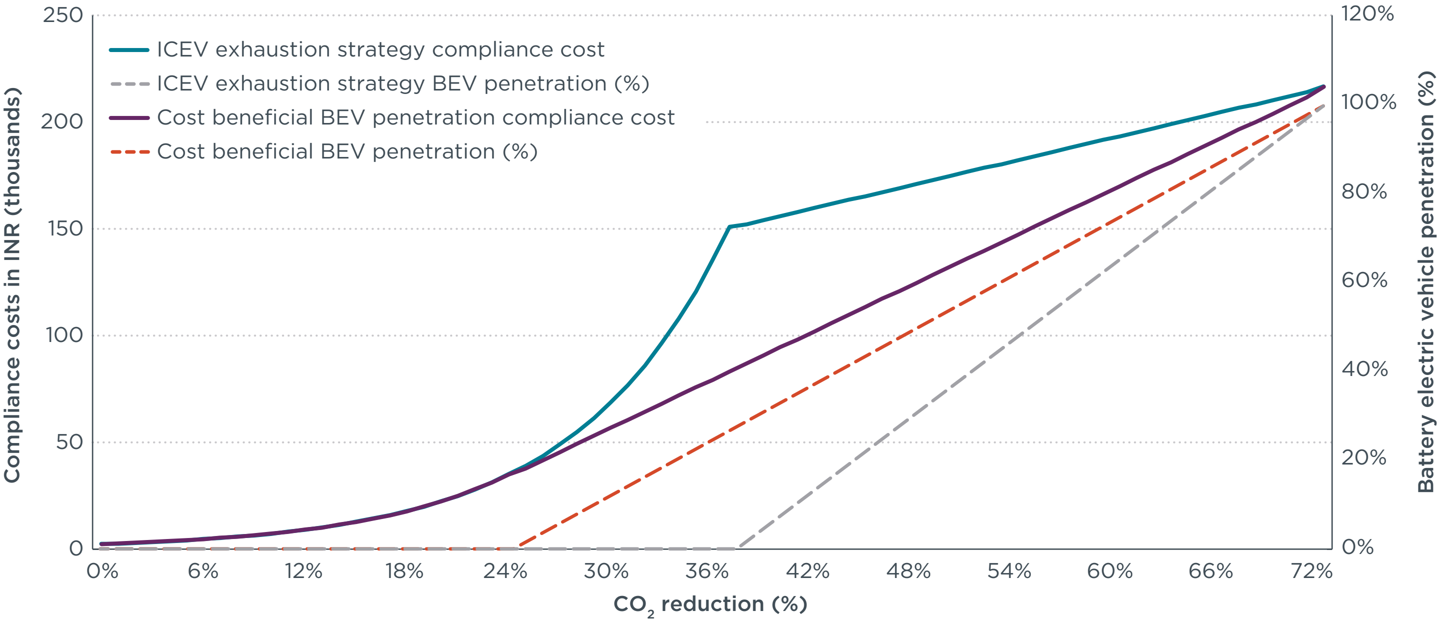

Figure B1. Compliance cost curves for gasoline A class passenger car in 2030 with no super credit.

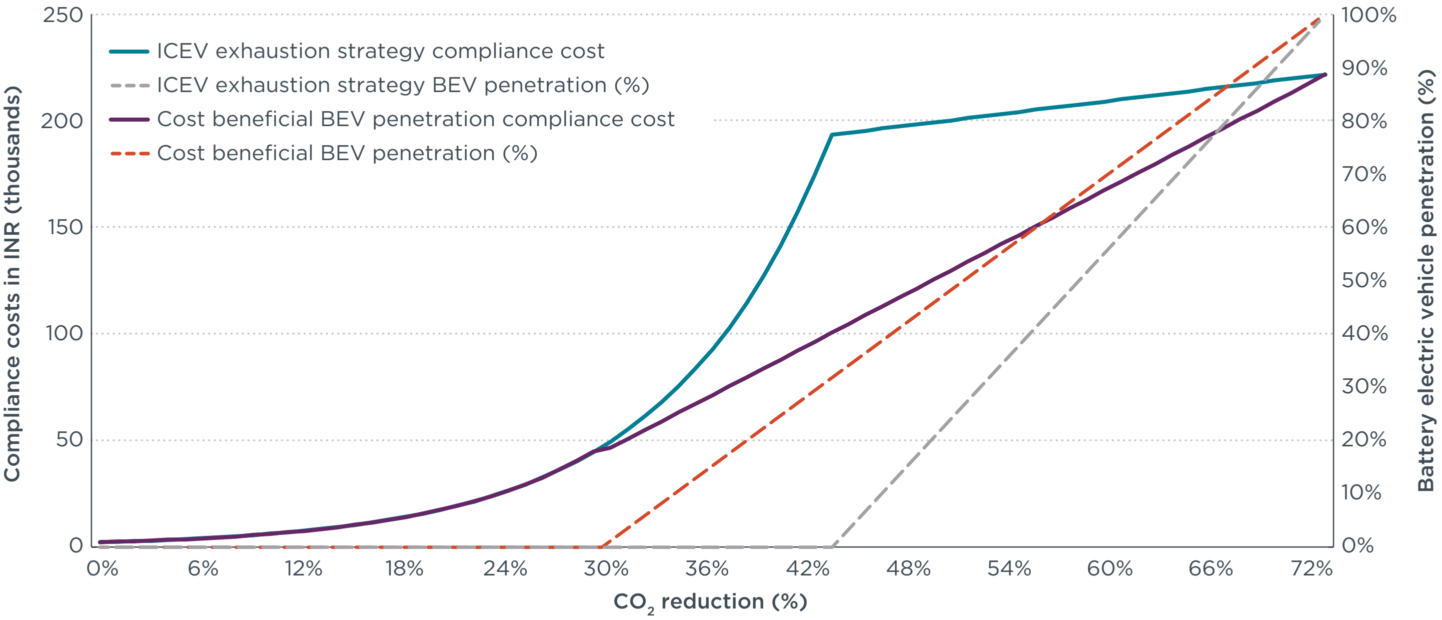

Figure B2. Compliance cost curves for gasoline B class passenger car in 2030 with no super credit.

