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Impacts of a super credit policy on electric vehicle penetration and compliance with China's Corporate Average Fuel Consumption regulation

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ABSTRACT

A super credit policy provides favorable accounting rules for extremely low emission vehicles under several passenger vehicle fuel economy regulations. This policy was initially designed to promote promising advanced technologies complying with fleet-wide fuel economy regulations so that these technologies could achieve cost-effective breakeven points. The favorable multipliers offered range from 3.5 to 1.33 in the various fuel economy regulations by the year 2021. Under China's Corporate Average Fuel Consumption regulation, two types of super credit schemes are designed in the Phase IV Corporate Average Fuel Consumption regulation through 2020. One is the fuel-efficient vehicle super credit for vehicles with fuel consumption rates below the threshold of 2.8 L/100 km. Another is the new energy vehicle super credit for battery electric vehicles and plug-in hybrid electric vehicles. However, the effectiveness of this incentive in promoting electric vehicles and the optimal size of the multiplier are not well understood. This paper analyzes the impacts of the super credit policy from the perspective of automakers. A mathematical model based on combinational optimization is established to describe an automaker's decision-making process, and a genetic algorithm is employed to solve this problem. The conventional and plug-in hybrid electric vehicles cost-effectiveness frontier curves are fitted to illustrate the principle of new energy vehicle and fuel-efficient vehicle super credit schemes. Various multipliers of new energy vehicle and fuel-efficient vehicle super credit policy scenarios are simulated under the 2020 and 2025 Corporate Average Fuel Consumption targets. By analyzing the impact of the policy on the reduction of compliance costs, the super credit multiplier, the cost and the fuel consumption rates reduction effect are found to be the determining factors. The results confirm that the multiplier and China's super credit policy scheme will be effective by 2020, under which plug-in hybrid electric vehicles would account for 7.8% of the fleet at a cost of 6.6% Corporate Average Fuel Consumption target impairment. Under the assumed next phase of regulation by the year 2025, the optimal multipliers for the new energy vehicle and fuel-efficient vehicle super credit will be 1.5 and 1, respectively. It is noteworthy that the super credit policy may impair the energy saving target of Corporate Average Fuel Consumption regulations while promoting the market penetration of the targeted technologies. Despite other policies that benefit battery electric vehicles over plug-in hybrid electric vehicles, battery electric vehicles are not competitive with plug-in hybrid electric vehicles under either the 2020 or 2025 Corporate Average Fuel Consumption regulations. The fuel-efficient vehicle super credit policy will not promote the targeted advanced technologies under the next phase of regulation unless the 2.8 L/100 km fuel-efficient vehicle definition threshold can be adjusted along with the strengthened 2025 Corporate Average Fuel Consumption target.

1. Introduction

Electric vehicles (EVs) have been considered a promising technology for both reducing direct oil demand and mitigating

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greenhouse gas emissions in the road transport sector in the next half-century [1]. Major vehicle markets worldwide have issued preferential policies or established regulations to promote EVs in the past decade, such as EV demonstration programs, fleet-wide compulsory fuel economy targets or zero emission vehicle programs with credit systems, preferential tax and subsidy policies and target amounts of EV usage and access incentives [2]. The super credit, one of these incentives considered to be a favorable policy for extremely low emission vehicles, aims to promote market penetration by offering beneficial accounting rules under various fleet-wide compulsory fuel economy regulations. For instance, there are 2 super credit schemes in China's Phase IV Corporate Average Fuel Consumption (CAFC) regulation. One is for new energy vehicles (NEV), which consist of battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) with an over-50 km all electric range (AER). Another is for fuel-efficient vehicles (FEV), defined as those with a fuel consumption rate (FCR) below 2.8 L/100 km. By taking advantage of the super credit schemes, each NEV and FEV could be accounted for as 2 and 1.5 models, respectively, under the CAFC by the year 2020.

EV penetration has been remarkably accelerated by these incentives in the past 5 years. In 2016, the market share of passenger EVs reached 0.86%, and sales increased by 15 times to 774 thousand compared with 2011 [3]. Along with the dynamic automobile market in the past decade, China has also become the main contributor to this ongoing EV market explosion. In 2016, 336 thousand passenger NEVs consisting of 257 thousand passenger BEVs and 79 thousand passenger PHEVs were sold in China [4]. In Fig. 1, the left axis of the stacked column chart presents EV sales, and the right axis presents China's share in the world's EV market.

