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TECHNOLOGY ROADMAP AND COSTS FOR FUEL EFFICIENCY INCREASE AND CO_2 REDUCTION FROM CHINESE NEW PASSENGER CARS IN 2030

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ABBREVIATIONS

AER	All-electric range
AT	Automatic transmission
BEV	Battery electric vehicles
CNY	Chinese yuan
CO_2	Carbon dioxide
DCT	Dual-clutch transmission
DMC	Direct manufacturing cost
DVVL	Dual variable valve lift
DVVT	Dual variable valve timing
EGR	Exhaust gas recirculation
EPA	Environmental Protection Agency
EV	Electric vehicle
FC	Fuel consumption
g	Gram
GDI	Gasoline direct injection
HEV	Hybrid electric vehicle
IC	Indirect costs
ICCT	International Council on Clean Transportation
ICE	Internal combustion engine
ICM	Indirect cost multiplier
km	Kilometer
L	Liter
LPM	Lumped Parameter Model
MPFI	Multi point fuel injection
MPV	Multipurpose vehicle
MT	Manual transmission
NEDC	New European Driving Cycle
NEV	New energy vehicle
PFI	Port fuel injection
PHEV	Plug-in hybrid electric vehicle
PV	Passenger vehicle
SUV	Sport utility vehicle
TC	Total cost
VCR	Variable compression ratio
VVT	Variable valve timing
WLTP	Worldwide Harmonized Light Vehicles Test Procedure

EXECUTIVE SUMMARY

To help secure oil independence and conserve energy, China has introduced five phases of fuel efficiency regulations for passenger vehicles (PVs). Additionally, *Made in China 2025*, released in 2015, outlined a preliminary fuel efficiency target of 3.2 liters (L) per 100 kilometers (km), equivalent to about 75 grams (g) of carbon dioxide (CO_2) per km, from average new passenger cars by 2030. No detailed regulations are included in the document. To support the development of stringent yet cost-effective fuel efficiency standards for Chinese passenger cars for the 2025–2030 time frame, this study evaluates the potential technology pathways for and incremental costs of meeting the 2030 target proposed by *Made in China 2025*.

Because the amount of CO_2 a car emits is directly related to the amount of fuel it consumes, this study also illuminates potential technological pathways to reduce CO_2 emissions from the new passenger car fleet. This will help China address its concerns about the climate impacts of the transportation sector. For this reason, the three concepts—fuel efficiency, fuel consumption (FC), and CO_2 emissions—are often used interchangeably. Fundamentally, this study evaluates the potential of a number of engine and vehicle technology packages to improve fuel efficiency and reduce CO_2 emissions, and assesses their cost. By combining these elements, we derive cost curves for the entire Chinese passenger car fleet and its major market segments. The study also highlights the impact of various electrification scenarios on the overall fleet fuel efficiency, with regard to CO_2 emissions, and cost.

The cost curves help answer two key questions for future policymaking:

1. How much would it cost for industry to comply with a set of more stringent CO_2 standards?
2. Would an accelerated electrification timeline ease the compliance burden for auto manufacturers?

This study uses methods developed in previous ICCT studies focused on the European Union to derive China-specific cost curves. Generally, technologies needed to meet EU 2025–2030 passenger car standards can also be used to meet equally stringent vehicle efficiency standards in other regions. It is possible to derive reasonable technology impact and cost estimates for one area from associated studies and methodologies performed in another, as long as certain adjustments are made for local applicability.

The teardown cost estimate approach adopted by this study is very similar to the approach employed by automotive manufacturers, and it results in objective, consistent, transparent, and reproducible impact estimates. In developing cost curves, we used fuel efficiency impact data developed in the European Union, with appropriate adjustment for China, in conjunction with cost data developed specifically for China and comparable cost data for the European Union. This is detailed in Figure ES1.

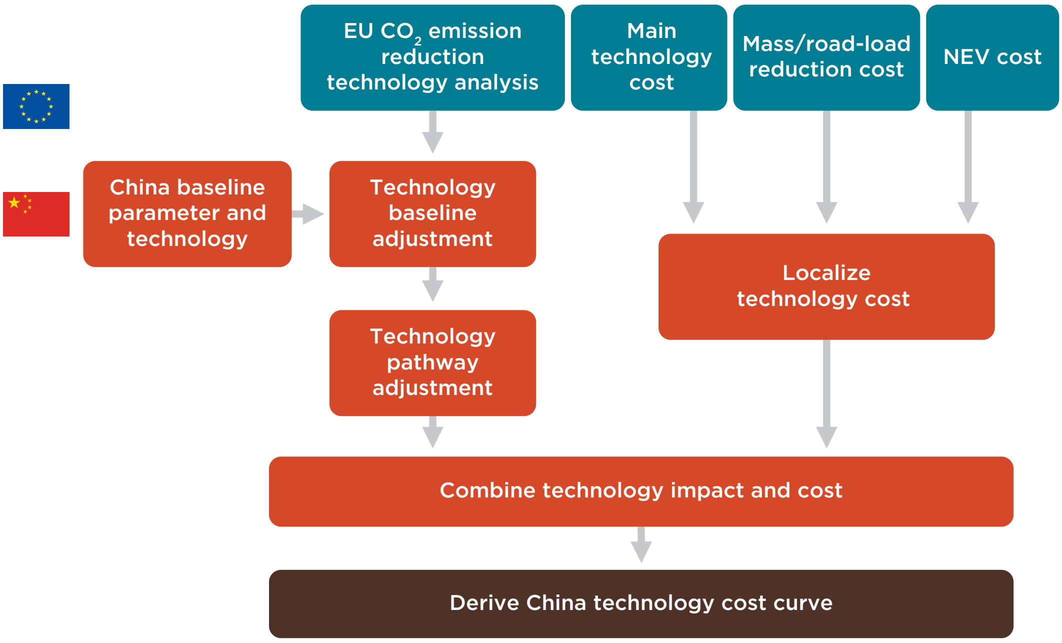

Figure ES1. Overview of China technology cost curve methodology.

The analyses developed for the European Union were adjusted or expanded to reflect conditions in China by adapting or developing data to vehicle classes that are unique to China, adjusting data to reflect differing baseline vehicle characteristics, augmenting data to include additional technologies more suitable for China, adapting cost estimates to reflect these various changes, and more. This adaptation of baseline and technology package impacts and costs applied for both internal combustion engine (ICE) vehicles and electric vehicles, i.e., battery electric vehicles and plug-in hybrid electric vehicles. Fuel cell electric vehicles are not analyzed in this paper.

The resulting incremental compliance cost estimation consists of two compliance strategies—one reflecting the level of CO_2 reduction that can be achieved through the introduction of more effective ICE technology, and the other reflecting the CO_2 reduction that can be achieved by combining ICE technology improvement with increased market penetration of electric vehicles. By incremental cost, we mean the relative cost increase—or decrease—to the 2017 vehicle production cost. The resulting cost curves for the two strategies are illustrated in the following two figures.

Figure ES2 presents passenger vehicle fleet average cost curves under the ICE strategy for fuel consumption targets measured over the New European Driving Cycle (NEDC) in 2030. Given the current state of ICE technology, we estimate that a passenger vehicle fuel consumption standard of 3.2 L/100km can be attained by 2030 for around ¥4,900 in direct manufacturing cost (DMC) or ¥6,700 in total cost (TC), which includes DMC and markups per vehicle compared with the 2017 baseline; again, this is without deploying electrification technologies. Passenger vehicle fleet average fuel consumption as low as 2.5 L/100km can be achieved without electric vehicle penetration at an incremental compliance cost of around ¥11,100 DMC or ¥15,600 TC.

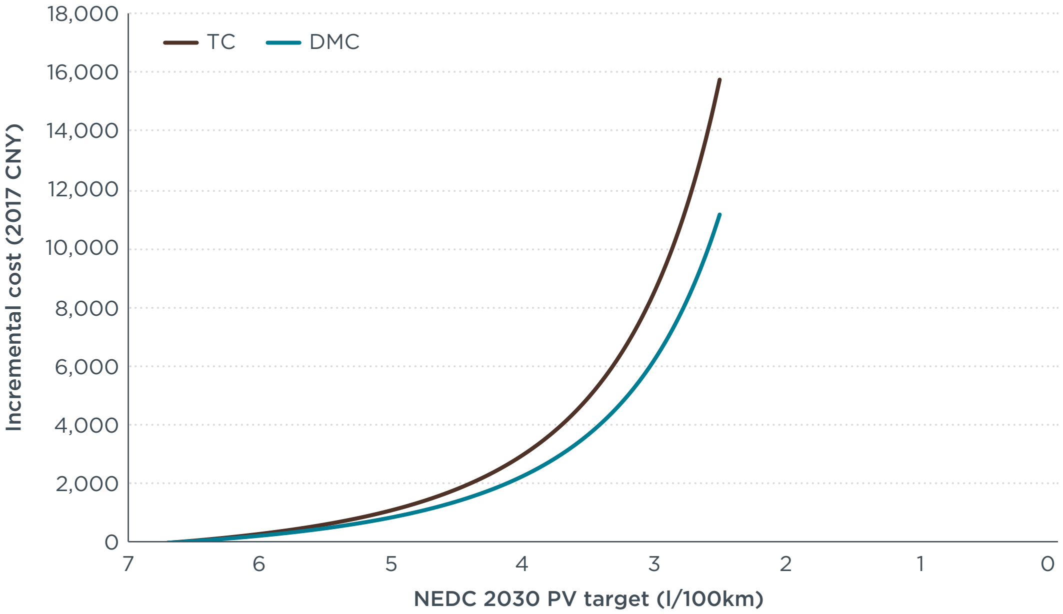

Figure ES2. 2030 NEDC fuel consumption incremental compliance costs for passenger vehicles under ICE strategy.

Figure ES3 compares the compliance cost to meet the 3.2 L/100km target in 2030 through ICE technology only with a strategy that combines ICE technology with electric vehicle uptake. Because the incremental cost of most electric vehicles will be cheaper than alternative ICE vehicles by 2030, increasing electric vehicle share in the passenger car fleet will be a more cost-effective pathway to comply with fuel consumption standards. Under the electric vehicle strategy, any increase of electric vehicle uptake in the fleet will reduce the fleet average incremental cost to comply with the fuel consumption standards in 2030. To meet the 3.2 L/100km target, the total incremental cost of compliance is ¥1,100 per vehicle with a fleet average electric vehicle penetration of 20%. The incremental compliance cost will turn into a cost saving of ¥5,000 compared with the 2017 vehicle production cost when the 3.2 L/100km target is met by a fleet average electric vehicle penetration of 40%.

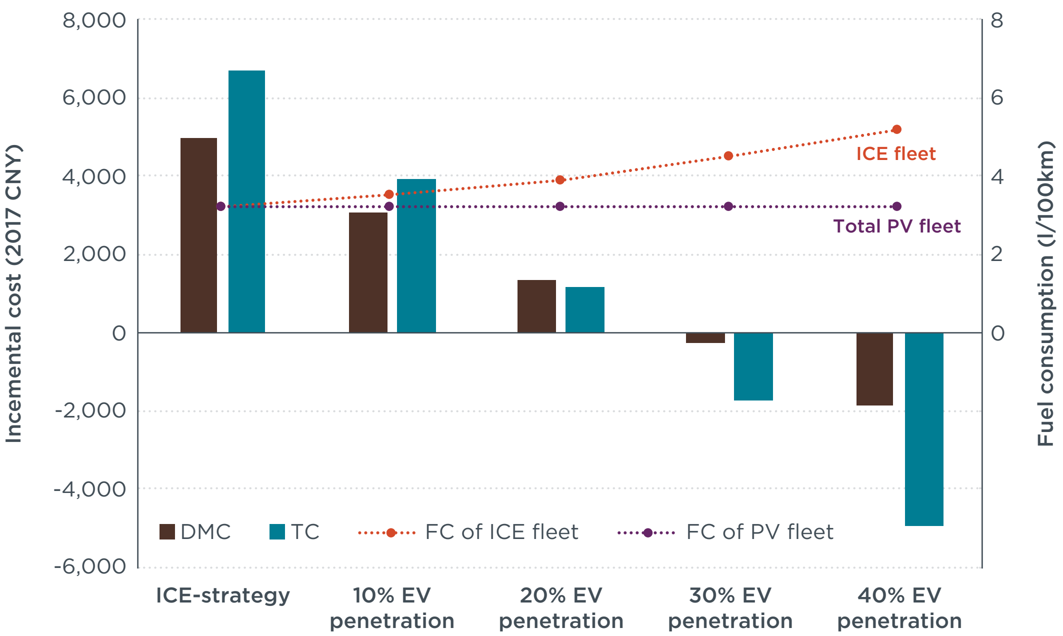

Figure ES3. Comparison of incremental compliance cost for the 3.2 L/100km target in 2030 between the ICE strategy and a strategy combining ICE technology with electric vehicle uptake.

The developed incremental compliance costs are technology neutral and do not consider the impacts associated with any potential regulations or incentives that might discount the cost of any ICE or electric vehicle technology. Additionally, the compliance costs presented apply only to the average vehicle market. Costs for individual manufacturers will be different, and different manufacturers will apply different mixes of technology. Because Chinese manufacturers are likely to choose a combination of ICE and electric vehicle strategy before electric vehicles reach cost parity, the actual compliance cost will likely fall between the compliance cost under the two scenarios.

Although the cost curves are based on extensive vehicle simulation modeling and detailed bottom-up cost assessments, the limitations to this approach include that the cost estimation is conservative. Conventional vehicle technology is frozen based upon 2015 information and does not include any technology improvements or cost reductions beyond basic learning on the older technology. Additionally, the analysis assumed that market shares of fuels and vehicle segments will not change in the future, and all fuel-saving technologies are evaluated on a constant performance basis. The costs for reduced performance vehicles would be lower than depicted in the cost curves presented here.

Nonetheless, our study shows that increasing electric vehicle penetration will likely 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 inadequacy of charging infrastructure that can hinder a quick transition into electrification. These factors are all hidden costs of electric vehicle technology that are not evaluated in this study. Government and industry will need to take collective action to help remove these barriers for electric vehicles to truly reach a cost parity with conventional ICE vehicles. In the meantime, before electric vehicles become fully mainstream, there are still many cost-effective ICE technologies that can reduce CO_2 emissions and fuel use.

1. INTRODUCTION

To help secure oil independence and conserve energy, China has introduced phase 5 of its passenger car fuel consumption standards, which requires a fleet average fuel consumption of 4 liters per 100 kilometers (L/100km) by 2025. Additionally, following the lead of the European Union and Japan, which have rolled out longer-term efficiency or efficiency-equivalent carbon dioxide (CO_2) performance targets for the 2025–2030 time frame, *Made in China 2025* (MIIT, 2015) and Technology Roadmap for Energy Saving and New Energy Vehicles (SAE-China, 2016) proposes a preliminary target of 3.2 L/100km, equivalent to about 75 grams (g) of CO_2 per kilometer, in 2030. Meeting this proposed target would require an ambitious annual reduction rate of 4.4% from 2025 to 2030, for which scant details are provided. Meanwhile, China has also set an aggressive new energy vehicle (NEV) development goal of 40%–50% of new vehicle sales by 2030, up from 15%–20% by 2025. The uptake of NEVs will, to some extent, support manufacturers in achieving their fuel efficiency targets.

Although China has been widely praised for the stringency of its 2030 proposal and electric vehicle (EV) target, the technology and associated costs required to achieve these goals have not generally been studied in detail. This paper presents the results of a study designed to estimate such impacts. To evaluate potential technology pathways and the incremental costs associated with compliance with proposed 2030 passenger car standards in China, this study translates the International Council on Clean Transportation (ICCT) approach to estimating the technology impact and costs of the European Union's 2025–2030 CO_2 emission standards to the Chinese vehicle fleet. By doing so, we intend to support the development of stringent yet cost-effective vehicle efficiency standards for Chinese passenger cars for the 2025–2030 time frame.