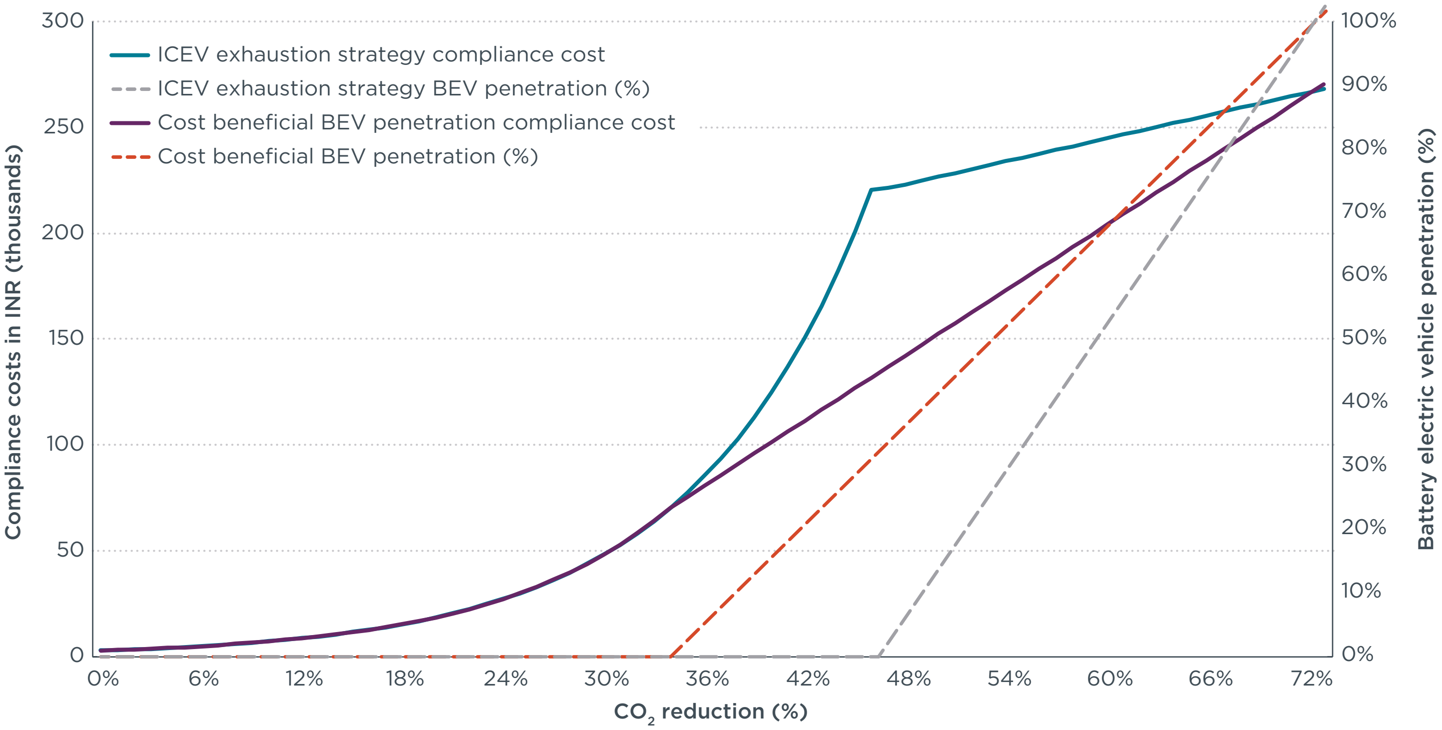

Figure B3. Compliance cost curves for gasoline C class passenger car in 2030.