China's market share has increased remarkably during the past 5 years, accounting for 43.4% of global passenger EV sales by 2016. When electric buses are taken into consideration, the proportion reaches 53.7%.

A booming EV adoption rate is usually promoted by a series of incentives, including fiscal and nonfiscal incentives [6]. The incentives can be further categorized into regulatory incentives, direct consumer incentives, indirect consumer incentives, charging infrastructure and complementary policies [7]. Four obstacles need to be overcome to promote EV penetration, namely costs, infrastructure for recharging, consumer acceptance and the evolution of other technologies [8]. China has been promoting the development of EVs for over 20 years [9]. After 2000, China accelerated the adoption of EVs. The “EV key project” program was established in 2002 [10] and was proposed to significantly improve national EV technology. In 2009, the EV demonstration project was launched [11]. Additionally, to improve the cost competitiveness of NEVs, which are defined as BEVs, PHEVs and fuel cell vehicles (FCVs) in China, subsidies based on battery capacity were issued in 2010 [12]. This policy continued subsidizing NEVs based on AER: BEV and PHEV consumers could acquire ¥60,000 and ¥35,000, respectively, at most in 2013 [13]. Considering technological evolution and the economy of scale effect, the subsidy is phasing down to ¥33,000 and ¥18,000 respectively for BEVs and PHEVs in 2020 [14]. Based on the ownership cost compared with conventional internal combustion engine (ICE) vehicles, this subsidy scheme is assessed to be necessary for NEVs to become cost competitive [15]. Among these incentives, the subsidy policy plays a dominating role in China's NEV market penetration and powertrain options, particularly for commercial electric vehicles [16]. The results from a discrete choice experiment also show that exemption from purchase and driving restrictions has the most significant positive effect on passenger NEV acceptance in China [17].

Regulatory incentives also play a remarkably important role in the market adoption of NEVs, in addition to demonstration programs, technology projects and purchasing subsidies in China. China published the NEV development plan in 2012, in which the accumulative sales volume of NEVs was set at a target of 500,000 and 2,000,000 by 2015 and 2020, respectively [18]. To mitigate carbon dioxide emissions and reduce oil consumption by vehicles, four phases of vehicle fuel economy regulations have been issued since 2004. Vehicles failing to satisfy the FCR limits specified by the regulation cannot acquire a selling license in the domestic market [19]. Furthermore, the CAFC system was established in 2011, and vehicle models are divided into different categories based on the curb weight and specified with an FCR target [20].

Many studies have explored the effects of fiscal and nonfiscal policy incentives on improving the adoption of EV, aiming to determine the major driving factors or barriers. EV incentives are usually adopted in the phases of EV purchase and usage. Van der Steen et al. compared policy incentives in countries and found that most policies focus downstream of the EV value chain, which in the short term has paid off. However, policies on the service segment would be more effective in further introducing EVs in the long run [21]. Regarding the policies on the EV usage stage, some studies explored the impact of policies such as free parking, access to high occupancy vehicle (HOV) lanes, preferential access to registrations in vehicle purchase quota cities, etc. The impact of EV incentives on different groups of people was studied based on a state-choice experiment, and the results showed that nonfiscal measures such as free parking and access to fast bus lanes are highly valued by consumers [22]. Merksy et al. examined the effectiveness of road toll exemptions, access to bus lanes and charging infrastructure policies in Norway by using sales, policy and demographic data and a standard linear regression method. They concluded that access to charging infrastructure, adjacency to major cities and regional income are the most influential factors determining BEV sales [23]. Vehicle purchase quotas and lottery policies were taken into