The amount of CO_2 a car emits is directly related to the amount of fuel it consumes, and thus this study also illuminates a potential technological pathway to reduce CO_2 emissions from the new passenger car fleet. This can also help China address its growing concerns about the climate impact of its transportation sector. For this reason, the three concepts—fuel efficiency, fuel consumption, and CO_2 emissions—are often used interchangeably in this paper.

This study evaluates the potential of a number of engine and vehicle technology packages to improve fuel efficiency and reduce CO_2 emissions, and assesses their cost of compliance. By combining these elements, we derive cost curves for the entire Chinese passenger car fleet and its major market segments. The study also highlights the impact of various electrification scenarios on the overall fleet fuel efficiency, as reflected in CO_2 emissions, and cost. These cost curves help answer two key questions for future policy:

1. How much would it cost for industry to comply with a more stringent set of CO_2 standards?
2. Would an accelerated electrification timeline ease the compliance burden for auto manufacturers?

Section 2 of this report describes the general research methods employed. Section 3 specifies the data used for technology impact and cost estimates, and cost curve development. Sections 4 to 6 discuss specific adjustments implemented to ensure that the data are fully consistent with Chinese fleet characteristics. Section 7 summarizes the methods used to generate electric vehicle CO_2 impacts and costs. Section 8 presents the developed cost curves, and Section 9 presents conclusions.

2. GENERAL METHODOLOGY

Determining the cost effectiveness of a given fuel economy standard requires in-depth knowledge of vehicle technology fuel efficiency impacts and costs. Traditionally, surveys of vehicle manufacturers and parts suppliers were conducted to evaluate the fuel saving potential and cost of future technology advancements. Such an approach is useful in collecting basic information and understanding general trends across manufacturers, but it is not systematic, consistent, or transparent enough to reliably evaluate technology impacts and costs. Indeed, the costs developed through this approach have historically been significantly overestimated.

ICCT, when supporting the development of EU 2025–2030 CO_2 emission standards, adopted the approach to technology impact and cost estimation that was used by the U.S. Environmental Protection Agency (EPA) in developing U.S. 2017–2025 light-duty vehicle fuel efficiency standards. In this approach, the fuel saving impacts of various vehicle technologies are estimated through detailed vehicle simulation modeling, and the associated costs are estimated through detailed teardown analysis.

Vehicle simulation modeling is the state-of-the-art approach to determining technology impacts on vehicle operation; it fully considers all of the interactions among the components, subsystems, and systems that are required to operate a vehicle over a given driving cycle. All major automotive manufacturers rely on vehicle simulation modeling during the fundamental design stages of vehicle development.

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

This study uses basic methodologies developed in past ICCT studies of the EU vehicle market (Meszler et al., 2016), hereafter referred to as the ICCT EU study, to derive China-specific fuel efficiency cost curves. The automotive market is global in nature. To minimize costs, major manufacturers typically design and deploy new technologies on a global basis. Generally, technologies needed to meet EU 2025–2030 passenger car standards can also be used to meet equally stringent vehicle efficiency standards in other regions. The general independence of fuel efficiency technology from established standards also provides the basis for applying technology impact studies performed in one area to cost effectiveness evaluations in another. Although adjustments are required to adapt to a given local fleet, it is possible to derive reasonable technology impact and cost estimates for one area from associated studies and methodologies performed in another. 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 developed specifically for China and comparable cost data for the European Union. This is illustrated in Figure 1.

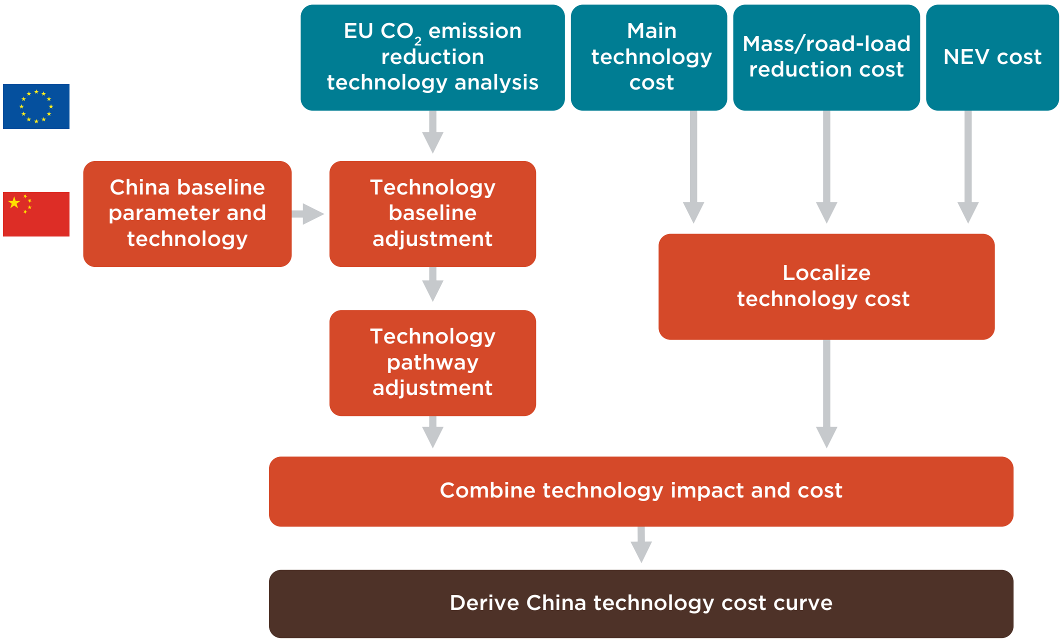

Figure 1. Overview of China technology cost curve methodology.

In the European Union, efficiency is regulated in terms of CO_2 emissions. Although developed cost curves for this study are presented in terms of fuel consumption, which is appropriate for China, many of the steps leading up to the development of the curves were performed in terms of CO_2. Thus, the discussion and graphics that follow will, at times, be based on CO_2 rather than explicit fuel consumption. Because both metrics are directly relatable, references to fuel consumption and CO_2 are used interchangeably. This does not affect the accuracy of the cost curves presented here.

3. OVERVIEW OF DATA SOURCES

The primary CO_2 emissions and associated technology cost data used in the development of the China cost curves are from simulation modeling and bottom-up cost-estimation work performed for the ICCT by FEV Inc. (FEV, 2015). These are the same data used by the ICCT EU study.

The model used for CO_2 simulation in the ICCT EU study is the GT-Suite Simulation Model developed by FEV. GT-Suite is a commercial simulation software for engine and vehicle simulation. The FEV model consists of all relevant sub models for the simulation of vehicle, engine, vehicle control, internal combustion engine (ICE) thermal model, driver, transmission, auxiliaries, shift strategy, and raw and tailpipe emissions. In the detailed model, all relevant engine control unit functions are included, for example catalyst heating and fuel cutoff during coasting. The model has various detailed sub-model levels, a base level, and one or two advanced levels. The degree of detail increases in the advanced levels to consider more realistic effects. For example, the auxiliary power consumption of the board net is only a simple constant power consumption in the base level. Thus a more advanced level for simulation of intelligent alternator management, including a 12-volt battery model and alternator model, was used. Figure 2 illustrates the structure of the model.

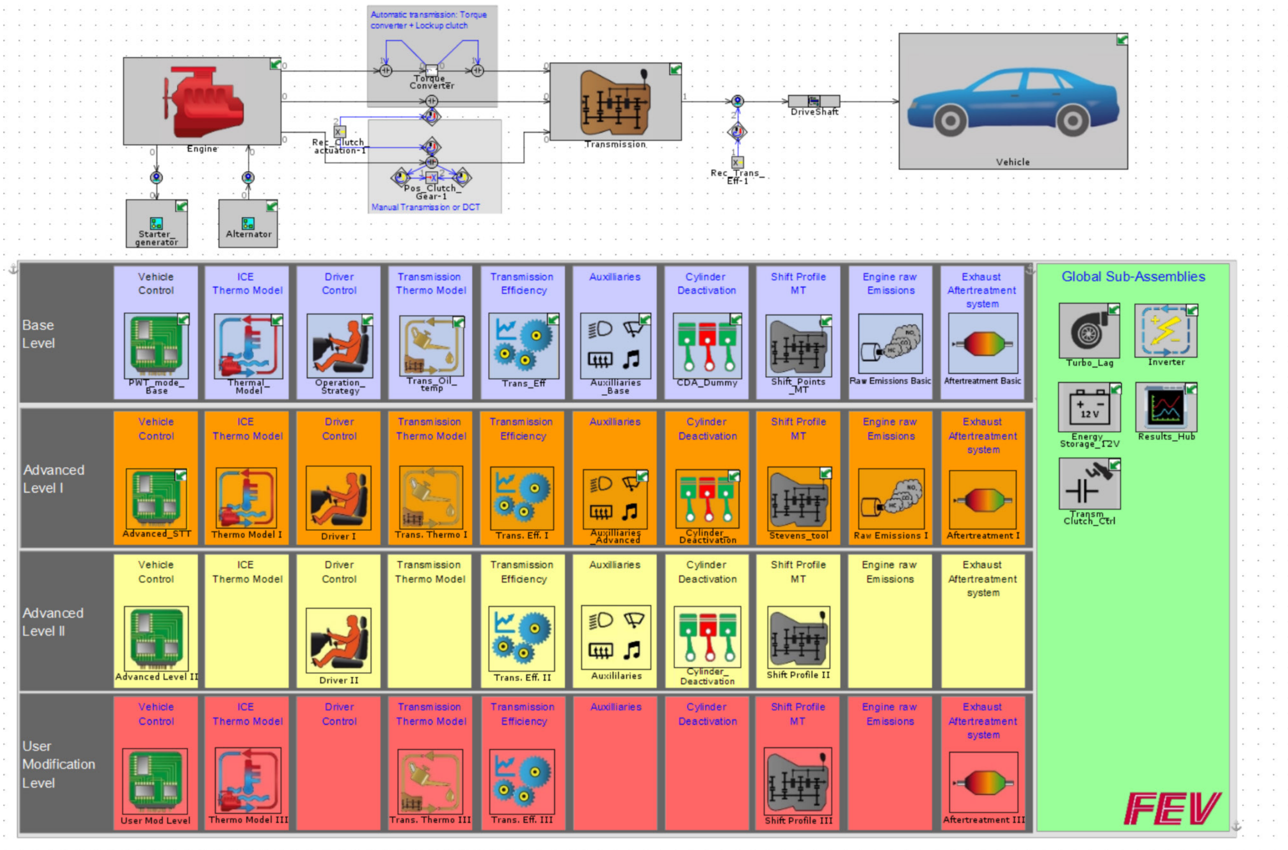

Figure 2. FEV GT-Suite Simulation Model (FEV, 2015).

The technology cost assessment mainly refers to the FEV teardown analysis. But several limitations of the FEV cost data necessitate the use of supplemental data sources for some technologies and supplemental processing for cost curve development. Besides the data sources used by the ICCT EU study, additional data sources are used to accurately reflect vehicle characteristics and market conditions in China. Table 1 summarizes the sources employed. Further details are described in the following sections.

Table 1. Data sources employed in the development of cost curves for the Chinese vehicle market

	Technology fuel consumption impacts	Technology cost
Primary data source	FEV, 2015	FEV, 2015[a] U.S. EPA, 2012 (learning and indirect cost factors)
Road-load parameter[b]	FEV, 2015	FEV, 2013a (mass reduction) U.S. EPA, 2012 (rolling resistance and aerodynamics drag)
New energy vehicle technology	FEV, 2015 SAE-China, 2016	Lutsey and Nicholas, 2019[c] SAE China, 2016
Off-cycle credit	Ricardo, 2015	Ricardo, 2015
Others	EPA Lumped Parameter Model (LPM) v2.12) (U.S. EPA, 2015)	

[a] Estimate cost as high-volume production direct manufacturing costs in 2014.
[b] E.g. mass, rolling resistance, aerodynamic drag
[c] The methodology and associated relations are documented as part of a series of papers previously produced by the ICCT for an earlier analysis on the cost of penitential 2020–2025 EU CO2 standards.

Vehicle fleets in different markets differ in key physical characteristics and baseline technology levels. Therefore, analysis developed specifically for the European Union may need to be adjusted or expanded to accurately reflect conditions in China. Such adjustments can include adapting or developing data to vehicle classes that are unique to China, adjusting data to reflect differing baseline vehicle characteristics, augmenting data to include additional technologies more suitable for China, adapting cost estimates to reflect these various changes, and more. Analyzing new vehicle classes, new technology packages, or driving cycles may require additional simulation modeling work. Meanwhile, other adjustments can be conducted using existing modeling data in conjunction with complementary analytical techniques. Such adaptation is generally possible given the relatively high degree of similarity in physical vehicle characteristics between the EU and Chinese gasoline passenger car markets. Sections 4 to 6 specify how we adapted technology impacts and costs for internal combustion engine vehicles and Section 7 specifies the methodology used for electric vehicles.

4. CHINA BASELINE ADAPTATION TO FEV STUDY

4.1. CHINA BASELINE SPECIFICATIONS

This study uses China's 2017 vehicle fleet as the baseline for developing the cost curves. To reflect the differences between the baseline fleets of China and the European Union, we mapped China baseline vehicles to the EU baseline vehicles in the FEV study and made adjustments to the baseline estimation.

Table 2 provides an overview of the baseline vehicle characteristics for China's 2017 fleet. The baseline vehicles were selected to reasonably reflect the average China market of that era. For each vehicle class, the technologies reflect the mainstream technology of the fleet. The penetration of some advanced technologies that have increasing market share today but had not become mainstream technologies in 2017 are taken into consideration in the following evaluation process in Section 5. Additionally, because we do not have sufficient valve technology information for the 2017 fleet, we used the mainstream valve technology of the 2014 fleet as the representative technology for the baseline fleet. We expect some changes to the mainstream valve technology of some vehicle classes in the actual 2017 fleet, but the changes will not be significant. This assumption results in a slightly overestimated cost. This study categorizes Chinese vehicles into eight classes as derived by the ICCT (Zhou & Yang, 2018). E+ class combines E class (upper medium), F class (large), and luxury/sport class, because of their low level of representation in Chinese fleet. All relevant characteristics of the E+ class are the sales-weighted average of these three classes.

Table 2. 2017 China vehicle class characteristics

Vehicle class[a]	A	B	C	D	E+	SUV	MPV	Minivan
Market share	1%	4%	30%	14%	1%	37%	10%	3%
Mapped FEV EU vehicle class	B	B	C	D	E	D	C	B
Displacement (liters)	1.2	1.5	1.5	1.6	2.1	1.7	1.6	1.3
Engine configuration	I4	I4	I4	I4	I4	I4	I4	I4
Injection system[b]	MPFI	MPFI	MPFI	MPFI	GDI	MPFI	MPFI	MPFI
Turbocharged	No	No	No	No	Yes	Yes	No	No
Rated engine output (kW)	63	80	88	106	169	122	98	70
Valve technology	No	No	VVT	VVT	DVVT	VVT	VVT	No
Transmission	M5	M5	M5	A6	A8	M6	M5	M5
Mass in running order (kg)	1051	1231	1346	1475	1839	1660	1592	1253
Idle-off technology	No	No	No	Yes	Yes	No	No	No
CO_2 emission (g/km)[c]	**122.7**	**133.0**	**140.7**	**146.3**	**169.4**	**171.8**	**172.2**	**151.4**

Notes: Vehicle classes from Zhou & Yang (2018). Additional information provided by China Automotive Technology and Research Center (CATARC).
[a]For the description of each vehicle class, see Appendix C. [b]Gasoline direct injection (GDI); multi point fuel injection (MPFI); variable valve timing (VVT); dual variable valve timing (DVVT). [c]CO_2 emissions are average CO_2 values from vehicle registration data for each class.

The FEV study is based on 2014 EU vehicle characteristics of 10 vehicle classes, including four gasoline vehicle classes and six diesel vehicle classes. Because diesel vehicle penetration is negligible in China, only the gasoline vehicle characteristics associated with the 2015 FEV modeling are used, and those are class B, C, D, and E. Among eight classes in China, A class, SUV, MPV, and minivan were not modeled for gasoline vehicles by the FEV study, and are therefore new segments added here. Each of the indicated classes in China is mapped onto one of the FEV classes based on similarity of class specifications (see Table 3).