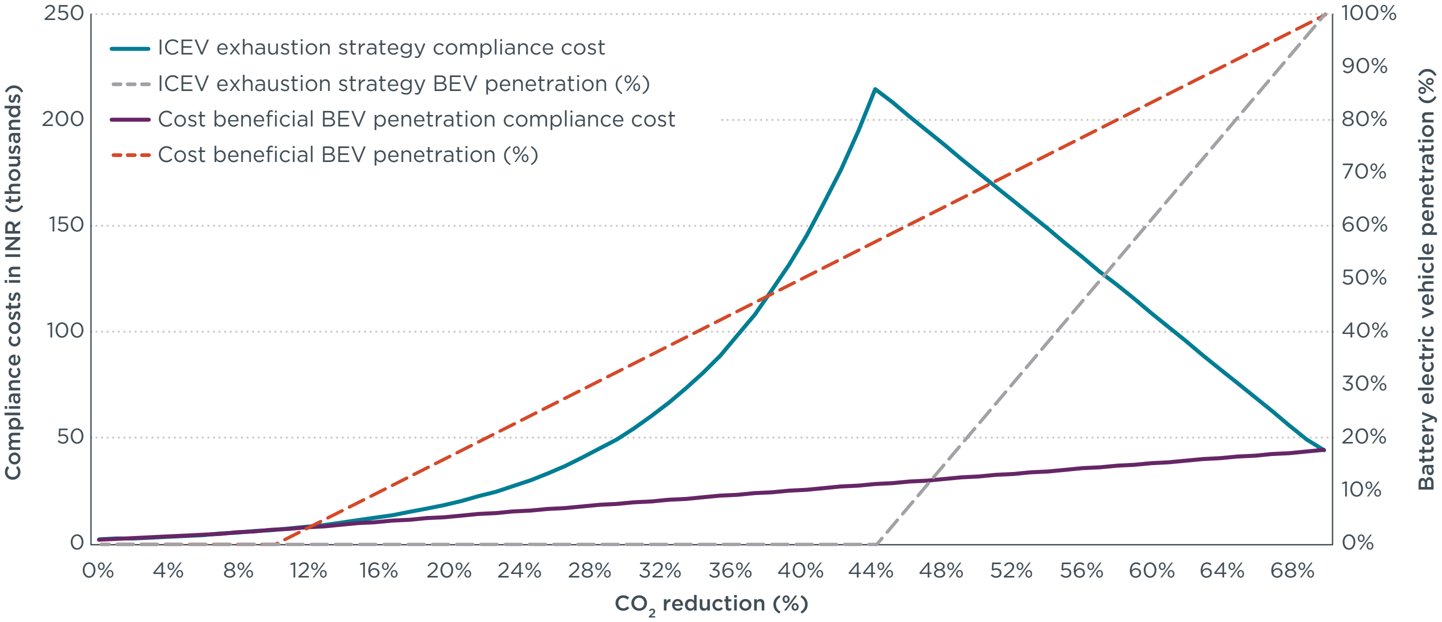

Figure B4. Compliance cost curves for gasoline D class passenger car in 2030.

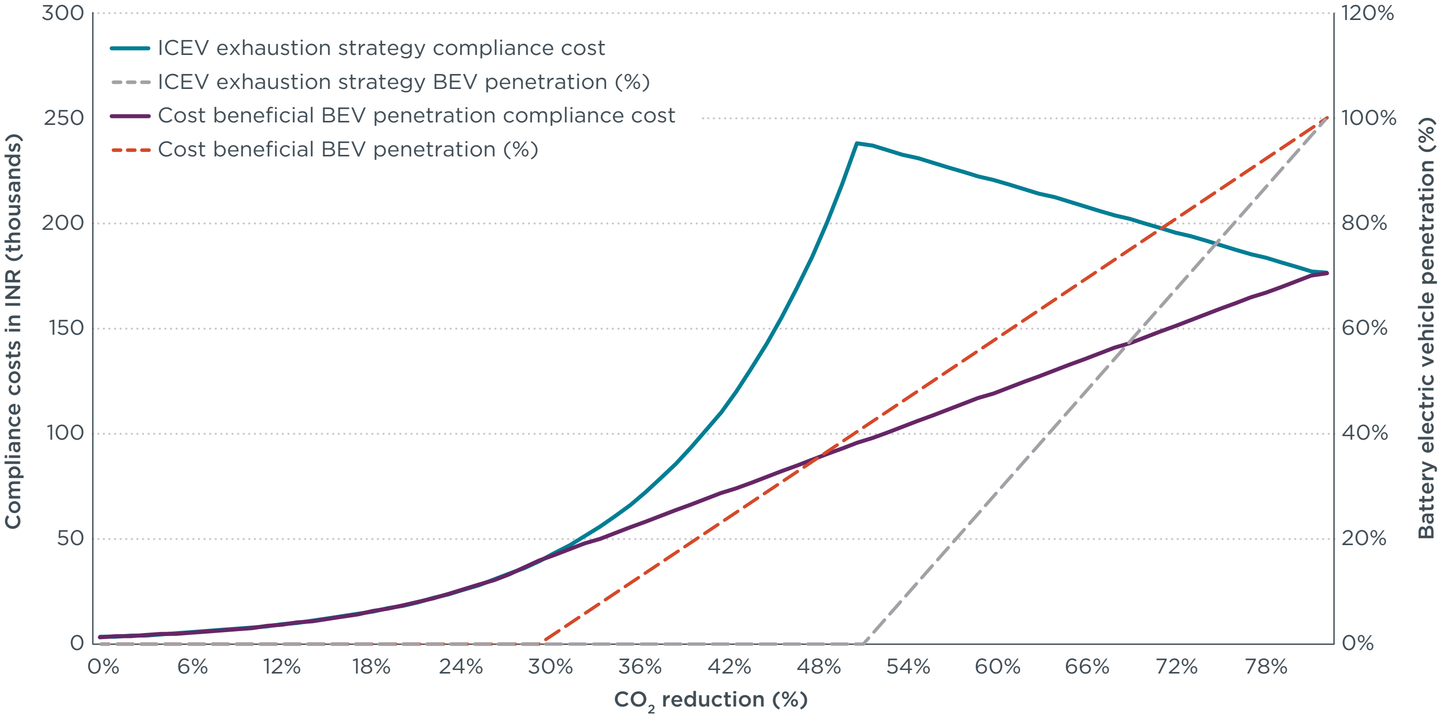

Figure B5. Compliance cost curves for gasoline compact SUVs in 2030.