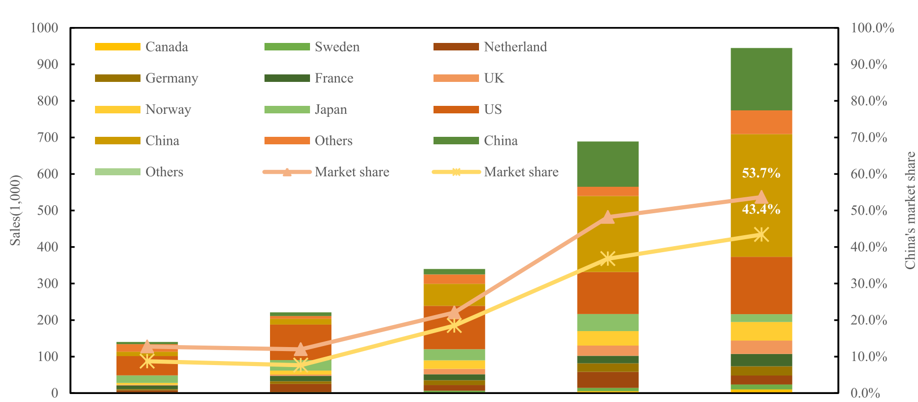


Fig. 1. Historical global EV sales data and China's market share [5].

consideration when analyzing the complex EV incentive system in China's Jing-Jin-Ji region [24]. According to a survey, registration and traffic restriction privileges for EVs in Beijing also showed a remarkable ability to promote market penetration [25]. Diao et al. quantified the intangible cost of EV privileges on driving and purchase restrictions in China and found that these preferential EV traffic and purchase policies were prominent in mega-cities [26]. Survey data of 3400 EV owners' in Norway were employed, and demographic parameters such as education, age and gender were proven influential when making BEV purchasing decisions [27]. Carley et al. also examined the factors that influenced consumer interest in EVs by survey. They found that the interest in PHEVs is greater than that in EVs and that consumers with high education and environmental sensitivity were more interested in adopting EVs [28].

The cost and energy density of batteries, which significantly affect the price and mileage of EVs, are considered to be the main barriers to promoting EVs. The impact of some technical attributes and subsidies on EV penetration were examined in some studies. Egbue and Long investigated consumers' preferences and perceptions of EVs to identify potential socio-technical barriers and found that the biggest concern for consumers was battery range [29]. Newbery and Strbac set different scenarios for battery price, discount rate, fuel and electricity price and mileage to determine the key factors determining the competitiveness of BEVs in the next decade [30]. Some studies have investigated the effectiveness of subsidies [31]. Helveston et al. developed a consumer preference model for vehicles with different powertrains and found that Chinese consumers preferred BEVs and midrange PHEVs at similar rates [32]. Masiero et al. reviewed the subsidies from China's central and local governments and explored the reasons behind the successful expansion of the EV industry by investigating the BYD case [33].

While most of the fiscal and nonfiscal EV incentives in the literature reviewed above were designed from the perspective of potential EV consumers, compulsory regulation usually affects automakers' technology roadmap decision-making directly. Therefore, automakers need to produce a certain amount of EVs to avoid violating regulations and being penalized. For instance, the zero emission vehicle (ZEV) program requires that automakers earn a proportion of ZEV credits based on sales volume by selling HEV, PHEV, BEV, FCV, etc. From 2018 to 2025, this proportion of an automaker's sales is set to increase from 4.5% to 22% [34]. Monetary support for NEVs in China is considered to be not sustainable [35]; thus, a similar NEV credit scheme was released in 2017, requiring a proportion of 12% NEV credits by 2020 [36]. These mandatory requirements would strongly promote the market penetration of EVs. The ZEV mandate received special attention when Greene et al. conducted a scenario analysis of the ZEV transition through 2050 [37]. In addition, fleet-wide Corporate Average Fuel Economy (CAFE) regulations have been issued in all major vehicle markets and will be instrumental in spurring innovation and the market penetration of alternative vehicles [38]. Some studies have investigated the effectiveness of these regulatory incentives. Under US CAFE regulations, PHEVs could contribute to compliance and effectively reduce compliance costs in the near term [39], and BEVs' market share could even reach 29% by 2030 [40]. Brown et al. explored the impact of regulation, EV certification and related training on EV adoption. They found that new adaptions of current regulation in terms of infrastructure, electricity distribution, etc., were needed [41]. Results show that implementing alternative powertrains, such as diesel, HEV and PHEV could serve as a main technology roadmap to satisfy CAFE from 2016 to 2025 [42].