Table 3. Eight vehicle classes for China cost curve analysis and counterpart EU class in 2015 FEV analysis

China	A (Mini)	B (Small)	C (LM)	D (Medium)	E+ (UM+)	SUV	MPV	Minivan
EU	B	B	C	D	E	C	D	B

Table 4 compares the China 2017 baseline vehicle characteristics with the 2014 EU baseline for FEV simulation. It is noticeable that the China 2017 fleet differs from the EU 2014 fleet in average displacement, engine power, weight, and in the adoption of key efficiency technologies. Therefore, a series of adjustments were implemented to the 2014 EU baseline for each class to apply the FEV methodology to the China fleet. These adjustments are specified in the following sections.

Table 4. Comparison of China 2017 baseline specifications with 2014 EU baseline[a]

Vehicle class	China	A	B	C	D	E+	SUV	MPV	Minivan
	EU[a]	B	B	C	D	E	D	C	B
Market share		1%	4%	30%	14%	1%	37%	10%	3%
Displacement (liters)	China	1.2	1.5	1.5	1.6	2.1	1.7	1.6	1.3
	EU	1.3	1.3	1.8	2.4	3.0	2.4	1.8	1.3
Engine configuration	China	I4	I4	I4	I4	I4	I4	I4	I4
	EU	I4	I4	I4	V6	V6	V6	I4	I4
Injection system	China	MPFI	MPFI	MPFI	MPFI	GDI	MPFI	MPFI	MPFI
	EU	MPFI	MPFI	MPFI	MPFI	MPFI	MPFI	MPFI	MPFI
Turbocharged	China	No	No	No	No	Yes	Yes	No	No
	EU	No	No	No	No	No	No	No	No
Rated engine output (kW)	China	63	80	88	106	169	122	98	70
	EU	65	65	95	135	180	135	95	65
Valve technology	China	No	No	VVT	VVT	DVVT	VVT	VVT	No
	EU	DVVT	DVVT	DVVT	DVVT	DVVT	DVVT	DVVT	DVVT
Transmission	China	M5	M5	M5	A6	A8	M6	M5	M5
	EU	M5	M5	M5	A8	A8	A8	M5	M5
Mass in running order (kg)	China	1,051	1,231	1,346	1,475	1,839	1,660	1,592	1,253
	EU	1,150	1,150	1,345	1,578	1,800	1,578	1,345	1,150
Idle-off technology	China	No	No	No	No	Yes	No	No	No
	EU	No	No	No	No	No	No	No	No
CO_2 emission (g/km)	China	122.7	133.0	140.7	146.3	169.4	171.8	172.2	151.4
	EU	138.8	138.8	170.2	183.0	213.6	183.0	170.2	138.8

[a] Mapped FEV EU vehicle class

It is expected that the market is dynamic, and the market share of each vehicle class will change over time. In this analysis, although the class-specific cost curves are independent of market share, the fleetwide cost curve will be impacted by the market share of each class. Based on communication with several experts in the field, especially with regard to the expected market share of SUVs, we expect that although the market share of SUVs may change in future years, the changes are unlikely to be as significant as the trend has been in the past few years. Because of the challenge inherent in predicting minor changes in market share, and to avoid introducing higher uncertainties in the fleetwide estimation, this analysis assumes that the market shares of fuels and vehicle segments will remain the same.

4.2. BASELINE CO_2 EMISSIONS

The CO_2 emissions of the FEV study baseline are modeled using the simulation tool developed by FEV based on vehicle specifications in the European Union. The type-approval CO_2 values of EU models were used to validate the simulation model performance. Different from the EU approach, the CO_2 emissions for the 2017 Chinese fleet are fleet sales-weighted average type-approval CO_2 emissions.

The comparison in Table 4 shows different CO_2 emission levels between the China and EU fleets, and there are larger differences for some classes. The reasons for the difference mainly come from three aspects. First, the application of a key efficiency technology reduces CO_2 emissions only if other elements are consistent. For example, for B class, the EU vehicles mostly adopt dual variable valve timing (DVVT), whereas the China vehicles do not adopt an advanced valvetrain system. Additionally, for the E+ class, the China vehicles mostly adopt turbocharger and direct gasoline injection, whereas the EU vehicles do not.

Second, the specifications of the fleet, such as engine size, power, and weight, influence CO_2 emissions when adopting the same technology package. For example, compared with the C class in China, the EU fleet has a larger average engine size, 1.8 L compared with 1.5 L, and is more powerful, 95 kW compared with 88 kW. Those differences will increase CO_2 emissions of the EU C class if other elements are the same between the two baseline fleets.

Third, the rolling resistance and aerodynamic drag of vehicles affect CO_2 emissions. Even though the rolling resistance coefficient and aerodynamic drag coefficient are not listed and compared in Table 4, their difference, if any, and corresponding impact on CO_2 emissions are reflected in the CO_2 values of the China and EU baseline fleets.

Because the differences in baseline CO_2 emissions are either reflected by the technologies and specifications differences listed in Table 4, or covered by the type-approval process of CO_2 emissions, this study uses type-approval CO_2 values for the China 2017 baseline.

4.3. BASELINE TECHNOLOGY COST

FEV's (2015) teardown approach considers four major components that determine direct manufacturing cost (DMC)—material, labor, manufacturing overhead, and supplier markup. ICCT evaluated the necessity of adapting these costs to Chinese context by updating the database on these components. In 2014, ICCT, FEV, and the China Automotive Technology and Research Center jointly conducted a survey that developed localized costs for the four components (CATARC, 2014; He, 2013). By comparing the results with EU DMC for each of the advanced technologies, we found, generally, that the material cost and markup of suppliers in China is higher than in the European Union; labor costs are lower than in the European Union; and the difference in manufacturing overhead varies according to the complexity of the technology and equipment. Taken together for an individual technology or a technology package, these cost differences may be offsetting. As a result, the China-specific DMC is adjusted slightly downward compared with the EU DMC for individual technologies or technology packages. This adjustment is made to all EU-specific DMC listed later in this report.

For the baseline technology cost, the FEV baseline cost is adjusted to reflect the China baseline fleet. Table 5 presents a summary of the DMC adjustment in 2014 Euros.[1] The adjustment methodology is further explained below.

1 The final cost curve will be presented in 2017 RMB values.

- The adjusted cost of the engine takes into account the difference in the number of engine configurations, the injection system, and the adoption of a turbocharger, and it is adjusted based on engine power. The FEV study includes all gasoline aftertreatment impacts and turbocharger changes due to downsizing as part of engine costs. Thus, both are accounted for in the adjustment linked to engine configuration and power. Comparing the China baseline with the FEV baseline, the I4 engine configuration of D, E+, and SUV classes is less advanced than the V6 configuration in their counterpart FEV classes. The injection system and idle-off technology of E+ class and turbocharging of E+ and SUV classes in China are more advanced than their FEV counterparts. Except for B class vehicles, the engine power of China vehicle classes is lower than their FEV counterparts. In total, only B class has an increased baseline engine cost compared with the FEV baseline. All other classes have their baseline engine cost adjusted downward.

- The adjusted cost of transmissions takes into account the transmission technology difference between the China 2017 baseline and the FEV baseline. Because the 2015 FEV study does not include the incremental cost of A8 over A6 transmission, additional research was conducted. This analysis used the average A8 over A6 incremental cost from a variety of studies conducted by the U.S. EPA and FEV (2011; 2013b).[2] The value appears very consistent with the incremental cost of other transmission technologies in the FEV study.

Table 5. Baseline direct manufacturing cost adjustments (2014 €) (**orange** highlights China baseline specifications that are different from FEV baseline)

Vehicle class		China	A	B	C	D	E+	SUV	MPV	Minivan
		FEV	**B**	**B**	**C**	**D**	**E**	**D**	**C**	**B**
Engine[a]	**Rated engine output (kW)**	China	**63**	**80**	**88**	**106**	**169**	**122**	**98**	**70**
		FEV	65	65	95	135	180	135	95	65
	Engine configuration	China	I4	I4	I4	**I4**	**I4**	**I4**	I4	I4
		FEV	I4	I4	I4	V6	V6	V6	I4	I4
	Injection system	China	MPFI	MPFI	MPFI	MPFI	**GDI**	MPFI	MPFI	MPFI
		FEV	MPFI	MPFI	MPFI	MPFI	MPFI	MPFI	MPFI	MPFI
	Turbocharged	China	No	No	No	No	**Yes**	**Yes**	No	No
		FEV	No	No	No	No	No	No	No	No
	Idle-off technology	China	No	No	No	No	Yes	No	No	No
		FEV	No	No	No	No	No	No	No	No
	Cost difference (€)		**-44**	**29**	**-33**	**-954**	**-330**	**-633**	**-11**	**18**
Transmission	**Transmission**	China	M5	M5	M5	**A6**	A8	**A6**	M5	M5
		FEV	M5	M5	M5	A8	A8	A8	M5	M5
	Cost difference (€)		**0**	**0**	**0**	**-83**	**0**	**-83**	**0**	**0**
Net China baseline adjustment (€)			-7	55	-25	-1037	-330	-716	-11	18

[a] The impact on baseline engine cost includes basic engine cost changes due to different engine configurations and power, the cost changes due to different engine sizes, and the aftertreatment and turbocharging changes due to downsizing.

The difference in other technologies between the EU 2014 and China 2017 baselines are not accounted for in baseline cost because the FEV study does not include the cost of these other technologies in the baseline cost. The cost difference resulting from any technology advancement will be captured in the advanced technology packages, as described in Section 5.3.

2 Volpe CAFE Model input data for 2018 U.S. LDV Fuel Economy Rollback Proposal; EPA OMEGA Model input data for 2016 TAR.

5. CHINA TECHNOLOGY PACKAGE ADAPTATION TO FEV STUDY

5.1. CHINA TECHNOLOGY PATHWAY DESIGN

The technologies included in this study are the same as those in the FEV evaluation, including engine downsizing; conversion from port fuel injection (PFI) to turbocharged direct injection; advanced valve control; advanced turbocharging technology; advanced exhaust gas recirculation (EGR) techniques; friction-reduction strategies; variable compression ratio (VCR) technology; advanced transmissions; various hybridization approaches, ranging from 12-volt start-stop to full parallel hybrid electric systems; and a range of road-load reductions in terms of mass, rolling resistance, and aerodynamic drag.

Table 6 through Table 13 present a summary of the evaluated technology packages and their associated CO_2 and cost impacts on different vehicle classes in China. For each vehicle class, technology package 0 reflects the 2017 technology baseline of Chinese vehicles. Because the differences in key technologies are not significant between the China baseline and the FEV baseline fleet, except for E class,[3] technology package 1 of each class in China study was matched with the 2014 EU baseline technology packages in the FEV estimates without other interim technology packages. Beginning with technology package 2 of each class, the advancement of technologies in the Chinese vehicles is synchronized with the technology advancement in the FEV estimates.

We are aware that the FEV study does not reflect some recent evaluations. For example, whereas the technology pathways chosen by the FEV study are mostly downsized turbocharging, a later study (Lutsey et al., 2017) suggests that high-compression ratio, Atkinson cycle engines, and other technologies may be more efficient than downsized turbo engines.[4] We chose turbocharging as one of the main technology pathways because this is the technology trend that we observed in China (Xiao, Yang, & Isenstadt, 2018).

With limited exceptions, CO_2 reduction technology is generally evaluated on a constant performance basis—which is to say, constant power and constant top speed—relative to the associated baseline vehicle performance.

5.2. TECHNOLOGY PACKAGE CO_2 EMISSIONS ADAPTATION

The estimation of technology package CO_2 impact emissions is based on the simulation results of FEV data. We adapt the CO_2 emissions impacts to the different technology packages in two steps.

The first step is to evaluate the CO_2 emissions reduction by matching China baseline vehicles with the next available EU technology packages for each class. That means we evaluate the CO_2 emissions reduction that comes from moving from technology package 0 to package 1. The technologies that get adjusted in the evaluation are valvetrain technology and transmission. The CO_2 impact of both technologies is determined by the EPA Lumped Parameter Model.[5]

The second step is to evaluate CO_2 emissions reduction by evolving from one technology package to the next. Because the China technology packages are

3 The baseline for E class Chinese vehicles includes start-stop technologies, which are not in the baseline for the corresponding E class in FEV. For that reason, technology package 1 of E class is matched with technology package 2, rather than baseline technology package 0, of E class in FEV.

4 For example, the Mazda gasoline compression ignition engine.

5 Based on EPA LPM for a low horsepower-to-weight vehicle, A8 reduces CO_2 emissions by 7% compared with A6; intake cam phasing reduces CO_2 emissions by 2.1% compared with fixed flow control valve; dual cam phasing reduces CO_2 emissions by 1.9% compared with intake cam phasing.

synchronized with the FEV technology packages from technology package 1 of each class onward, the CO_2 reduction rate from package to package is assumed to change according to the same ratio as their counterpart technology packages in the FEV modeling. For example, the difference in CO_2 reduction rate from technology package A1 to A2 of A class vehicles is the same as the counterpart EU CO_2 reduction rate from B0 to B1.

Although the China data presented include CO_2 impact estimates for road-load-influencing mass, rolling resistance, and aerodynamic drag reduction technology, the associated costs of achieving the reductions were not estimated by FEV and are not included in the costs presented in Table 6 through Table 13. Costs for road-load technologies are included in the cost analysis underlying this paper, and such costs were independently estimated according to the description in Section 6.1.

5.3. TECHNOLOGY PACKAGE COST ADAPTATION

Specific technology costs are adjusted to Chinese vehicles according to vehicle characteristic differences. For some technologies, the cost depends on engine power or other technical parameters. For others, the costs are assumed to be constant for all variants. Cost adjustments made in this analysis were as follows:

» **Engine**: The engine cost of each technology package is the adjustment of the engine cost of the counterpart technology package in the ICCT EU study. Just as the method used to adjust the baseline, the adjusted engine cost accounts for the difference in the number of engine configurations, the injection system, the adoption of a turbocharger, and is further adjusted based on engine power. To map the engine technologies to EPA technologies, which are used to identify the learning factor and estimate the cost of future years, engine downsizing costs are disaggregated into three components: a direct injection component, a turbocharging component, and a downsizing component. This follows the same method as in the 2015 FEV estimate.

» **Transmissions**: The cost of transmissions comes from the same data source as in the 2015 FEV study.

» **EGR technology**: The cost of EGR is adjusted by vehicle power based on the EGR cost/power relationship derived from FEV data.

» **Turbocharger technology**: Because turbocharger changes due to downsizing are accounted for as part of engine costs, we estimate the cost of turbocharging technology as the incremental cost of advanced turbo technology relative to single stage waste gate turbo. Single stage variable geometry turbo cost is estimated at a fixed cost, which is the same as in the FEV estimates. Two-stage waste gate turbo cost is adjusted by vehicle power, with the cost relation derived from FEV data. For D class 1.0 L and E class 1.2 L engines, FEV includes the cost of a second turbo in its engine cost estimates. For these two engines and their China equivalents, two-stage turbo costs are treated as zero.

» **Valvetrain technology**: Costs of DVVT, dual variable valve lift (DVVL), and valvetrain technology with Miller cycle vary with cylinder count and are therefore adjusted to the cylinder count of Chinese vehicles. This analysis recognizes the penetration of no cam phasing, intake cam phasing, and dual cam phasing in the baseline of each class in order to more precisely evaluate the incremental costs of moving from baseline technology to advanced technologies. Note that because the implementation of a Miller or Atkinson cycle with DVVT and DVVL is possible at no additional cost, the cost of a technology package may remain the same when there is a change in valvetrain technology.

» **VCR technology**: While VCR costs vary with both cylinder count and specific torque, the specific torque data for the China engines is not available. Thus, power density was used as a surrogate indicator, and this allows for the derivation of a cost/power density relationship for a given cylinder count engine, in this case four cylinders. However, this cannot account for variations in cylinder count. As a result, the derived relationship is used only to adjust FEV costs; the FEV estimates for any cylinder count are taken as the base China cost estimate and are adjusted by the fractional adjustment calculated on the basis of the 4-cylinder power density relation. This accounts for cylinder count influences while also tailoring the specific cost estimates to better reflect China engine characteristics.