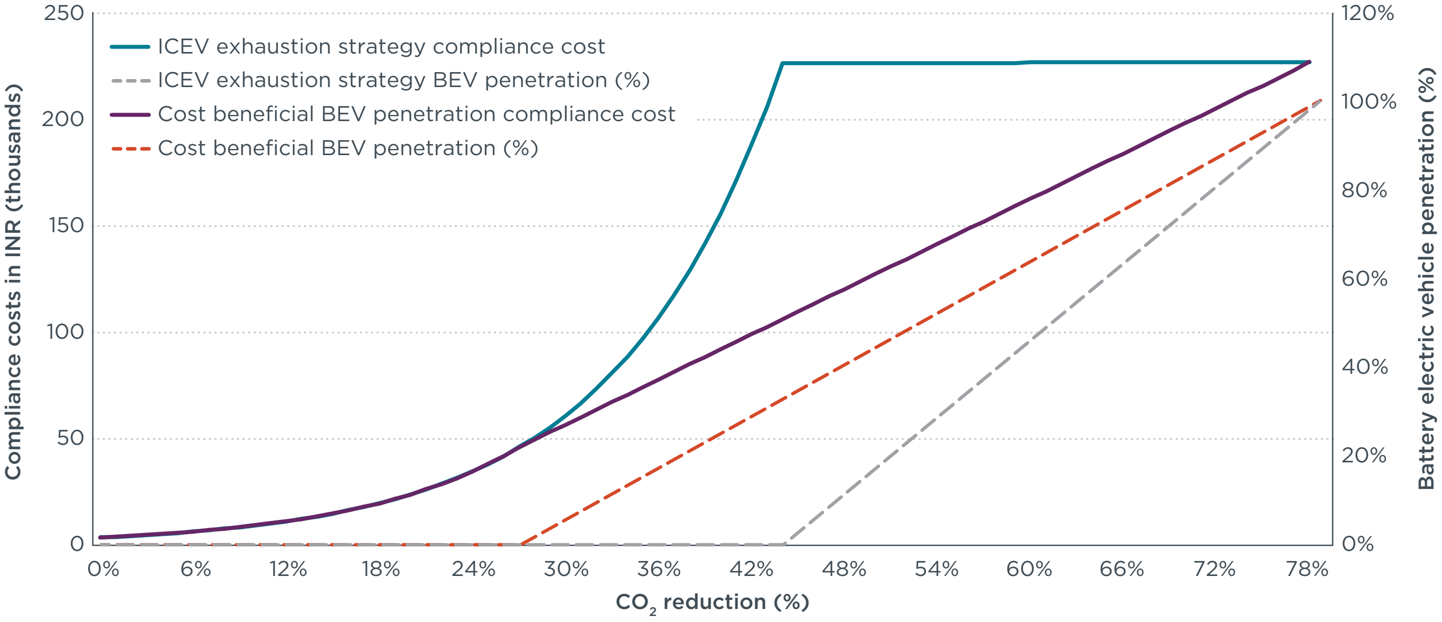

Figure B6. Compliance cost curves for gasoline midsize SUVs in 2030.

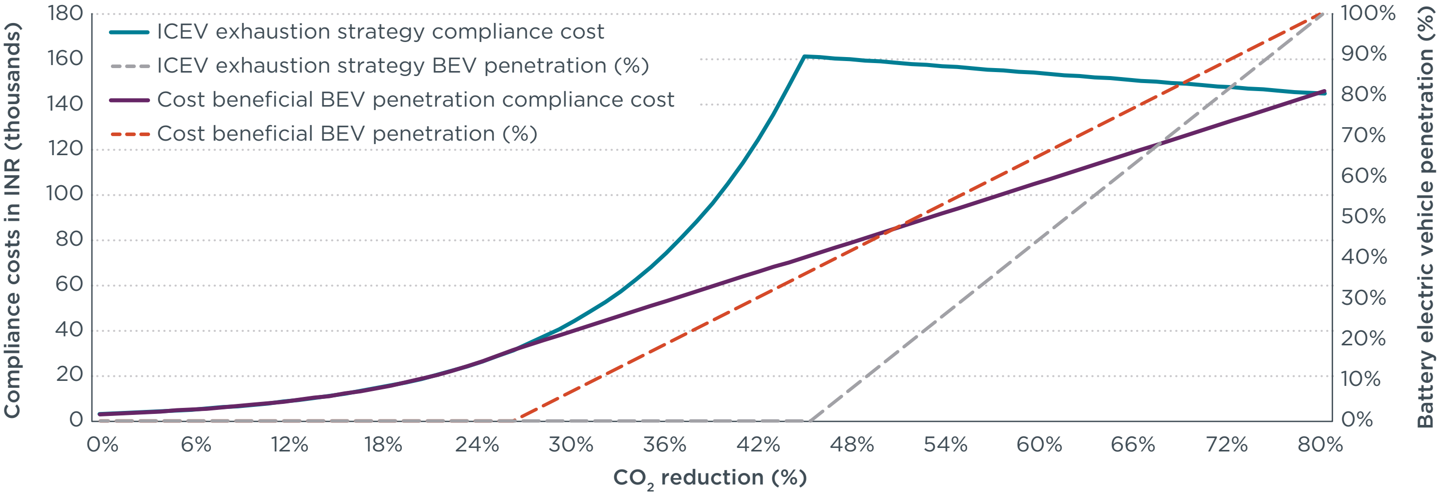

Figure B7. Compliance cost curves for gasoline entry MPVs in 2030.