With the purpose of promoting the penetration of advanced powertrains that may currently be below the cost-effective break-even point, most mandated regulations offer flexible preferential compliance options for these promising technologies. The super credit incentive did not originate in China's CAFC regulation: several similar schemes have been implemented or proposed in other mandatory fleet-targeted regulations. The multipliers of super credit schemes worldwide are shown in Fig. 2. In the EU, the super credit scheme has been implemented in two separate stages since 2012. Light-duty passenger cars (PC) with CO_2 emissions under 50 g/km could be calculated as a number ranging from 3.5 to 1 from 2012 to 2016 and 2 to 1 from 2020 to 2023 [43]. Low emission light commercial vehicles (LCV) could also use the super credit from years 2013–2018 [44]. In the US, GHG regulation is issued by the EPA and uses a multiplier incentive for CO2 emissions compliance purposes for BEVs, PHEVs and FCVs sold in model years 2017 through 2021 [45]. In China, not only are the NEVs discussed above eligible for super credit but also FEVs, which are defined as vehicles with FCR under 2.8 L/100 km. The details are presented in Table 2. Some studies have investigated the effect of super credits [46]. Katsis et al. conducted scenario analysis by assuming different EV penetration ratios and found that super credits had a decisive effect on the fleet average emissions [47]. From the life-cycle emission perspective, assigning zero emission to BEVs means ignoring energy consumption and emissions upstream. These super credit policies could erode GHG emission benefits by 20% [48]. Super credit efficiency was explored by taking electricity mix, real-world driving and traffic conditions into consideration. The results showed that super credit policy should be implemented based on the drivers' behavior, the electricity generation mix and the traffic

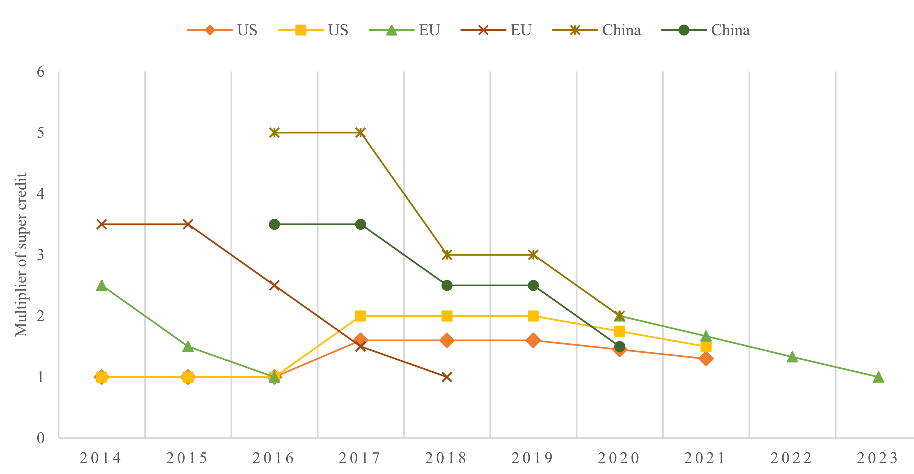


Fig. 2. The super credit policy multiplier under various regulations.

Table 1
Summary of the researches on EV incentives in this paper.

Targeting agent	Category	Research perspective	Literature
Consumers	Usage	Consumer preference and demographic groups	Langbroek, Joram HM et al., 2016 [22] Mersky, Avi Chaim et al., 2016 [23] Wang, Yunshi, et al., 2017 [35]
		Local government incentives	Zhang, Xiang, and Xue Bai, 2017 [24] Sun, Lishan et al., 2017 [25] Diao, Qinghua et al., 2016 [26] Wang, Ning, et al., 2017 [17]
	Purchasing	Central and local government incentives	Hao, Han et al., 2014 [15] Zhao,Xin et al., 2015 [31] Du, Jiuyu, and Danhua Ouyang.,2017 [16] Masiero, Gilmar et al., 2016 [33]
Automakers	Regulatory	ZEV program	Greene, David L. et al., 2014 [37]
		Fuel economy standard: fleet-wide target	Cheah, Lynette, and John Heywood., 2011 [42] Andress, David et al.,2012 [38] Al-Alawi, Baha M., and Thomas H. Bradley, 2014 [39] Sen, Burak, et al., 2017 [40]
		Fuel economy standards: super credit scheme	Lutsey, N. and Sperling, D., 2012 [48] Katsis, Petros, et al., 2014 [47] Álvarez, Roberto et al., 2015 [49]

conditions of each EU country [49].