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

» **Hybridization**: Hybridization cost is determined based on power and calculated depending on transmission type. The costs of start-stop, P0, and P2 are adjusted by vehicle power on the basis of the cost/power relationship derived from FEV data. The FEV estimates for start-stop are different for vehicles with manual transmission (MT) and automatic transmission (AT). The China cost estimate adjusts the start-stop cost for vehicles with manual and 7-speed dual-clutch transmissions (DCT) based on the MT cost/power relationship derived from FEV and adjusts the start-stop cost for vehicles with automatic transmissions and DCT-10 transmissions based on the AT cost/power relationship derived from FEV. The 12-volt advanced start-stop is treated as a fixed cost in addition to regular start-stop. To map the engine technologies onto EPA technologies, which are used to identify the learning factor and estimate the cost of future years, hybridization costs are disaggregated into two components, a battery system component and a non-battery system component.[6] The disaggregation is performed using detailed data presented in the 2015 FEV study.

Table 6. Adjusted China technology package for A class gasoline vehicles

TP	FEV	Disp	Cyl	Eng	TC	VT	EGR	CR	Fr	HEV	XM	MR	RL	AT	CO_2	Cost
A0	—	1.20	4	PFI	No	F	No	No	BL	No	M5	M0	RL0	3W0	122.7	0
A1	B0	1.20	4	PFI	No	T	No	No	BL	No	M5	M0	RL0	3W0	118.2	69
A2	B1	1.20	4	PFI	No	T	No	No	BL	SS	M5	M0	RL0	3W0	111.7	142
A3	B2	0.90	3	DI	1S	T	No	No	BL	No	M5	M0	RL0	3W0	100.9	329
A4	B3	0.90	3	DI	1S	T	No	No	BL	SS	M5	M0	RL0	3W0	95.9	402
A5	B4	0.70	3	DI	1S	T	No	No	BL	SS	M6	M1	RL0	3W2	88.5	448
A6	B5	0.70	3	DI	1S	T	No	No	BL	SS	M6	M2	RL0	3W2	83.8	448
A7	B6	0.70	3	DI	1S	T	No	No	BL	SS	M6	M2	RL1	3W2	78.7	448
A8	B7	0.70	3	DI	1S	T	No	No	BL	SS	M6	M2	RL2	3W2	74.6	448
A9	B8	0.70	3	DI	1S	T	No	No	FR	SS	M6	M2	RL1	3W2	75.3	525
A10	B9	0.70	3	DI	1S	TL	No	No	FR	SS	M6	M2	RL1	3W2	73.9	610
A11	B10	0.70	3	DI	1S	TLM	No	No	FR	SS	M6	M2	RL1	3W2	69.6	610
A12	B11	0.70	3	DI	1S	TL	CL	No	FR	SS	M6	M2	RL1	3W2	72.1	702
A13	B12	0.70	3	DI	1S	TLM	CL	No	FR	SS	M6	M2	RL1	3W2	68.7	702
A14	B13	0.70	3	DI	1S	TLM	CL	No	FR	SS	D7	M2	RL1	3W2	66.2	1,208
A15	B14	0.70	3	DI	1S	TLM	CL	No	FR	SS	M6	M0	RL1	3W2	76.6	702
A16	B15	0.70	3	DI	1S	TLM	CL	No	FR	P0	D7	M2	RL1	3W2	63.1	1,898

6 The non-battery system component includes all costs except those associated with the battery.

Table 7. Adjusted China technology package for B class gasoline vehicles

TP	FEV	Disp	Cyl	Eng	TC	VT	EGR	CR	Fr	HEV	XM	MR	RL	AT	CO_2	Cost
B0	—	1.50	4	PFI	No	F	No	No	BL	No	M5	M0	RL0	3W0	133.0	0
B1	B0	1.50	4	PFI	No	T	No	No	BL	No	M5	M0	RL0	3W0	129.1	54
B2	B1	1.50	4	PFI	No	T	No	No	BL	SS	M5	M0	RL0	3W0	122.0	130
B3	B2	1.20	3	DI	1S	T	No	No	BL	No	M5	M0	RL0	3W0	110.2	330
B4	B3	1.20	3	DI	1S	T	No	No	BL	SS	M5	M0	RL0	3W0	104.8	406
B5	B4	1.00	3	DI	1S	T	No	No	BL	SS	M6	M1	RL0	3W2	96.7	452
B6	B5	1.00	3	DI	1S	T	No	No	BL	SS	M6	M2	RL0	3W2	91.5	452
B7	B6	1.00	3	DI	1S	T	No	No	BL	SS	M6	M2	RL1	3W2	86.0	452
B8	B7	1.00	3	DI	1S	T	No	No	BL	SS	M6	M2	RL2	3W2	81.6	452
B9	B8	1.00	3	DI	1S	T	No	No	FR	SS	M6	M2	RL1	3W2	82.3	529
B10	B9	1.00	3	DI	1S	TL	No	No	FR	SS	M6	M2	RL1	3W2	80.7	614
B11	B10	1.00	3	DI	1S	TLM	No	No	FR	SS	M6	M2	RL1	3W2	76.1	614
B12	B11	1.00	3	DI	1S	TL	CL	No	FR	SS	M6	M2	RL1	3W2	78.8	712
B13	B12	1.00	3	DI	1S	TLM	CL	No	FR	SS	M6	M2	RL1	3W2	75.1	712
B14	B13	1.00	3	DI	1S	TLM	CL	No	FR	SS	D7	M2	RL1	3W2	72.4	1,218
B15	B14	1.00	3	DI	1S	TLM	CL	No	FR	SS	M6	M0	RL1	3W2	83.7	712
B16	B15	1.00	3	DI	1S	TLM	CL	No	FR	P0	D7	M2	RL1	3W2	68.9	1,904

Table 8. Adjusted China technology package for C class gasoline vehicles

TP	FEV	Disp	Cyl	Eng	TC	VT	EGR	CR	Fr	HEV	XM	MR	RL	AT	CO_2	Cost
C0	—	1.50	4	PFI	No	I	No	No	BL	No	M5	M0	RL0	3W0	140.7	0
C1	C0	1.50	4	PFI	No	T	No	No	BL	No	M5	M0	RL0	3W0	137.6	41
C2	C1	1.50	4	PFI	No	T	No	No	BL	SS	M5	M0	RL0	3W0	129.3	118
C3	C2	1.20	4	DI	1S	T	No	No	BL	No	M5	M0	RL0	3W0	114.4	452
C4	C3	1.20	4	DI	1S	T	No	No	BL	SS	M5	M0	RL0	3W0	108.1	529
C5	C4	0.90	3	DI	1S	T	No	No	BL	SS	M6	M1	RL0	3W2	95.4	440
C6	C5	0.90	3	DI	1S	T	No	No	BL	SS	M6	M2	RL0	3W2	90.1	440
C7	C6	0.90	3	DI	1S	T	No	No	BL	SS	M6	M2	RL1	3W2	85.5	440
C8	C7	0.90	3	DI	1S	T	No	No	BL	SS	M6	M2	RL2	3W2	81.0	440
C9	C8	0.90	3	DI	1S	T	No	No	BL	SS	M6	M0	RL0	3W2	101.1	440
C10	C9	0.90	3	DI	1S	T	No	No	BL	AS	D7	M2	RL1	3W2	78.7	934
C11	C10	0.90	3	DI	1S	T	No	No	FR	AS	D7	M2	RL1	3W2	74.1	1011
C12	C11	0.90	3	DI	1S	TL	No	No	FR	AS	D7	M2	RL1	3W2	72.8	1096
C13	C12	0.90	3	DI	2S	TLM	No	No	FR	AS	D7	M2	RL1	3W2	69.5	1270
C14	C13	0.90	3	DI	2S	TL	CL	VR	FR	AS	D7	M2	RL1	3W2	69.2	1480
C15	C14	0.90	3	DI	2S	TLM	CL	No	FR	AS	D7	M2	RL1	3W2	68.9	1370
C16	C15	0.90	3	DI	2S	TLM	CL	No	FR	AS	D7	M0	RL1	3W2	76.8	1370
C17	C16	0.70	3	DI	2S	TL	CL	No	FR	AS	D7	M2	RL1	3W2	71.7	1346
C18	C17	0.90	3	DI	2S	TLM	CL	No	FR	P0	D7	M2	RL1	3W2	66.4	2067
C19	C18	0.70	3	DI	2S	TL	CL	No	FR	P0	D7	M2	RL1	3W2	67.8	2043

Table 9. Adjusted China technology package for D class gasoline vehicles

TP	FEV	Disp	Cyl	Eng	TC	VT	EGR	CR	Fr	HEV	XM	MR	RL	AT	CO_2	Cost
D0	—	1.60	4	PFI	No	I	No	No	BL	No	A6	M0	RL0	3W0	146.3	0
D1	D0	1.60	4	PFI	No	T	No	No	BL	No	A8	M0	RL0	3W0	133.7	115
D2	D1	1.60	4	PFI	No	T	No	No	BL	SS	A8	M0	RL0	3W0	121.8	179
D3	D2	1.20	4	DI	1S	T	No	No	BL	No	A8	M0	RL0	3W3	119.5	583
D4	D3	1.20	4	DI	1S	T	No	No	BL	SS	A8	M0	RL0	3W3	109.7	647
D5	D4	0.90	3	DI	1S	T	No	No	BL	AS	D10	M1	RL0	3W1	95.1	649
D6	D5	0.90	3	DI	1S	T	No	No	BL	AS	D10	M2	RL0	3W1	90.6	649
D7	D6	0.90	3	DI	1S	T	No	No	BL	AS	D10	M2	RL1	3W1	86.2	649
D8	D7	0.90	3	DI	1S	T	No	No	BL	AS	D10	M2	RL2	3W1	81.6	649
D9	D8	0.90	3	DI	1S	T	No	No	BL	AS	D10	M0	RL0	3W1	99.6	649
D10	D9	0.90	3	DI	1S	T	No	No	FR	AS	D10	M2	RL1	3W1	82.5	726
D11	D10	0.90	3	DI	1S	TL	No	No	FR	AS	D10	M2	RL1	3W1	80.9	811
D12	D11	0.90	3	DI	2S	TLM	No	No	FR	AS	D10	M2	RL1	3W1	77.3	995
D13	D12	0.90	3	DI	2S	TL	CL	No	FR	AS	D10	M2	RL1	3W1	76.3	1221
D14	D13	0.90	3	DI	2S	TLM	CL	No	FR	AS	D10	M2	RL1	3W1	76.4	1102
D15	D14	0.90	3	DI	2S	TLM	CL	No	FR	AS	D10	M0	RL1	3W1	84.9	1102
D16	D15	1.20	4	DI	SS	T	D	No	FR	AS	D10	M2	RL1	3W1	82.5	1044
D17	D16	0.70	3	DI	2S	TL	CL	No	FR	AS	D10	M2	RL1	3W1	78.7	963
D18	D17	0.90	3	DI	2S	TLM	CL	No	FR	P2	D10	M2	RL1	3W1	69.5	2903
D19	D18	0.70	3	DI	2S	TL	CL	No	FR	P2	D10	M2	RL1	3W1	72.0	2764

Table 10. Adjusted China technology package for E+ class gasoline vehicles

TP	FEV	Disp	Cyl	Eng	TC	VT	EGR	CR	Fr	HEV	XM	MR	RL	AT	CO_2	Cost
E0	—	2.10	4	DI	1S	I	No	No	BL	No	A8	M0	RL0	3W3	169.4	0
E1	E2	2.10	4	DI	1S	T	No	No	BL	No	A8	M0	RL0	3W3	168.1	16
E2	E3	1.70	4	DI	1S	T	No	No	BL	SS	A8	M0	RL0	3W3	146.8	187
E3	E4	1.70	4	DI	1V	T	No	No	BL	AS	D10	M1	RL0	4W	139.6	187
E4	E5	1.70	4	DI	1V	T	No	No	BL	AS	D10	M2	RL0	4W	131.9	187
E5	E6	1.70	4	DI	1V	T	No	No	BL	AS	D10	M2	RL1	4W	125.7	187
E6	E7	1.70	4	DI	1V	T	No	No	BL	AS	D10	M2	RL2	4W	153.4	187
E7	E8	1.70	4	DI	1V	T	No	No	BL	AS	D10	M2	RL0	4W	126.5	266
E8	E9	1.70	4	DI	1V	T	No	No	FR	AS	D10	M2	RL1	4W	124.4	376
E9	E10	1.70	4	DI	1V	TL	No	No	FR	AS	D10	M2	RL1	4W	119.3	534
E10	E11	1.70	4	DI	2S	TLM	No	No	FR	AS	D10	M2	RL1	4W	116.3	804
E11	E12	1.70	4	DI	2S	TL	CL	VR	FR	AS	D10	M2	RL1	4W	118.3	662
E12	E13	1.70	4	DI	2S	TLM	CL	No	FR	AS	D10	M2	RL1	4W	132.1	662
E13	E14	2.60	4	DI	2S	TLM	CL	No	FR	AS	D10	M0	RL1	4W	133.9	571
E14	E15	1.30	3	DI	1S	T	D	No	FR	AS	D10	M2	RL1	4W	121.2	427
E15	E16	1.70	4	DI	2S	TL	CL	No	FR	AS	D10	M2	RL1	4W	106.1	2613
E16	E17	1.30	3	DI	2S	TLM	CL	No	FR	P2	D10	M2	RL1	4W	110.2	2378

Table 11. Adjusted China technology package for SUV gasoline vehicles

TP	FEV	Disp	Cyl	Eng	TC	VT	EGR	CR	Fr	HEV	XM	MR	RL	AT	CO_2	Cost
S0	—	1.70	4	PFI	No	I	No	No	BL	No	A6	M0	RL0	3W0	171.8	0
S1	D0	1.70	4	PFI	No	T	No	No	BL	No	A8	M0	RL0	3W0	157.0	115
S2	D1	1.70	4	PFI	No	T	No	No	BL	SS	A8	M0	RL0	3W0	143.1	182
S3	D2	1.30	4	DI	1S	T	No	No	BL	No	A8	M0	RL0	3W3	142.1	304
S4	D3	1.30	4	DI	1S	T	No	No	BL	SS	A8	M0	RL0	3W3	130.4	371
S5	D4	1.00	3	DI	1S	T	No	No	BL	AS	D10	M1	RL0	3W1	113.1	405
S6	D5	1.00	3	DI	1S	T	No	No	BL	AS	D10	M2	RL0	3W1	107.7	405
S7	D6	1.00	3	DI	1S	T	No	No	BL	AS	D10	M2	RL1	3W1	102.5	405
S8	D7	1.00	3	DI	1S	T	No	No	BL	AS	D10	M2	RL2	3W1	97.0	405
S9	D8	1.00	3	DI	1S	T	No	No	BL	AS	D10	M0	RL0	3W1	118.4	405
S10	D9	1.00	3	DI	1S	T	No	No	FR	AS	D10	M2	RL1	3W1	98.0	482
S11	D10	1.00	3	DI	1S	TL	No	No	FR	AS	D10	M2	RL1	3W1	96.2	567
S12	D11	1.00	3	DI	2S	TLM	No	No	FR	AS	D10	M2	RL1	3W1	91.9	759
S13	D12	1.00	3	DI	2S	TL	CL	VR	FR	AS	D10	M2	RL1	3W1	90.7	992
S14	D13	1.00	3	DI	2S	TLM	CL	No	FR	AS	D10	M2	RL1	3W1	90.8	871
S15	D14	1.00	3	DI	2S	TLM	CL	No	FR	AS	D10	M0	RL1	3W1	100.9	871
S16	D15	1.30	4	DI	1S	T	D	No	FR	AS	D10	M2	RL1	3W1	98.0	773
S17	D16	0.70	3	DI	2S	TL	CL	No	FR	AS	D10	M2	RL1	3W1	93.5	724
S18	D17	1.00	3	DI	2S	TLM	CL	No	FR	P2	D10	M2	RL1	3W1	82.6	2710
S19	D18	0.70	3	DI	2S	TL	CL	No	FR	P2	D10	M2	RL1	3W1	85.5	2563