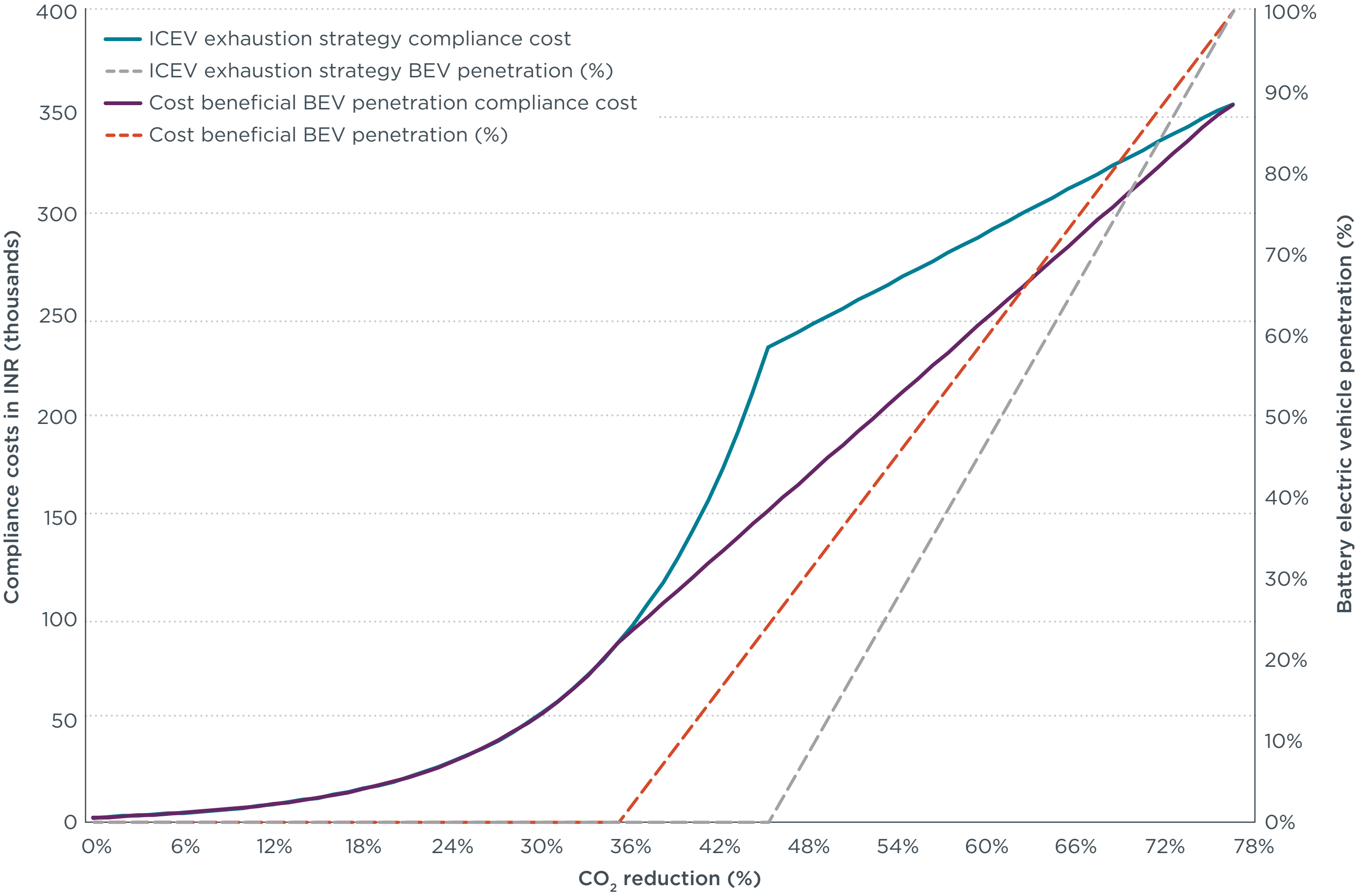

Figure B8. Compliance cost curves for gasoline midsize MPVs in 2030.

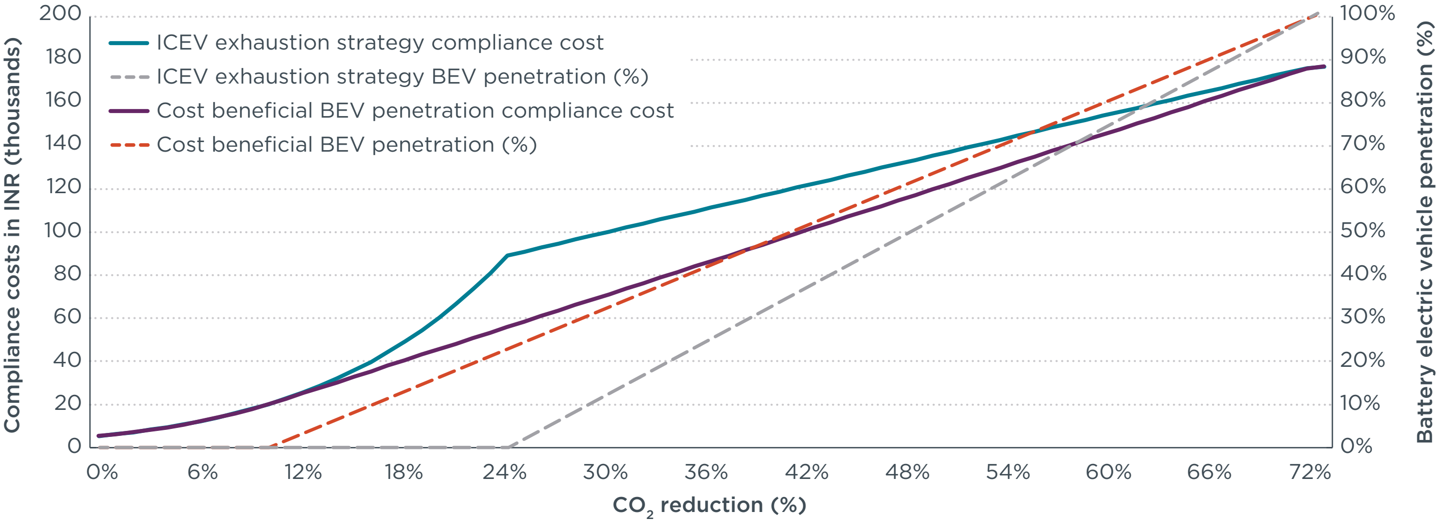

Figure B9. Compliance cost curves for diesel B class passenger cars in 2030.