As summarized in Table 1, most of the studies reviewed above explored the effectiveness of incentives from the consumers' perspective to identify the most influential factors determining EV adoption. Several studies have investigated the impact of regulatory incentives on EV adoption, but few have conducted quantitative studies on super credit policies. The unanswered question is whether super credit policies have an impact on the penetration of EVs and, if they do, how great an impact. Researchers have noted that super credits would cause a gap between the calculated and the actual fleet average fuel economy, which is believed to offset the fuel saving target [50]. However, studies did not take this effect into consideration when simulating the carbon footprint of PCs in China [51]. Also in Europe, this impairment effect on the actual fleet fuel economy was neglected [52]. Moreover, as presented in Table 2, the super credit multipliers are quite different under other regulations. The EU even implemented a two-stage super credit scheme. While the cost of advanced technologies is declining with learning by doing, mandated fuel economy and emission targets are strengthening yearly, and the effectiveness of a particular technology almost remains constant. A quantitative analysis of the super credit should be conducted to examine its impact in the current and upcoming regulation phases. The results could allow the super credit multiplier to be formulated more reasonably so that EVs can be promoted as policymakers' originally intended. With the aim of filling these research gaps, in this paper, from the perspective of the automakers' decision-making process, a mathematical model using combinational optimization is established to examine the impact of the super credit on EV adoption rates, CAFC target impairment and automaker's compliance costs. The following sections are organized as follows: the next section describes the mathematical model of complying with CAFC regulation from the perspective of an automaker as well as the case, data, and main assumptions in the simulated scenarios. Then, the principle of the super credit scheme is analyzed by employing the cost-effectiveness frontier method. After that, various multipliers of the NEV and FEV super credits are simulated under the CAFC target in 2020 and 2025, and the results are illustrated in terms of compliance parameters and fleet powertrain structure in section 4. Finally, some policy implications are discussed, and some recommendations for the super credit scheme are offered.

2. Materials and methods

This section serves to explain the methods, model structure, parameters and other materials in greater detail. First, China's CAFC regulation structure and the super credit policy scheme are described. Second, from the perspective of automakers, the decision-making process of fuel-efficient technology combination aiming at complying with the CAFC regulation and minimizing the incremental cost is established. Following that, subsection 2.3 defines two evaluation parameters to measure the impairment of the CAFC target and the effectiveness of the super credit policy. Finally, in subsections 2.4 and 2.5, the data resource, selected case and designed scenarios are explained.

2.1. China's Corporate Average Fuel Consumption regulation and super credit policy scheme

Under CAFC regulation, each automaker should satisfy the fleet-wide CAFC target, which is a sales weighted average of vehicle models sold domestically. The CAFC regulation is described as:

$$\begin{cases} t_j = StT(m_j) \\ T_{CAFC} = \dfrac{\sum\limits_j s_j f_j}{\sum\limits_j s_j} \\ CAFC = \dfrac{\sum\limits_j s_j t_j}{\sum\limits_j s_j w_j} \\ CAFC \le T_{CAFC} \end{cases} . \quad (1)$$

Table 2
Super credit schemes under various regulations.

Region	US		EU		China	
Regulation	GHG regulation		CO2 Emission regulation		CAFC regulation	
Vehicle type	PHEV	BEV, FCV	PC	LCV	BEV, FCV, PHEV	FEV
Eligibility	AER>10.2mile	/	Under 50g/km	Under 50g/km	AER>50 km for PHEV	FCR<2.8 L/100 km
Preferential accounting	0g/mile (electric portion)		None		0 L/100 km (electric portion)	

where t_j and f_j are the FCR target and FCR of vehicle version j, respectively. s_j is the sales of a vehicle version. w_j is the CAFC calculation multiplier, which will be further discussed below. t_j is determined by the step function $StT(m_j)$ according to its curb weight. $CAFC$ and T_{CAFC} are the CAFC and CAFC target of the automaker, respectively. The nationwide FCR target is 5.0 L/100 km in 2020, and the CAFC target of each automaker varies with the curb weight of its vehicle products. It is estimated that with the CAFC system playing an essential role, the impact of fast-growing passenger vehicle ownership on energy consumption and GHG emissions could be effectively offset [53]. However, because the CAFC targets in 2020 and beyond are formidable for automakers, especially automakers with large size and high curb weight vehicles, BEVs and PHEVs with notable fuel economy improvement are indispensable technology roadmaps to comply with future regulations, which will promote the development and adoption of NEVs among automakers considerably.