Table 12. Adjusted China technology package for MPV gasoline vehicles

TP	FEV	Disp	Cyl	Eng	TC	VT	EGR	CR	Fr	HEV	XM	MR	RL	AT	CO_2	Cost
M0	—	1.60	4	DI	Np	I	No	No	BL	No	M5	M0	RL0	3W0	172.2	0
M1	C0	1.60	4	PFI	No	T	No	No	BL	No	M5	M0	RL0	3W0	167.8	48
M2	C1	1.60	4	PFI	No	T	No	No	BL	SS	M5	M0	RL0	3W0	157.6	128
M3	C2	1.20	4	DI	1S	T	No	No	BL	No	M5	M0	RL0	3W0	139.5	447
M4	C3	1.20	4	DI	1S	T	No	No	BL	SS	M5	M0	RL0	3W0	131.8	527
M5	C4	0.90	3	DI	1S	T	No	No	BL	SS	M6	M2	RL0	3W2	116.3	462
M6	C5	0.90	3	DI	1S	T	No	No	BL	SS	M6	M2	RL0	3W2	109.9	462
M7	C6	0.90	3	DI	1S	T	No	No	BL	SS	M6	M2	RL1	3W2	104.3	462
M8	C7	0.90	3	DI	1S	T	No	No	BL	SS	M6	M2	RL2	3W2	98.8	462
M9	C8	0.90	3	DI	1S	T	No	No	BL	SS	M6	M0	RL0	3W2	123.3	462
M10	C9	0.90	3	DI	1S	T	No	No	BL	AS	D7	M2	RL1	3W2	96.0	956
M11	C10	0.90	3	DI	1S	T	No	No	FR	AS	D7	M2	RL1	3W2	90.3	1033
M12	C11	0.90	3	DI	1S	TL	No	No	FR	AS	D7	M2	RL1	3W2	88.7	1118
M13	C12	0.90	3	DI	2S	TLM	No	No	FR	AS	D7	M2	RL1	3W2	84.8	1298
M14	C13	0.90	3	DI	2S	TL	CL	VR	FR	AS	D7	M2	RL1	3W2	84.4	1517
M15	C14	0.90	3	DI	2S	TLM	CL	No	FR	AS	D7	M2	RL1	3W2	84.0	1402
M16	C15	0.90	3	DI	2S	TLM	CL	No	FR	AS	D7	M0	RL1	3W2	93.6	1402
M17	C16	0.70	3	DI	2S	TL	CL	No	FR	AS	D7	M2	RL1	3W2	87.4	1378
M18	C17	0.90	3	DI	2S	TLM	CL	No	FR	P0	D7	M2	RL1	3W2	80.9	2095
M19	C18	0.70	3	DI	2S	TL	CL	No	FR	P0	D7	M2	RL1	3W2	82.6	2071

Table 13. Adjusted China technology package for minivan gasoline vehicles

TP	FEV	Disp	Cyl	Eng	TC	VT	EGR	CR	Fr	HEV	XM	MR	RL	AT	CO_2	Cost
MV0	—	1.30	4	PFI	No	F	No	No	BL	No	M5	M0	RL0	3W0	151.4	0
MV1	B0	1.30	4	PFI	No	T	No	No	BL	No	M5	M0	RL0	3W0	146.1	65
MV2	B1	1.30	4	PFI	No	T	No	No	BL	SS	M5	M0	RL0	3W0	138.1	139
MV3	B2	1.00	3	DI	1S	T	No	No	BL	No	M5	M0	RL0	3W0	124.8	332
MV4	B3	1.00	3	DI	1S	T	No	No	BL	SS	M5	M0	RL0	3W0	118.7	406
MV5	B4	0.80	3	DI	1S	T	No	No	BL	SS	M6	M2	RL0	3W2	109.5	452
MV6	B5	0.80	3	DI	1S	T	No	No	BL	SS	M6	M2	RL0	3W2	103.6	452
MV7	B6	0.80	3	DI	1S	T	No	No	BL	SS	M6	M2	RL1	3W2	97.4	452
MV8	B7	0.80	3	DI	1S	T	No	No	BL	SS	M6	M2	RL2	3W2	92.3	452
MV9	B8	0.80	3	DI	1S	T	No	No	FR	SS	M6	M2	RL1	3W2	93.2	529
MV10	B9	0.80	3	DI	1S	TL	No	No	FR	SS	M6	M2	RL1	3W2	91.4	614
MV11	B10	0.80	3	DI	1S	TLM	No	No	FR	SS	M6	M2	RL1	3W2	86.1	614
MV12	B11	0.80	3	DI	1S	TL	CL	No	FR	SS	M6	M2	RL1	3W2	89.2	709
MV13	B12	0.80	3	DI	1S	TLM	CL	No	FR	SS	M6	M2	RL1	3W2	85.0	709
MV14	B13	0.80	3	DI	1S	TLM	CL	No	FR	SS	D7	M2	RL1	3W2	81.9	1215
MV15	B14	0.80	3	DI	1S	TLM	CL	No	FR	SS	M6	M0	RL1	3W2	94.8	709
MV16	B15	0.80	3	DI	1S	TLM	CL	No	FR	P0	D7	M2	RL1	3W2	78.0	1904

Key:

TP = Technology package with entries coded as class (A, B, C, D, E+, S = SUV, M = MPV, MV = minivan), and package number

FEV = FEV technology package

Disp = Engine displacement (liters)

Cyl = Number of cylinders

Eng = Engine type (PFI = port fuel injection, DI = direct injection)

TC = Turbocharger type (No = no turbo, 1S = single stage waste gate turbo, 2S = two stage waste gate turbo, 1V = single stage variable geometry turbo)

VT = Valve control type (F = fixed, I = intake cam phasing, T = dual cam phasing, TL = dual cam phasing plus variable valve lift, TLM = dual cam phasing plus variable valve lift plus Miller cycle control)

EGR = Exhaust gas recirculation (No = no EGR, CL = cooled low-pressure EGR, D = dedicated EGR)

CR = Compression ratio technology (No = fixed compression ratio, VR = two-step VCR)

Fr = Engine friction technology (BL = baseline technology, RF = 20% friction reduction)

HEV = Hybrid electric technology (No = no hybrid technology, SS = 12 volt start-stop technology, AS = 12 volt advanced start-stop technology, P0 = 48 volt belt starter-generator, P2 = full parallel P2 HEV)

XM = Transmission technology (M5 = 5-speed manual, M6 = 6-speed manual, A8 = 8-speed automatic, D7 = 7-speed dual clutch, DX = 10-speed dual clutch)

MR = Mass reduction (M0 = baseline mass, M1 = nominal 10% mass reduction, M2 = nominal 20% mass reduction)

RL = Road load (RL0 = baseline rolling resistance and aerodynamic drag, RL1 = 25% rolling resistance reduction and 10% aerodynamic drag reduction, RL2 = 35% rolling resistance reduction and 20% aerodynamic drag reduction)

AT = Aftertreatment technology (3W0 = 3-way catalyst, 3W1 = 3-way catalyst with direct and port injection, 3W2 = 3-way catalyst with 350 bar direct injection, 3W3 = 3-way catalyst with piezo injectors, 4W = 4-way catalyst)

CO_2 = Carbon dioxide emissions over the EU NEDC (grams per kilometer)

Cost = Incremental cost relative to the baseline technology package (2014 euros)

6. ADAPTATION OF OTHER DATA SOURCES IN THE ICCT EU STUDY

The ICCT EU study referenced several complementary databases and conducted additional analyses to compensate for data not included in the FEV study. These methods are described in the ICCT EU study, which provides substantial additional detail on both the development of and application of the data. Unless otherwise specified, the same information is equally applicable to this work for China. Explained below are highlights of the methodologies and changes that are made, if any, for the adaptation to the China analysis.

6.1. MASS REDUCTION AND ROAD-LOAD COST ESTIMATES

The FEV 2015 study does not include the cost impacts of mass reduction, rolling resistance, and aerodynamic drag reduction technologies. Thus, supplemental data sources are used to estimate the costs of these technologies.

For mass reduction cost, we refer to FEV (2013). This study continues to be used, even though it is a relatively old analysis, because it included sophisticated crash simulations to validate that the use of lightweight materials did not negatively impact safety. Those studies generated different costs for western Europe and eastern Europe based on the difference in labor and manufacturing costs. The data are updated to 2014 euros to be consistent with the currency used for other technologies.

For rolling resistance and aerodynamic drag reduction costs, this study uses the original EPA (2012) data evaluated for the European Union. Because of resource limitations, we use the latest credible resource available for estimation. Most data are directly adopted, with the following alterations:

» The data are updated to 2014 euros to be consistent with the currency used for other technologies.

» The data have been expanded to address reductions greater than those explicitly treated in the EPA cost data. The EPA cost data for rolling resistance and aerodynamic drag reduction are directly applicable for reductions up to 20%. However, the technology packages in the 2015 FEV data consider rolling resistance reductions of 25% or 35%. To estimate the cost of these additional reductions, this analysis assumes that the cost per percentage point of reduction in the road-load parameter increases at the same rate as costs explicitly estimated by the EPA for reductions “up to 10%” and “between 10% and 20%.”[7]

Both the mass reduction cost from FEV (2013) and the road-load cost from EPA (2012) provide DMC and total cost (TC) data. The learning curve and indirect cost multiplier (ICM) data are derived from the EPA (2012) data, the same sources of the learning curve applied to 2015 FEV data described in the following section.

6.2. LEARNING CURVE AND INDIRECT COSTS

To produce a unit of output, auto manufacturers incur DMC and indirect costs (IC). As defined by the EPA, DMC includes the cost of materials and labor costs. ICs, meanwhile, may be related to production-related costs such as research and development, tooling, and other engineering; to business-related costs such as salaries, pensions, and manufacturer profits; or to retail sales-related costs such as dealer

7 The difference between the “between 10% and 20%” costs and the “up to 10%” costs is added to the “between 10% and 20%” costs to derive the “between 20% and 30%” costs, and is added to the “between 20% and 30%” costs to derive the “between 30% and 40%” costs. These calculations are performed for the base cost year as defined in the EPA cost data. Costs for other years are developed using the same learning and ICM assumptions used by the EPA for the “between 10% and 20%” reduction technology.

support, marketing, and dealer profit. The total of DMC and IC reflects estimations of total retail cost, including profit.

With the exception of VCR technology, the costs in the FEV study are presented as 2014-specific DMCs, assuming high-volume production. Because the base year for VCR technology DMCs is 2025, the ICCT EU study converted the 2025-specific DMCs for VCR technology to equivalent 2014 euros.

Because this analysis estimates costs for a series of future years, it is necessary to extrapolate the 2014 (or 2025, in the case of VCR technology) costs to the desired alternative evaluation years. As EPA summarized in its regulatory document, there are many factors that cause costs to decrease over time. As manufacturers gain experience in production, they are able to apply innovations that simplify machining and assembly operations, use lower-cost materials, and reduce the number or complexity of component parts. In addition, higher production volumes increase economies of scale and reduce production costs. All these factors allow manufacturers to lower the per-unit cost of production. Therefore, we developed manufacturer learning curves to reflect the reduction in unit production costs as a function of accumulated production volume.

Because technologies are developed and marketed globally, this China study applied the same learning potential and ICM complexity as in the EPA and ICCT EU studies, both of which were derived from the EPA's technical support document for its 2017–2025 U.S. light-duty vehicle GHG standards rulemaking (U.S. EPA, 2012). Generally, technologies that are either currently marketed or moderately evolutionary in nature relative to current technology are characterized as low complexity with only minor learning potential. Longer-term technologies are assigned higher-complexity ICMs and greater learning potential in accordance with their still-developing nature.

In most cases, there is a one-to-one relationship between the FEV study and the EPA technologies. However, this is not always the case. The specific mapping assignments employed in this analysis are described in Section 4 of the ICCT EU study. Because of the differences in representative vehicle specifications, there are several additional assignments employed in this China analysis regarding transmission technologies. Five-speed manual transmission (M5) is mapped to the EPA M6 learning curve and ICM data. Based on drivability preference,[8] 7- and 10-speed DCTs are mapped to the EPA 8-speed dry DCT learning curve and ICM data for vehicle classes A, B, C, MPV, and minivan, and to the EPA 8-speed wet DCT learning curve and ICM data for vehicle classes D, E, and SUV. Although the number of included gears is not identical in this mapping, the complexity of the technology is equivalent, and thus there is no introduced error.

6.3. TEST FLEXIBILITY ADJUSTMENTS TO FEV CO_2 ESTIMATES

The ICCT and Element Energy Limited (2015) identified test flexibilities in both the New European Driving Cycle (NEDC) and the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) that result in certification emissions from a given vehicle being lower than emissions from that same vehicle tested over the same test cycle using more realistic road-load and operational equipment settings. The vehicle simulation work of FEV (2015) took advantage of test flexibilities available to vehicle manufacturers under NEDC and WLTP, including road-load simulation and equipment-optimization parameters.[9] However, it is expected that the impact of the NEDC and

8 The wet clutch is usually used to provide a premium driving experience for the more expensive D, E, and SUV classes.

9 Such flexibilities include allowances related to beneficial tire selection and inflation, beneficial road-load determination conditions, beneficial vehicle test weight (excluding beneficially specified optional equipment), beneficial vehicle conditioning, and beneficial test and test equipment tolerances, which are among the various mechanisms that enable vehicle manufacturers to minimize test-specific CO_2 emissions.

WLTP test flexibilities will increase over time. China's upcoming shift from the NEDC to the WLTP in 2021[10] is expected to reduce test flexibilities, whereas the impact of test flexibility on the WLTP is expected to increase over time after test cycle shifting. To account for this evolution, the ICCT EU study extracted the increase rate of this difference from the ICCT and Element Energy Limited data from 2014 to 2020 and from 2020 to 2025. Because China and the European Union use the same NEDC test procedure and both plan to shift to WLTP from 2021, we can reasonably assume that the manufacturers that sell vehicles in China will gain familiarity with the nuances of flexibility at the same pace as manufacturers in the European Union. We therefore apply the same test flexibility adjustment as in the ICCT EU study.

6.4. PERFORMANCE-BASED ADJUSTMENTS TO THE FEV CO_2 ESTIMATES

Although the 2015 FEV data are generally developed on the basis of constant performance, there are two exceptions. First, engine downsizing was not implemented in conjunction with performance-improving P2 hybrid technology. Similarly, engine downsizing was not implemented in conjunction with energy demand-reducing mass reduction technology.

As in the ICCT EU study, this China study only implements adjustments to the FEV CO_2 data for technology packages that include mass reduction.[11] Because of a failure to develop a reliable adjustment for hybridization technology, the hybrid technology packages included in the FEV analysis are likely to underestimate associated CO_2 reductions.[12] Additionally, the ratio of energy requirements for changes in vehicle mass can be taken as a direct indicator of changes in associated fuel consumption and, by extension, CO_2 emissions. Therefore, this analysis uses the same adjustment factors as those used in the ICCT EU study.

The ICCT EU study evaluated modest mass changes assuming that the engine displacement changes with changing vehicle specifications and that the secondary effects of such changes, for example cylinder volume to surface area ratio, are reasonably small relative to the primary energy demand effect.

To generalize the CO_2 effects of mass reduction as reflected in the FEV study, FEV performed a detailed analysis using 26 technology packages that spanned all modeled vehicle classes and in which mass reduction was the only technology variant. Because 18 of the 26 technology packages were for diesel vehicles, they do not fit with our gasoline-only assumption for the China analysis. Thus, we reassessed the adjustment factors for gasoline alone based on the FEV data and applied it to the China analysis.