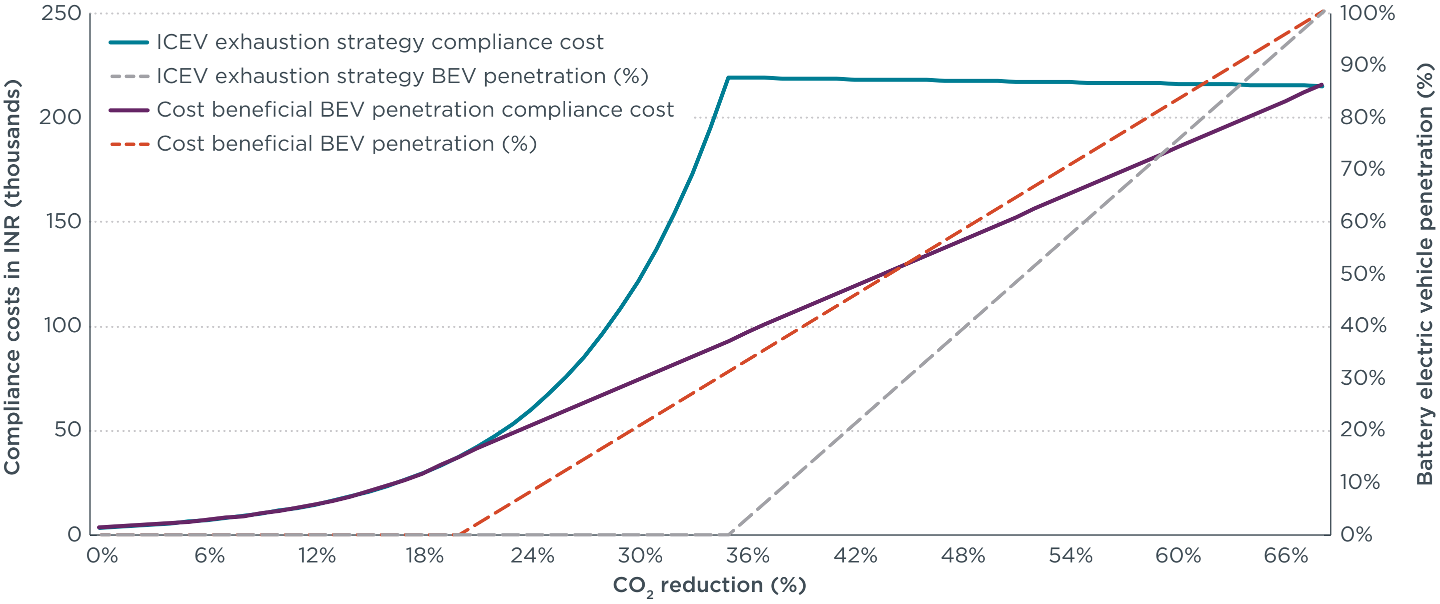

Figure B10. Compliance cost curves for diesel C class passenger cars in 2030.

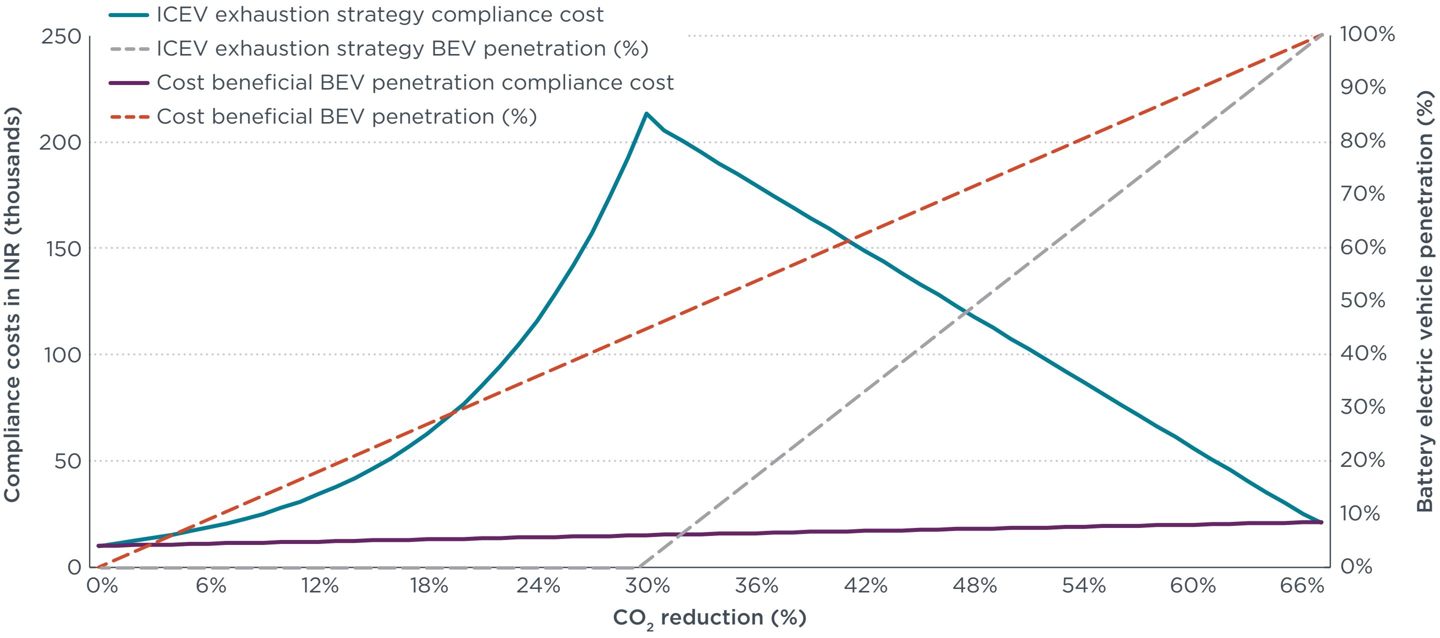

Figure B11. Compliance cost curves for diesel D class passenger cars in 2030.