In this CAFC system, two other regulatory incentives also contribute to the adoption of NEVs. The Phase IV regulation specifies that electricity consumed by NEVs should not be transferred into the conventional energy format and calculated into FCR. This means that the test cycle with half hybrid and half AER for PHEVs could lead to over 60% off the FCR result without calculating the electricity consumption in the AER portion. For BEVs and FCVs, the FCR is marked as zero. In addition, another regulatory incentive, super credit, is also applied to NEVs. As described in Equation (1), w_j is the CAFC calculation multiplier specified by the regulation. This multiplier for BEVs, FCVs and PHEVs with over 50 km AER are 5, 3 and 2 in 2016–2017, 2018–2019 and 2020, respectively. For conventional ICE vehicles, the multiplier is 1 [54].

2.2. Automaker decision-making framework

For automakers under CAFC regulation, selecting a portfolio of fuel-efficient technologies to implement in their vehicle products is defined as the technology combination (TC) problem. Several constraints should be satisfied when making strategic technology decisions, namely, regulatory constraints and technology compatibility constraints. Meanwhile, the automaker's target should be optimized. In this case, the target of the automaker is to minimize the incremental cost of complying with the regulation. Therefore, considering an automaker with n vehicle versions in this market and m feasible fuel-efficient technologies, the decision-making framework at time t could be formulated as :

$$\min \sum_t \sum_{j=1}^{n} s_{j,t} \sum_{i=1}^{m} (\tilde{x}_{i,j,0} - x_{i,j,t}) c_{i,t} \tag{2}$$

subject to:

- CAFC constraint
- FCR limit
- Technology compatibility

where $x_{i,j,t} \in \{0, 1\}$ is the implementation state of fuel-efficient technology$i$ in vehicle version j, while $\tilde{x}_{i,j,0}$ is the initial technology implementation state. $c_{i,t}$ is the incremental cost of technology i at time t. The cost of technologies follows various decreasing patterns determined by learning curves. Learning curves for conventional and relatively mature technologies such as turbocharging, gasoline direct injection, etc., are flatter than novel and promising technologies such as BEVs, PHEVs, etc. [55]. $s_{j,t}$ is the sales of vehicle version j.

There are three main constraints when optimizing the objective function. The first is the CAFC constraint. The fleet-wide CAFC of an automaker cannot be over the CAFC target, which is calculated by the individual FCR target based on vehicle curb weight, as described in Equation (1). Another constraint is the FCR limit constraint. The FCR limit value is higher than the FCR target value. A vehicle version with an FCR between the FCR target and FCR limit is permitted to be sold in the market as long as the automaker satisfies the CAFC constraint, while vehicle versions violating the FCR limit cannot enter the domestic market. Thus, this constraint is described as:

$$f_j \le l_j = StL(m_j) \tag{3}$$

where l_j is the FCR limit of vehicle version j determined by the regulation with a step function $StL(m_j)$. The last constraint is the technology compatibility constraint. Technologies from the same category, for example, automatic transmission (AT) and continuously variable transmission (CVT), cannot be implemented on one vehicle concurrently. Technologies that are only compatible with each particular powertrain and technologies with significant overlap in the FCR reduction potential are assumed to be incompatible as well. Thus, the constraint is formulated as:

$$x_{\alpha,j} + x_{\beta,j} \le 1 \tag{4}$$

where α and β are incompatible technologies. TC is a combinational optimization problem and could also prove nondeterministic polynomial-time hard (NP-hard) by restricting it to the 0–1 knapsack problem [56]. Therefore, unless P=NP, it is unlikely that an efficient polynomial algorithm can be found to solve it optimally. Heuristic algorithms are appropriate for solving it. In particular, a genetic algorithm is developed in this study.