It is important to note that all the CO_2 adjustments are average in nature and not precise for any given vehicle class. Therefore, the additional vehicle classes analyzed for China will not alter the FEV results. The majority of the technology packages included in the FEV study consisted of varying multiple technologies, so that the precise effects of any one technology cannot be isolated. Thus, although this analysis applies average factors to adjust or eliminate the effects of a given technology—specifically, engine downsizing and mass reduction—the actual effects may be moderately different so that the adjustments, although reasonably accurate, are not precise.

10 On January 24, 2019, the Ministry of Industry and Information Technology (MIIT) released for public comment the proposed China 2025 Phase 5 fuel consumption standards (GB 19578), in which it announced a shift from the NEDC to the WLTP from 2021. For more information, see https://www.theicct.org/news/comments-chinas-proposed-2021-2025-fuel-consumption-limits-evaluation-methods-and-targets

11 Although the China fleet has lower performance (in terms of engine power) than the EU fleet for most classes, this impact on CO_2 was already accounted for in the baseline vehicle calculations.

12 The ICCT EU study did not find available data to make reliable adjustments for hybridization technology.

6.5. PERFORMANCE-BASED ADJUSTMENTS TO THE FEV AND ELECTRIC VEHICLE COST ESTIMATES

The ICCT EU study assumed that there are both co-benefits and other market drivers for many technologies that also reduce CO_2. Such co-benefits include improved performance, reduced noise, improved handling, improved braking, enhanced safety, and increased durability. Therefore, the study applied conservative estimates of the value of various technologies. Because such co-benefits universally apply to vehicles in any market, the China analysis applies the same performance-based adjustments as in the ICCT EU study. These are summarized in Table 14.

Table 14. Assumed co-benefits of various technology and net CO_2 cost fractions

	Co-benefits					
	Torque	Noise	Home fueling	Handling & braking	Performance	Net CO_2 cost fraction
Turbocharged GDI	5%					95%
Onboard-only charged full hybrid	5%					95%
PHEVs[a]	10%	5%	5%			80%
BEVs	10%	10%	5%			75%
FCVs	10%	10%				80%
Mass reduction				10%		90%
Dual-clutch automated manual transmission					5%	95%

[a] Plug-in hybrid electric vehicles (PHEVs) here are assumed to be equipped with a 40 kW or larger motor.

6.6. OFF-CYCLE CO_2 REDUCTION CREDITS

As in the ICCT EU study, the emissions benefit and cost estimates for off-cycle technologies are developed from the data in the report developed by Ricardo-AEA for the EU Directorate-General for Climate Action (Ricardo, 2015). That report identified the impact of 21 off-cycle technologies. In China's 2020 fuel consumption standards, start–stop, gear shift indicator, and high-efficiency air conditioning are listed as off-cycle technologies and additional technologies may be considered upon application. Because of this chance to apply for off-cycle credits, this China study considers all 21 off-cycle technologies from the Ricardo-AEA report.

For this analysis, the China vehicle classes are mapped to Ricardo-AEA classes as follows in order to estimate the cost and CO_2 impact of the off-cycle technologies. The A, B, and minivan class data are mapped to the Ricardo AEA small car; China C and D class data are mapped to the Ricardo AEA lower-medium car and upper-medium car, respectively. China E, SUV, and MPV class data are mapped to the Ricardo AEA large car.

China 2020 fuel consumption standards allow 0.5 L/100km off-cycle allowance in addition to the fleet average target of 5 L/100km. We assume that the 0.5 L/100km off-cycle credit allowance will remain the same as China moves toward more stringent standards for the 2025–2030 time period. In other words, we assume the cap on off-cycle emissions credits is 11.7 g/km. The cap is based on NEDC-equivalent emissions, rather than the real world, to generalize the Ricardo-AEA off-cycle data. The analysis follows the rationale that manufacturers will choose to apply an off-cycle technology that appears to be the more cost-effective option over any other alternative in-cycle or off-cycle technologies, until the accumulated off-cycle credits reach the limit.

7. ELECTRIC VEHICLE DATA

7.1. ELECTRIC VEHICLE COST DATA

In April 2019, the ICCT published a working paper assessing electric vehicle costs in the 2020–2030 time frame in the United States. It used the best battery pack and electric vehicle component cost data available through 2018 and is hereafter referred to as the ICCT U.S. EV study (Lutsey & Nicholas, 2019). In this China study, we adapt the electric vehicle cost results of the ICCT U.S. EV study to the Chinese context using the following methods.

The incremental cost of electric vehicles is customized based on 2017 vehicle prices by vehicle class in China.[13] The ICCT U.S. EV study's breakdown of costs by powertrain components, vehicle assembly, indirect manufacturing costs, automaker profit, and dealer markup are scaled to match China sales-weighted average prices. To accomplish this, powertrain costs are scaled from U.S. values to the China power ratings, vehicle assembly costs are scaled proportional to vehicle sizes, and indirect costs scale with direct manufacturing costs. In addition, to precisely match China vehicle prices in each vehicle class, all the bottom-up costs are adjusted down for lower China-based manufacturing and indirect costs. Overall, this approach ensures the data include the best available bottom-up engineering costs and accurately represent the average price in each vehicle class in the China market.

To develop the electric vehicle component costs, similar to the approach used on the conventional powertrain, we applied the ICCT U.S. EV study's component cost assumptions. The manufacturing costs for electric components, for example the electric drive module, power electronics, and battery packs, are adjusted down to match the China supply chain. In addition, we assume that China battery pack manufacturing is one year ahead of the global average battery cost reduction applied in the ICCT U.S. EV study. This reflects how the China battery industry is growing more rapidly and achieving higher volumes to supply vehicle manufacturers in the China market. Electric vehicle battery costs are reduced by 7% per year from 2018 through 2030, but the precise cell and pack costs differ by battery pack size.

The evaluated battery electric vehicles (BEVs) have electric ranges of 150–500 kilometers (km), and the plug-in hybrid electric vehicles (PHEV) have electric range capabilities of 30–100 km. Electric vehicle efficiency improves by 1% per year based on vehicle-level efficiency improvements—aerodynamic, tire, and mass reduction, as assessed above—and incremental improvements in electric powertrain components. This reduces the battery pack size for a given vehicle class and range over time. Fuel cell electric vehicles are not analyzed; their associated costs are far more uncertain because their market maturity and the time frame for high-volume production by multiple manufacturers with competitive suppliers is years behind electric vehicle technology.

Figure 3 presents the electric vehicle manufacturing cost data, adapted from the ICCT U.S. EV study, for the C-segment vehicle class in China. Although representative conventional ICE vehicle costs are shown for context, as discussed throughout this paper, the ICE technologies and costs will vary. Selected electric ranges are shown (150, 250, 350, and 450 km for BEVs; 60, 80, and 100 km for PHEVs) to show the relative effect of battery pack size on vehicle manufacturing cost. Vehicle assembly is the largest cost component overall, but it is similar across the vehicle technologies. The major difference in the electric vehicle cases is the battery pack cost, which decreases greatly from 2018, to 2025, and to 2030. As indicated by 2025, and more so by 2030, BEVs with shorter electric ranges have lower costs than the conventional ICE case.

13 Data provided by Automotive Data Center of China Automotive Technology and Research Center (CATARC).

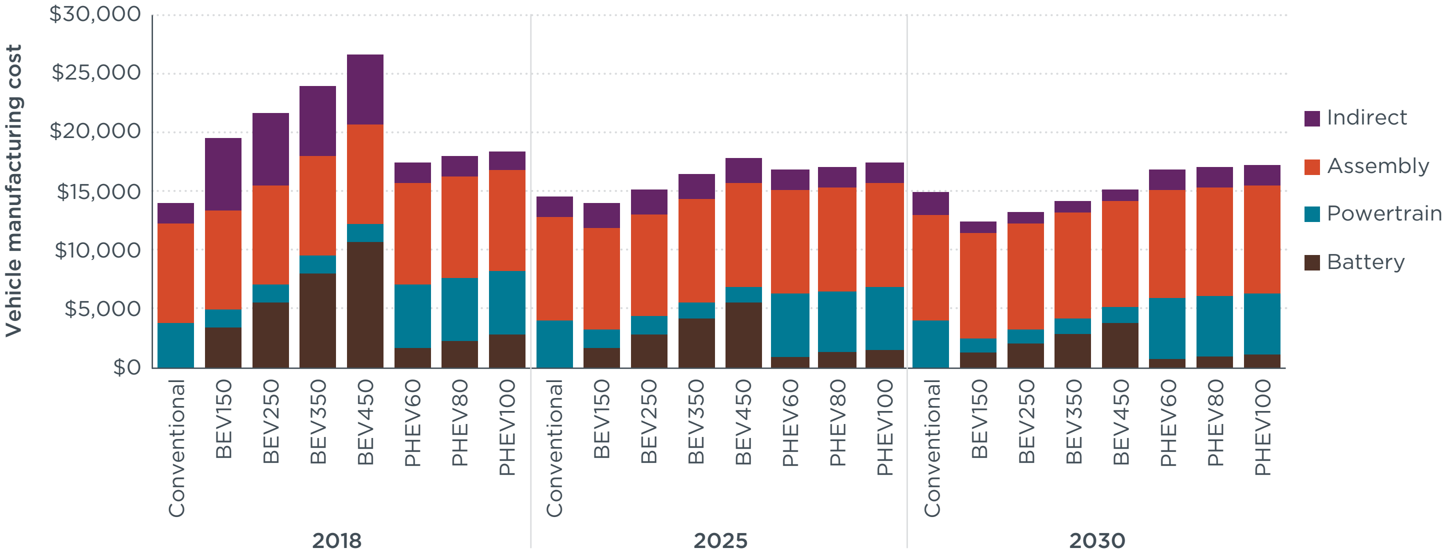

Figure 3. Per unit electric vehicle costs for C-class vehicles of varying electric ranges for 2018, 2025, and 2030 (in 2018 U.S. dollars).

7.2. ELECTRIC VEHICLE CO_2 DATA

BEVs have no tailpipe emissions. Although CO_2 is produced and emitted during the generation of the electricity used to charge BEVs, China's current and proposed regulatory programs treat BEVs as zero-emission vehicles. It is not certain when such allowances will be ended. This study assumes that such treatment will continue through at least 2030 and thus treats all BEVs as having zero CO_2 emissions. It is possible that the upstream CO_2 emissions will be considered for BEVs when assessing compliance with future fuel consumption standards. In that case, depending on the accounting rule, the cost of BEVs will be higher than the estimation in this analysis.

For PHEVs, determining net emission rates involves considering the emission rate during electric-only operation, the emission rate during ICE operation, and the fraction of time that PHEVs operate as electric-only vehicles, which is known as the utility factor. Once these three factors are known, the net emission rate for a PHEV is calculated as

$$ER_{net} = (UF)(ER_{el}) + (1 - UF)(ER_{ice})$$

Where: ER_{net} = Net emission rate

ER_{el}= Emission rate during electric-only operation

ER_{ice} = Emission rate during ICE operation

UF= Utility factor

As with BEVs, this study assumes a zero emission rate for PHEVs during electric-only operation. The emission rate during ICE operation is assumed to be equivalent to that of a P2 hybrid electric vehicle (HEV). P2 HEV emission rates are adapted from the data in the ICCT EU study based on the adaptation method introduced in section 6. Utility factor is a function of both the all-electric range (AER) of a PHEV and the driving cycle over which it operates.

For the NEDC, the utility factor is defined as

$$UF = \frac{\text{AER}}{\text{AER} + 25}$$

Where: UF = Utility factor

AER = All-electric range, in km

For the WLTP, the Ministry of Ecology and Environment (2016) defines the utility factor as

$$UF = 1 - e^{-\left(\sum_{j=1}\left(C_j \times \left(\frac{AER}{d}\right)^j\right)\right)}$$

Where UF = Utility factor,

C = Power series coefficients as follows:

C_1 = 4.58	C_2 = 16.32	C_3 = -29.54	C_4 = -37.03	C_5 = 54.03
C_6 = 92.06	C_7 = -14.69	C_8 = -158.49	C_9 = -22.98	C_{10} = 110.00

AER = All-electric range

d = Normalization distance = 400 km

In this study, the named AER for the various considered PHEVs is the NEDC AER. In other words, the NEDC AERs of PHEV-60, PHEV-80, and PHEV-100 vehicles are 60, 80, and 100 km. Based on the assumption that the WLTP AER is equal to 75% of the NEDC AER, PHEV-60, PHEV-80, and PHEV-100 vehicles have WLTP AERs of 45, 60, and 75 km, respectively. Accordingly, the NEDC utility factors for these specific PHEVs are 0.71, 0.76, and 0.80 and the WLTP utility factors are 0.49, 0.61, and 0.70.

Using the emission rate during electric-only operation, the emission rate during ICE operation, and the utility factors introduced above, net emission rates for all PHEVs over both NEDC and WLTP cycles were calculated.

8. RESULTING COST CURVES

CO_2 incremental compliance cost estimation consists of two compliance strategies. One reflects the level of CO_2 reduction that can be achieved through the introduction of progressively more effective ICE technology. The other reflects the CO_2 reduction that can be achieved by combining ICE technology improvements with an increase in the market penetration of electric vehicles. By incremental cost, we mean the relative cost increase or decrease to the 2017 vehicle production cost. Cost curves of the two strategies are shown in Figure 4 and Figure 5.

8.1. ICE STRATEGY

The ICE strategy represents the scenario where all fuel consumption reductions come from ICE technology upgrades. For ICE technologies, zero incremental cost is assigned to the baseline technology packages and corresponding CO_2 data. The estimated cost and CO_2 impact of a series of future technology packages are then subjected to regression analysis to generalize a cost curve. Note that not all the technology options listed in Section 5.3 were considered when developing these cost curves. Only the relatively cost-effective technology packages were selected, namely those with lower costs compared to others at the similar fuel-saving potential. The selection of technology packages may also be different for different segments.

Independent cost curves were developed for eight passenger vehicle classes. Based on surveys with experts in the China vehicle markets, the analysis assumed constant sales shares throughout the evaluation period of 2017–2030. Individual vehicle class estimates are sales weighted to determine overall fleet CO_2 levels using 2017 sales data.

After the cost curves were generated, CO_2 values were converted to fuel consumption values (L/100km) and costs were converted to 2017 China currency (CNY).[14] The incremental costs are plotted against associated fuel consumption values. The X-axis represents fuel consumption values whereas the Y-axis represents the corresponding incremental costs.

Figure 4 presents passenger vehicle fleet average cost curves under the ICE strategy with fuel consumption targets measured over the NEDC in 2030 based on ICCT's best estimation. The total cost curve reflects the retail-level cost change and the DMC curve reflects manufacturer-level cost change. The curves only account for gasoline vehicles, as the vast majority of the ICE passenger car fleet is powered by gasoline. The starting points on the curves represent the 2017 baseline fuel consumption level of the fleet. Appendix A presents the fuel consumption compliance cost curves under the ICE strategy for different vehicle classes.

14 The cost curves are generated in 2014 euros and then converted to CNY based on a 2014 exchange rate. The exchange rate is EUR: CNY = 8.19 :1, based on https://www.statista.com/statistics/412827/euro-to-yuan-average-annual-exchange-rate/

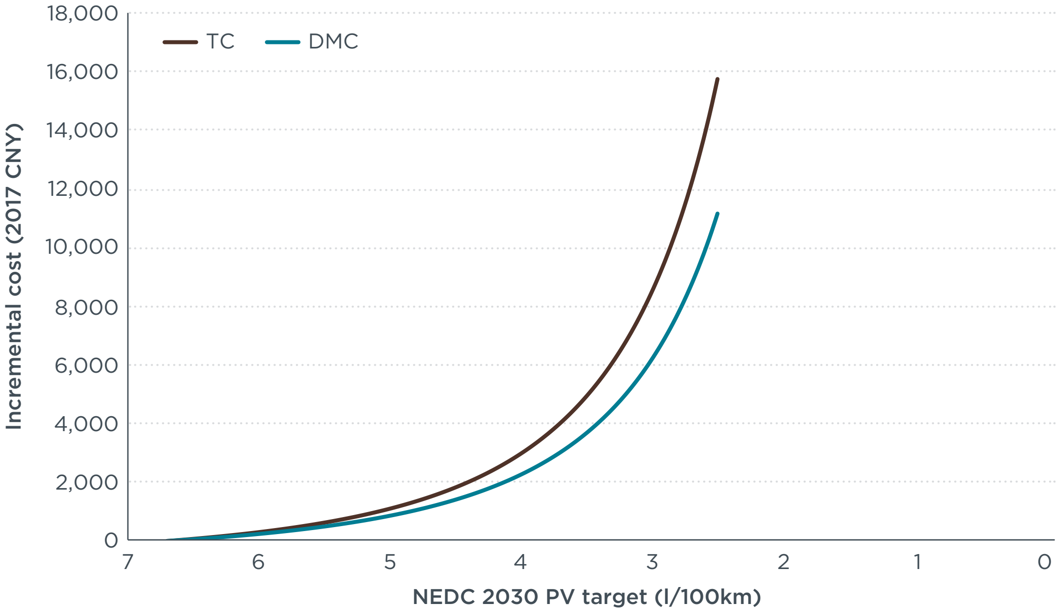

Figure 4. 2030 NEDC fuel consumption incremental compliance costs for passenger vehicles under ICE strategy.