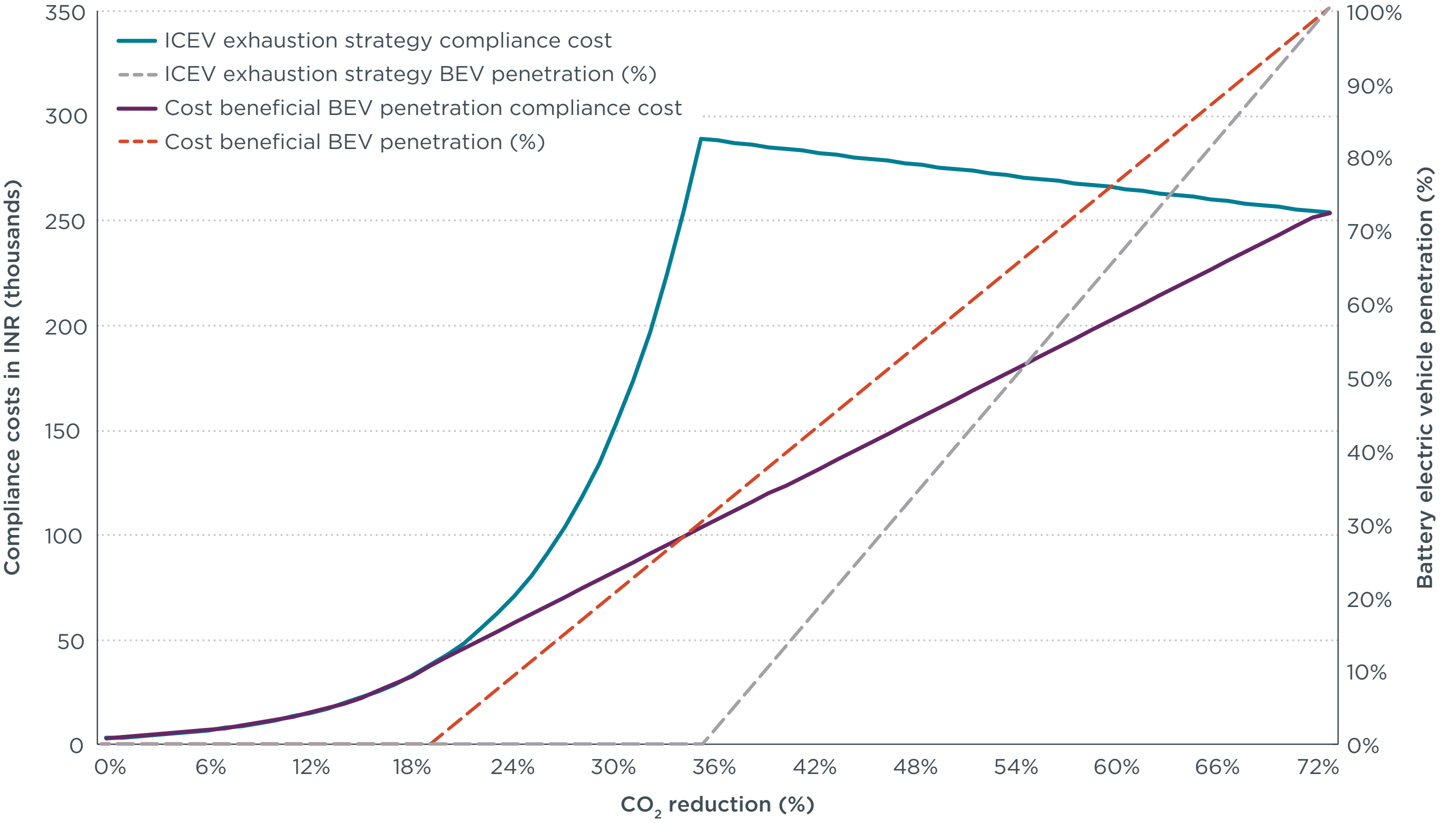

Figure B12. Compliance cost curves for diesel compact SUVs in 2030.