The cost curves show that for the ICE strategy, there is a maximum level of fuel consumption reduction that can be attained through the ICE technologies considered in this analysis. Nevertheless, the fleet average target of 3.2 L/100km can still be achieved by applying solely ICE technologies. Compared with the 2017 baseline, the incremental cost to meet the target of 3.2 L/100km in 2030 is estimated at about ¥4,900 (DMC) and ¥6,700 (TC). Table 15 summarizes the estimated compliance cost to meet different levels of fuel consumption targets by 2030.

The analysis also shows the full potential of fuel consumption reduction in the fleet can be as low as 2.5 L/100km, with a compliance cost of around ¥11,100 (DMC) or ¥15,600 (TC). This can be achieved mainly by adopting full hybrid and mild hybrid technologies in all vehicles along with other efficiency technologies.

Table 15. Estimation of fleet average compliance to meet 2030 fuel consumption targets

Fuel consumption target in 2030 (L/100km)	Direct manufacturing cost (2017 CNY)	Total cost (2017 CNY)
3.5	3,700	4,900
3.2	5,000	6,700
3.0	6,200	8,400
2.5	11,100	15,600

Although the cost estimation is based on the assumptions that ICCT considered most appropriate for conducting such cost analysis, Appendix B provides a fleet average cost curve under an alternative set of assumptions, the "upper bound" scenario. See Appendix B for a detailed comparison.

8.2. EV STRATEGY

The EV strategy represents the scenario where increasing EV market penetration is an option to comply with fuel consumption targets. Continuous increase in EV market share will result in changes to technology costs and lower CO_2 emissions. When the EVs on average are more expensive than ICE vehicles, it is reasonable to assume that manufacturers will exhaust ICE technologies to a maximum level of CO_2 reduction before switching to EVs to meet lower CO_2 targets. With policy interventions that accelerate early uptake of EVs, when EVs become, on average, a more cost-effective way to achieve CO_2 targets, the cost of reducing CO_2 levels will come from increasing EV penetration.

To evaluate the compliance cost with a given penetration of EVs, the analysis assumes that EVs are distributed across vehicle classes in accordance with the class sales shares. Based on the industry roadmap and the technology directions promoted by existing policies, the analysis assumes that EVs with different battery driving ranges will be used to satisfy EV demand for different segments. As Table 16 shows, for A and B class vehicles, the analysis assumes that all EV demand is met by BEVs. For other classes, the analysis assumes that both BEVs and PHEVs will be employed.

Table 16. Assumption of EV categories to meet EV demand by vehicle class

Class	BEV-150	BEV-250	BEV-350	BEV-450	PHEV-60	PHEV-80	PHEV-100
A	10%	90%					
B		80%	20%				
C		10%	60%	10%	5%	10%	5%
D			70%	10 %	5%	10%	5%
E+			70%	10%	5%	10%	5%
SUV				40%		30%	30%
MPV				30%		40%	30%
MV			70%			20%	10%

Based on our estimation, by 2030, most BEVs will be cheaper than comparable ICE vehicles and PHEV costs will be much closer to comparable ICE vehicles compared with the 2018 level (see Section 7 for details). After accounting for all vehicle classes and the penetration of different types of EVs in each class, in 2030, increasing EV penetration for compliance with 2030 fuel consumption target becomes more cost-effective than making improvements to ICE efficiency technologies. Figure 5 compares the incremental compliance cost to meet 3.2 L/100km target in 2030 through ICE technology only and combining ICE technology with EV uptake. With an increased share of EVs in the fleet, the fuel consumption improvement required for the ICE fleet decreases. The analysis shows that in 2030, higher EV uptake will result in lower incremental compliance costs. For example, to meet the 3.2 L/100km target, the total incremental cost of compliance is ¥1,100 per vehicle with a fleet average EV penetration of 20%. The incremental cost will turn into cost savings of ¥5,000 when the 3.2 L/100km target is met by a fleet average EV penetration of 40%.

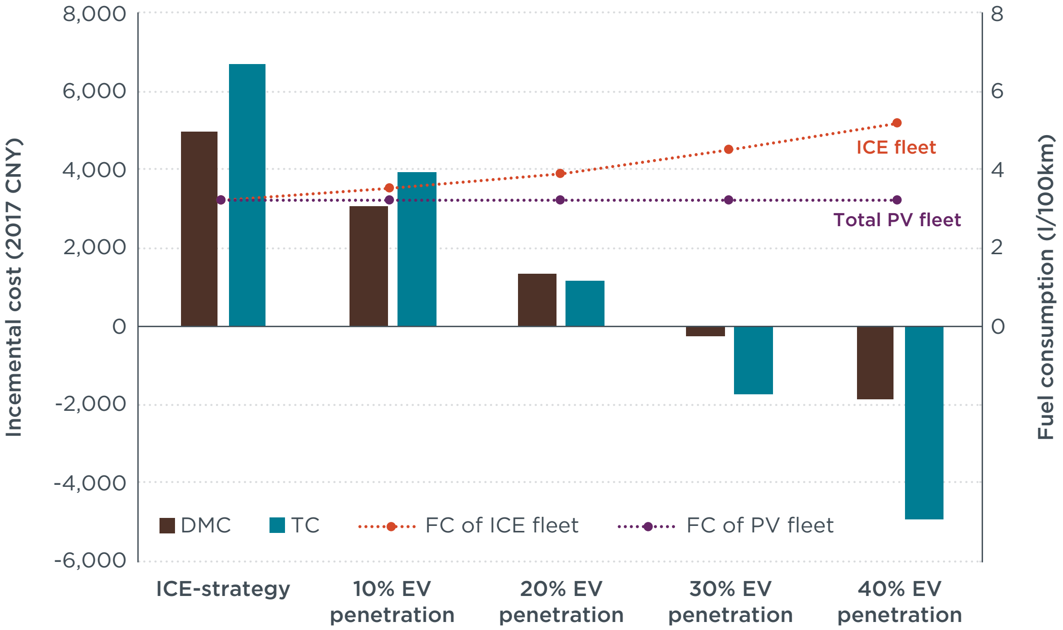

Figure 5. Comparison of incremental compliance cost to 3.2 L/100km target in 2030 between the ICE strategy and combining ICE technology with EV uptake.

Note that even though the 2030 compliance cost is lower with higher EV penetration, it does not mean that all investment will be directed to EV development before 2030. The analysis is only studying the compliance cost in 2030. Because the cost of EVs is expected to keep decreasing over time before reaching cost parity, the EV costs in earlier years are expected to be higher than the estimated cost for 2030. Manufacturer investment decisions and compliance planning would have to consider a combination of multiple-year efforts.

Nevertheless, the EV strategy scenario shows that any increase in EV uptake in the fleet will reduce the fleet average compliance cost to meet the fuel consumption standards in 2030. Individual manufacturers will have different paces of EV deployment, and how this is reflected in their decision-making will depend on the policy and market environment and individual company development strategy.

9. DISCUSSION AND CONCLUSIONS

This paper presents a set of fuel consumption cost curves for the China passenger car fleet and describes the methodology employed in their development. We consider two least-cost compliance strategies, one that relies on the exhaustion of ICE technology prior to the widespread introduction of EVs, and another that assumes different levels of EV introduction as soon as their onboard technology is more cost effective, from a fuel consumption standpoint, than alternative ICE technology.

Based on the derived curves, compliance costs can be estimated for a range of potential fuel consumption standards in 2030. We draw the following conclusions for the China market:

» Given the current state of ICE technology, a passenger vehicle fuel consumption standard of 3.2 L/100km can be attained by 2030 for around ¥4,900 (DMC) and ¥6,700 (TC) per vehicle compared with the 2017 baseline fleet, without EV market penetration.[15] Passenger vehicle fleet average fuel consumption as low as 2.5 L/100km can be achieved without EV penetration at compliance costs of around ¥11,100 (DMC) and ¥15,600 (TC).

» Because the incremental cost of most EVs will be cheaper than alternative ICE vehicles by 2030, increasing the EV share of the passenger car fleet will be a more cost-effective pathway to comply with fuel consumption standards compared with solely improving ICE technologies in 2030. Under an EV strategy, any increase of EV uptake in the fleet will reduce the fleet average incremental cost of complying with the fuel consumption standards in 2030. To meet the 3.2 L/100km target, the total incremental cost of compliance is ¥1,100 per vehicle with a fleet average EV penetration of 20%. The incremental compliance cost will turn into a cost saving of ¥5,000 compared with the 2017 vehicle production cost when the 3.2 L/100km target is met by a fleet average EV penetration of 40%.

The developed incremental compliance costs are technology neutral. They do not consider the impacts associated with any potential regulations or incentives that might discount the cost of any ICE or EV technology—for example, the multiplier benefit for EVs and low fuel consumption vehicles in the fuel consumption standards—nor any investment in the development of infrastructure.

Note that the compliance costs presented in this paper only apply to the average vehicle market. Costs for individual manufacturers will be different, and manufacturers will apply different technology mixes. Similarly, the strategy of EV deployment will be different for individual manufacturers. Investment decisions will not only take into account the fleet composition, the existing technology mix and future potential, and manufacturing cost, but will also include the consideration of policies like NEV mandates and NEV incentives, battery development, consumer barriers, and infrastructure deployment to support EV deployment and operation. Because Chinese manufacturers are likely to choose a combination of ICE and EV strategies before EVs reach cost parity, the actual compliance cost will likely fall between the compliance cost under the two scenarios.

Although our study shows that increasing EV penetration will likely reduce the incremental cost to comply with future fuel consumption targets in 2030, challenges stemming from the supply chain, consumer awareness of this relatively new technology, and the inadequacy of charging infrastructure remain. These factors are all hidden costs for EV technology that are not evaluated in this study. Government and the automobile industry will need to take collective action to help remove these

15 Unless otherwise noted, all CNY presented in Section 9 are 2017 CNY.

barriers for EVs to truly reach cost parity with conventional ICEs. However, there are still many cost-effective ICE technologies that can be used to reduce CO_2 and fuel before EVs enter the mainstream market.

Although the cost curves are based on extensive vehicle simulation modeling and detailed bottom-up cost assessments, there are limitations to this analysis.

- The cost estimate is conservative. The conventional vehicle technology is frozen based on 2015 information and does not include any technology improvements or cost reductions beyond basic improvements in the older technology. For example, there is some agreement that 50% thermal efficiency is likely to be achieved from ICE engines in the future. However, even the highest efficiency engine in FEV's study, the Miller cycle turbo engine, barely breaks 40% thermal efficiency. Such technology advances will influence the cost curves. The other limitations that make the cost curve conservative are described in the ICCT EU study.
- The analysis assumes that market shares of fuels and vehicle segments will not change in the future. In particular, it assumes that the market share of SUVs will remain constant over time. However, there is some likelihood that the market share of SUVs will increase in the future. The class distribution of electric vehicles is also assumed to the best of our knowledge, and the future market is challenging to predict. It is hard to predict the impact of these uncertainties without further market assessment.
- All fuel-saving technologies are evaluated on a constant-performance basis. It is assumed that the power and top speed of fuel-saving vehicles are unchanged from those of baseline vehicles. The costs for reduced performance vehicles would be lower than depicted in the cost curves.

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APPENDIX A. PASSENGER VEHICLE CLASS-SPECIFIC FUEL CONSUMPTION COMPLIANCE COSTS OVER THE NEDC IN 2030

This study developed multiple sets of cost curves across vehicle classes. The following figures show cost curves for the B, C, D, SUV, MPV, and minivan classes. Cost curves for other classes are not shown in this appendix due to their small share of the market. We generated the fleet average cost curve by considering the cost curve across all vehicle classes. TC denotes total cost and DMC denotes direct manufacturing cost.

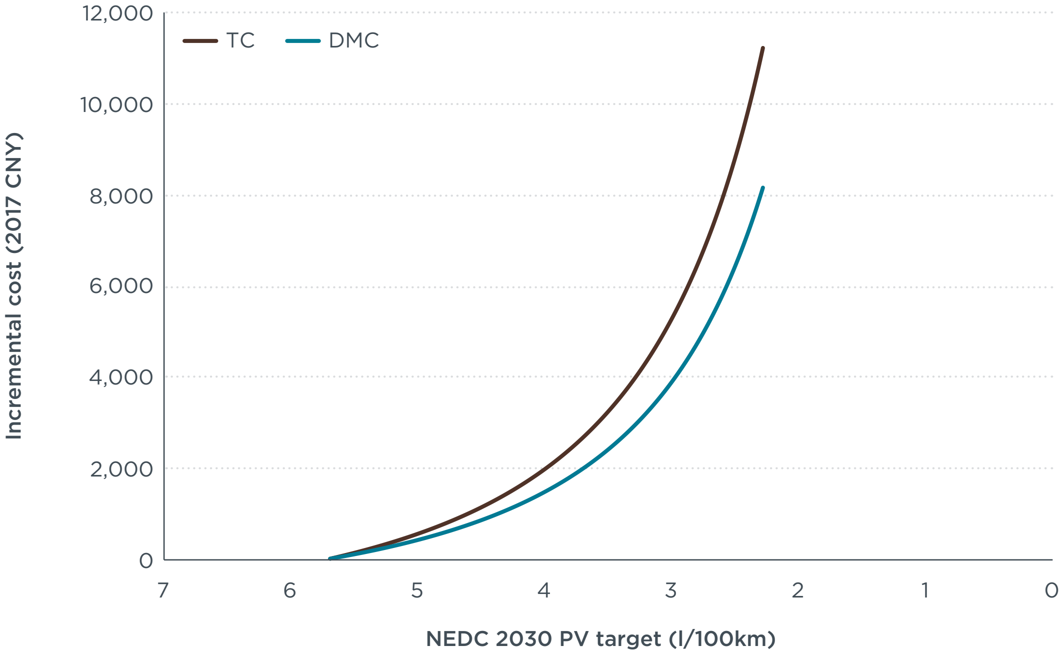

Figure A1. 2030 NEDC fuel consumption compliance costs for passenger vehicles (PV) under ICE strategy (B Class).