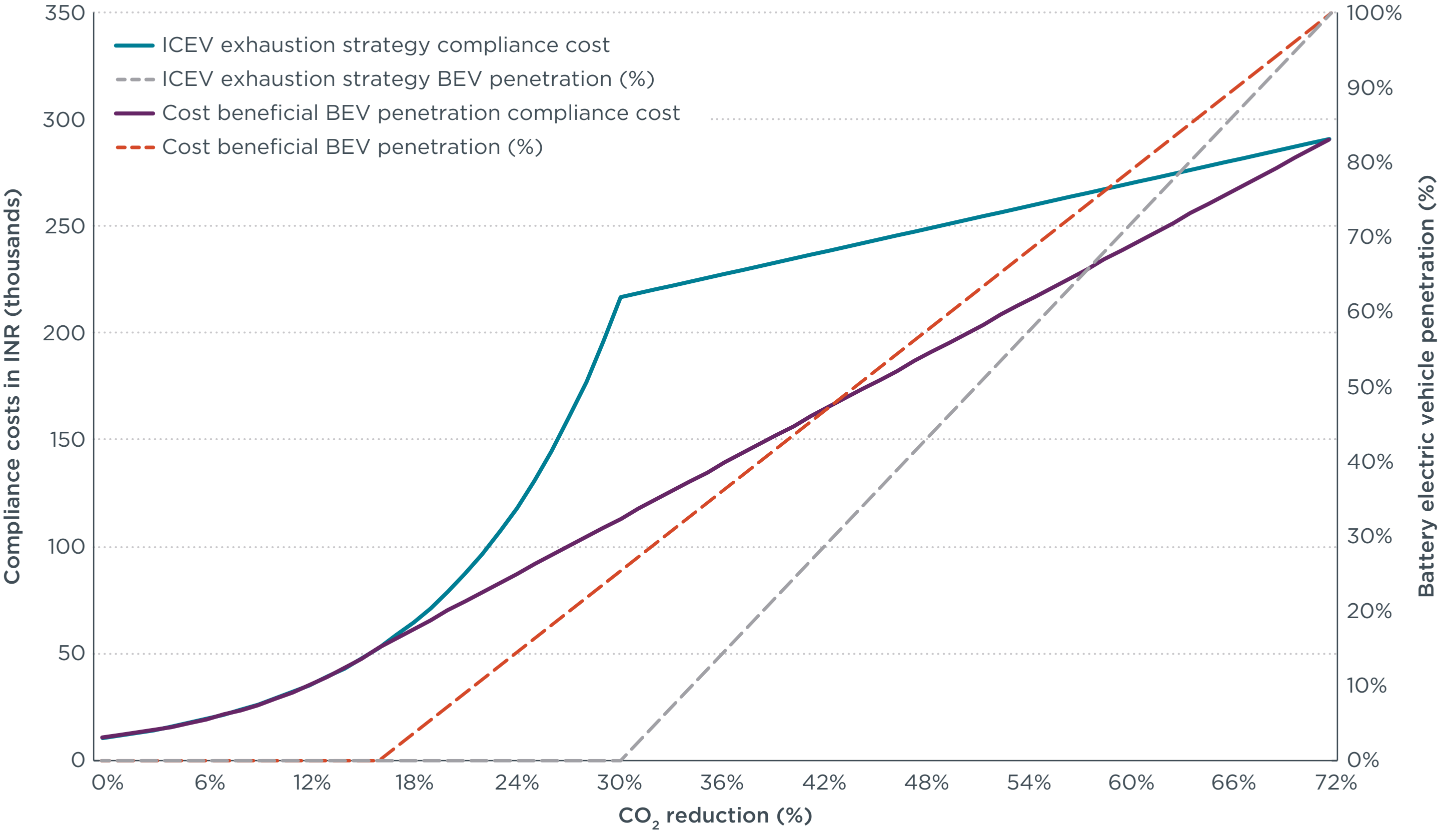

Figure B13. Compliance cost curves for diesel midsize SUVs in 2030.

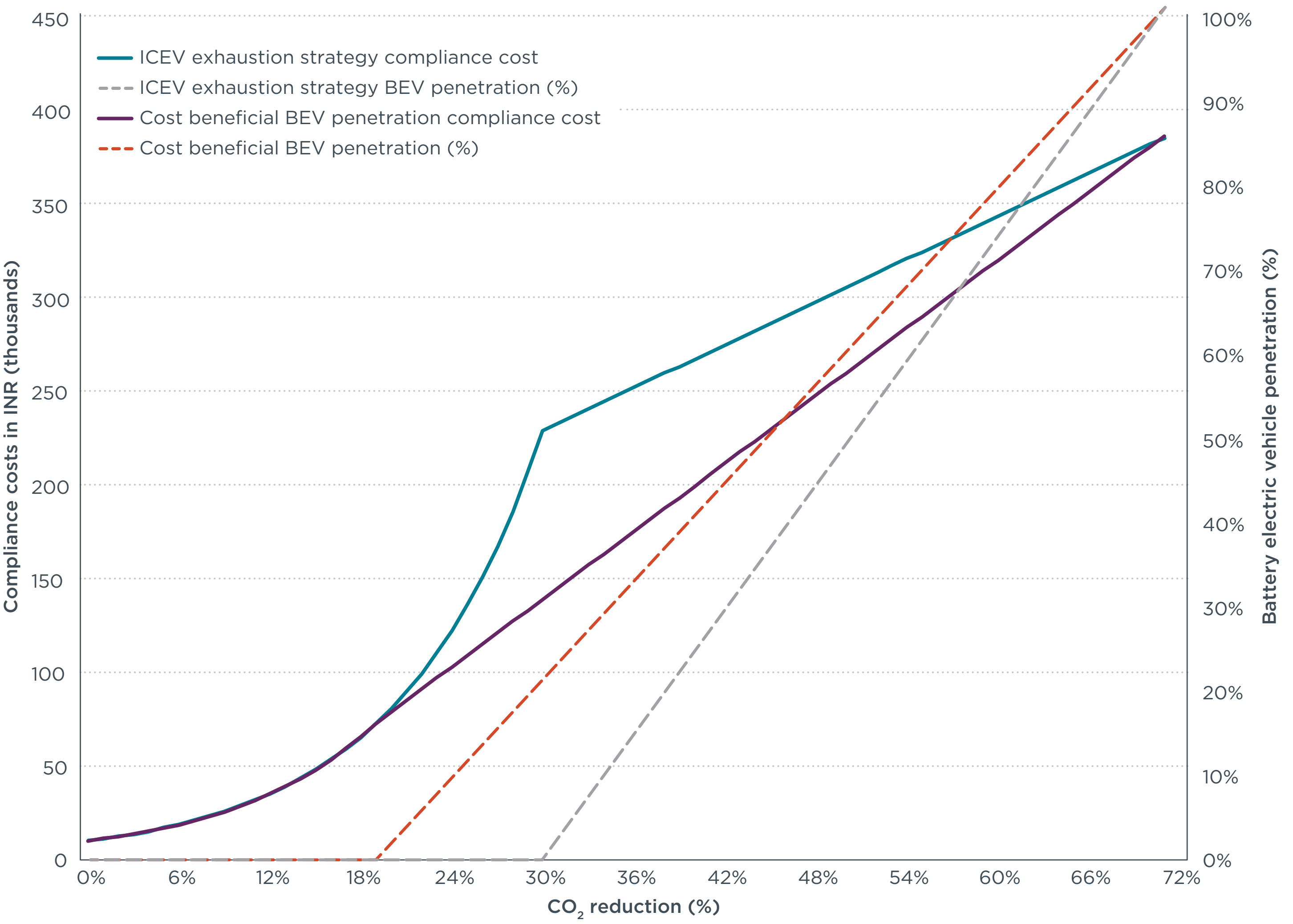

Figure B14. Compliance cost curves for diesel midsize MPV in 2030.