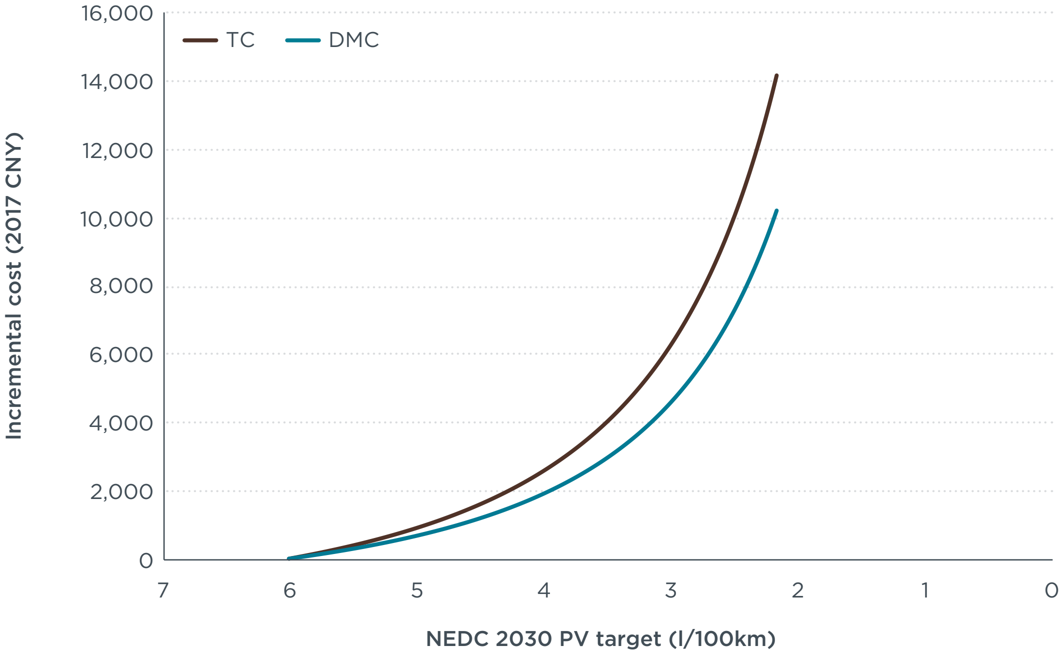

Figure A2. 2030 NEDC fuel consumption compliance costs for passenger vehicles under ICE strategy (C Class).

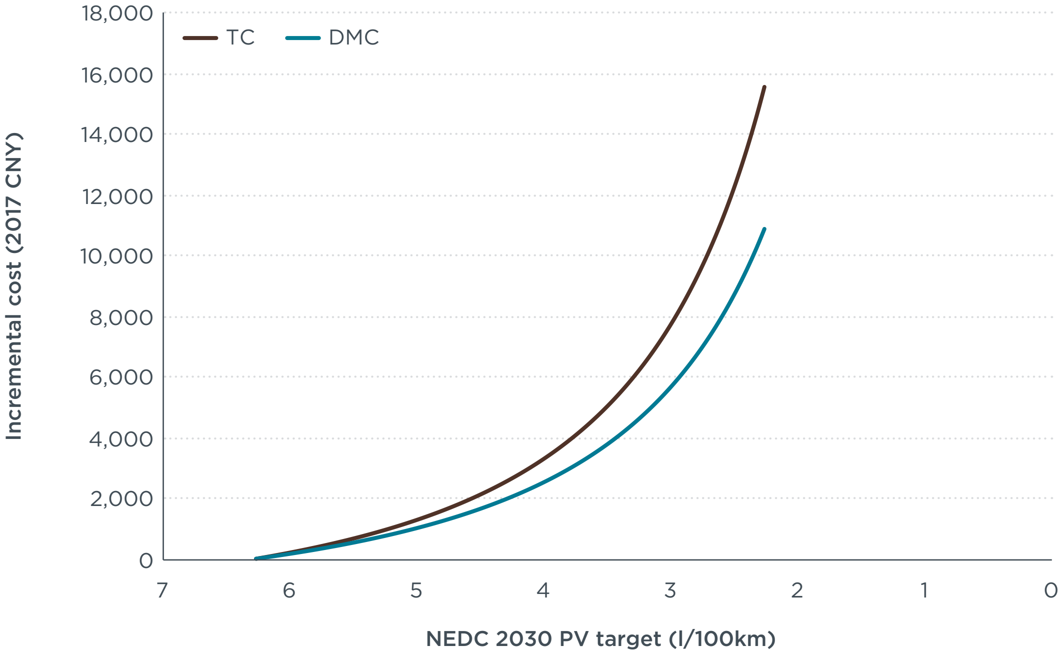

Figure A3. 2030 NEDC fuel consumption compliance costs for passenger vehicles under ICE strategy (D Class).

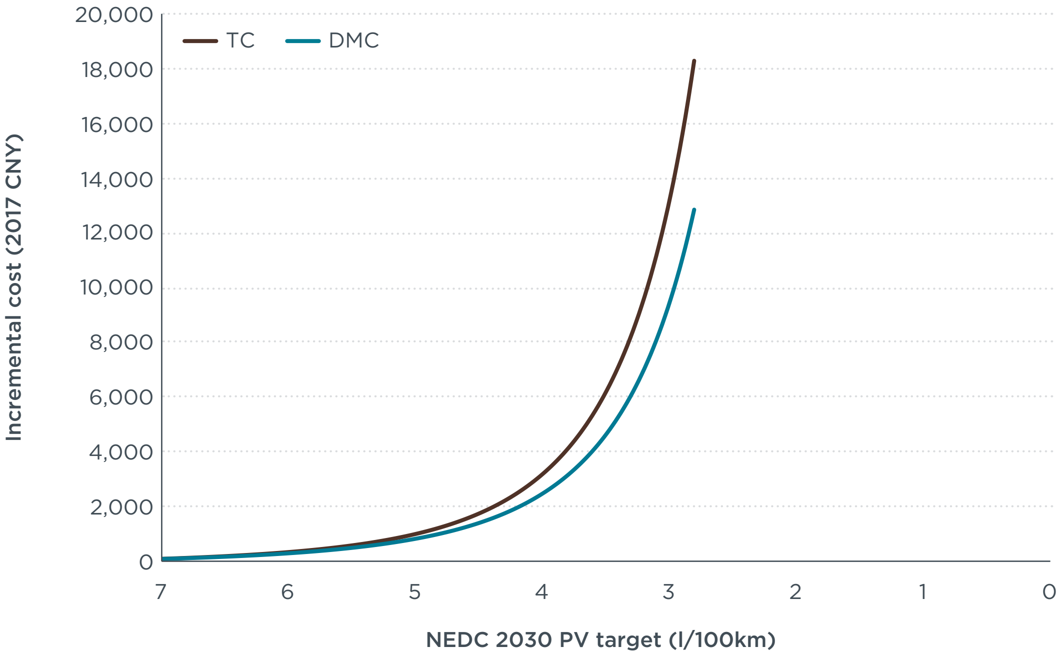

Figure A4. 2030 NEDC fuel consumption compliance costs for passenger vehicles under ICE strategy (SUV Class).

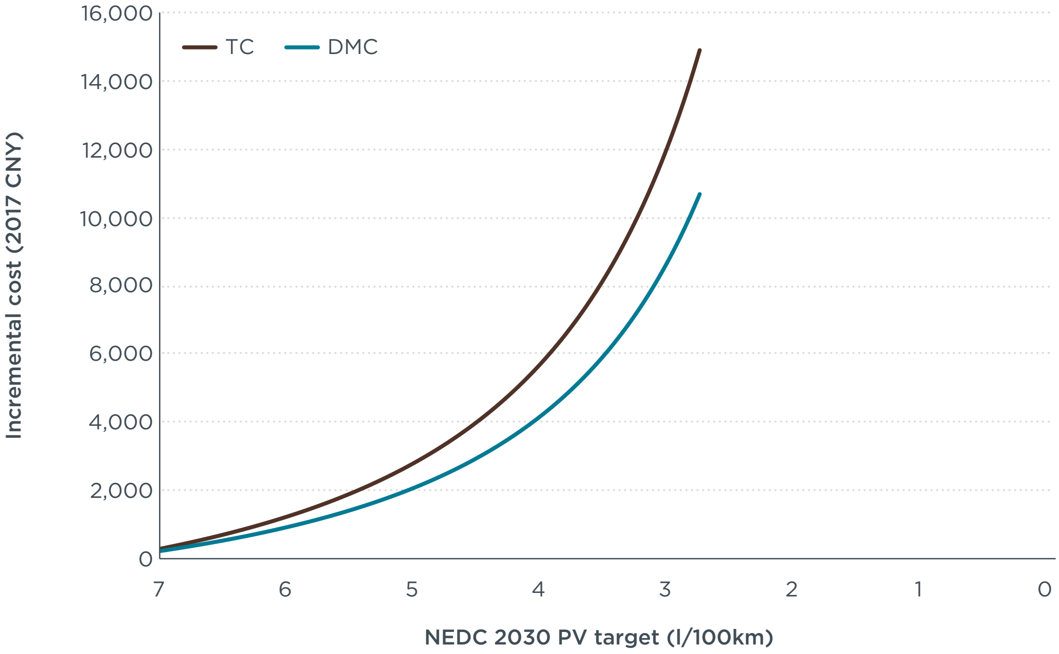

Figure A5. 2030 NEDC fuel consumption compliance costs for passenger vehicles under ICE strategy (MPV Class).

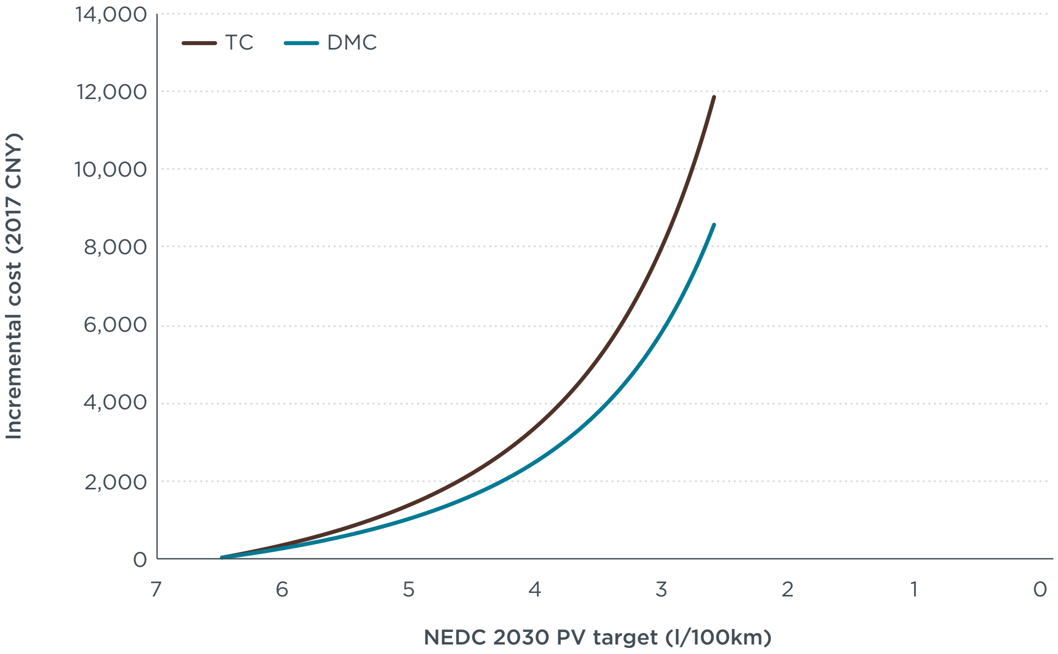

Figure A6. 2030 NEDC fuel consumption compliance costs for passenger vehicles under ICE strategy (minivan class).

APPENDIX B. UPPER BOUND COST CURVES

The cost curves in this report reflect ICCT's best estimates of compliance costs. To take into account various assumptions, we here evaluate an alternate set of assumptions, which is called the "upper bound" scenario. Although ICCT's estimates are based on our best judgment regarding the trends in the industry, the upper bound costs aim to provide comparative cases when different assumptions are made about some elements. The assumptions of the two scenarios are specified in Table B1.

Table B1. Assumptions of ICCT best estimate and upper bound cost

	ICCT best estimate	Upper bound cost
Mass reduction	Reflects assessments that found modest amounts of weight reduction can be achieved while also reducing cost	No level of mass reduction can be achieved at less than zero cost
Test flexibility exploitation	Included	Omitted
Performance-based CO_2 adjustments	Included	Omitted
Cost adjustments based on technology co-benefits	Included	Omitted
Off-cycle technology credits	Included	Omitted
EV cost estimate	ICCT best estimates	ICCT upper bound estimates*

* The ICCT upper bound estimates assume that electric vehicle battery costs are reduced by 5% per year from 2018 through 2030, compared to 7% in the ICCT best estimates.

The fleet average cost curves presented here are passenger vehicle 2030 cost curves under the upper bound scenario, where the full potential of fuel consumption reduction of the fleet can be reduced only to 3.26 L/100km with a compliance cost of around ¥15,800 (TC) and ¥11,000 (DMC).

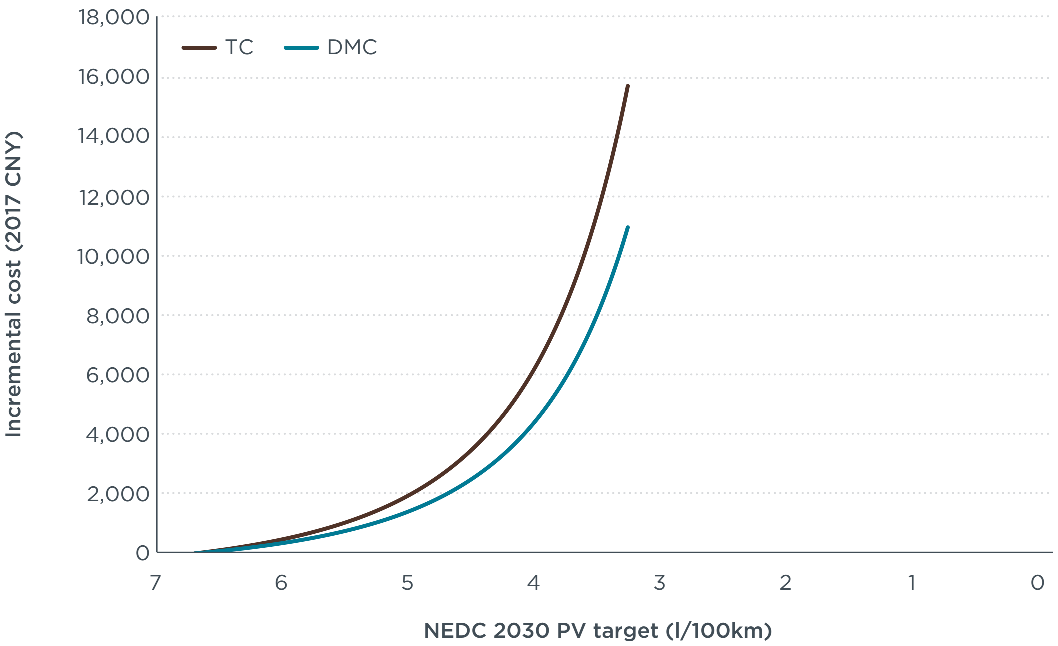

Figure B1. 2030 NEDC fuel consumption compliance costs for passenger vehicles under ICE strategy (upper bound scenario).

APPENDIX C. VEHICLE CLASSIFICATION DESCRIPTIONS

Class	Segment	Description
A	Mini	Hatchback, up to 3.75 meters long, price mainly around the ¥40,000 mark, with some outliers up to the ¥60,000 mark
B	Small	Hatchbacks up to 4.1 meters long, sedans up to 4.3 meters long, priced mainly around the ¥40,000 mark, with some outliers up to ¥60,000 mark
C	Lower medium	Hatchbacks between 4.1 meters and 4.5 meters long, sedans between 4.3 meters and 4.6 meters, priced mainly between ¥80,000 to ¥130,000
D	Medium	Usually a sedan, between 4.6 and 4.99 meters long, priced between ¥100,000 to ¥180,000
E+	Upper medium	Premium compact cars, around 4.5 meters long, priced greater than ¥270,000
	Large	Usually a sedan with length of 5 meters or more, priced greater than ¥220,000. But more likely ¥300,000+
	Sports	Usually a two-door coupe or convertible
SUV	Monocoque SUV	Compact SUV, seating for 5 people, engine usually around 2 liters
	Medium SUV	SUV often with separate chassis, engines 2.2 liters and upward, often 7 seats
MPV	Medium MPV	MPV with engine up to 2 liters, seating capacity 5 to 7 people
	Large MPV	MPV with engine above 2 liters, seating capacity 7 to 8 people
Minivan	Minivan	Small bus based on Japanese Kei-car platform, engine around 1 liter