2.3. Evaluation parameters

A super credit policy with a preferential multiplier would lead to the dilution of calculated CAFC. Therefore, the actual CAFC would be higher than the calculated CAFC, which impairs the energy saving target. The impairment can be defined by the ratio of the gap between calculated CAFC and actual CAFC to that under the baseline scenario, as presented in Equation (5)

$$r_I = \frac{CAFC_a - CAFC_c}{CAFC_{in} - T_{CAFC}} \tag{5}$$

where $CAFC_{in}CAFC_a$, and $CAFC_c$ are the initial, actual and calculated CAFC after implementing the technologies, respectively. r_I is the impairment ratio. To illustrate the effect of promoting advanced technologies at the cost of CAFC target impairment, an effectiveness factor is defined as Equation (6)

$$EF_w = \frac{p_w - p_b}{r_I} \tag{6}$$

where p_w and p_b are the proportions of the policy targeting technology under the super credit and baseline scenarios. $EF_w$is the effectiveness factor. PHEVs and BEVs are the targeted technologies of the NEV super credit policy, while HEVs and advanced diesel are defined as the targeted technologies of the FEV super credit policy.

2.4. Case and data input

Because fuel economy regulations are usually issued 4–8 years before the final fleet-wide target comes into effect, and vehicle re-engineering and redesign usually spans 4–6 years, automakers begin product planning 4–6 years before vehicle models finally launch. In this study, a representative automaker with intermediate sales volume is selected. The strategic planning time horizon is 5 years before the 2020 target finalizes; thus, the fleet parameters of model year 2015 are collected as a benchmark. The total sales in 2015 is approximately 580,000 in China. The vehicle products cover from subcompact cars to full-size sedans. The main input data in this research is about the attributes of fuel efficient technologies, which consists of curb weight effect, fuel consumption reduction effect and the incremental cost for each technology. The curb weight effect reflects the physical weight of each technology or the mass reduction effect of light-weighting and downsizing technologies [57]. Fuel consumption reduction effect accounts for the fuel saving potential of each technology relative to the baseline model [58]. And the incremental cost includes direct manufacturing cost and indirect cost [51]. The data is collected from several peer-reviewed reports published by US National Research Council and German Federal Ministry for Economic Affairs and Energy. In this case, 36 vehicle versions under 8 vehicle models as well as 54 fuel-efficient technologies are taken into account.

2.5. Scenario assumptions

Both the FEV and NEV super credit scenarios are assumed in the model year 2020 and 2025. In particular, the next phase of the CAFC standard is assumed to be fully phased in by 2025, with a national fleet-wide average FCR target of 4.0 L/100 km. Considering technology's evolution and learning effect, the incremental cost of technology is developed by using learning factors [51]. To maintain the comparability of these 2 time points, the product structure and sales of each vehicle model and version are assumed to remain the same. In addition, as experience goes, different vehicle versions sharing one vehicle model implement the same powertrain configuration when searching for feasible solutions for TCs. Different vehicle versions can be implemented with different technologies for the transmission and accessory fuel-efficient technologies. According to China's NEV definition, two technologies, PHEVs and BEVs, are super credit beneficial technologies. The AER of PHEVs is set at 60 km, while the AER of BEVs is set at 160 km and 240 km in 2020 and 2025, respectively, in accordance with battery development and cost reduction. In both policy scenarios, the FEV and NEV super credit multipliers are set from 1 to 6 at intervals of 0.5. Table 3 presents the parameters set for these various scenarios.

3. Theoretical analysis of super credit scheme

This section provides a theoretical analysis on the consequences and costs of this super credit policy. In section 3.1, a parameter is derived to measure the policy's effect on compliance cost reduction, allowing a better understanding of what the determining factors of compliance cost are and which technology policymakers should target. By fitting the cost-effectiveness frontier curve in section 3.1, the principles of FEV and NEV super credit as well as the consequence of CAFC target impairment are further explained.

3.1. Impact on compliance cost

The super credit policy scheme was initially designed to help promising technologies reach the breakeven point: compliance costs are reduced when using these technologies under a super credit scheme to spur market penetration. To analyze the impact of super credit policies on compliance costs, a simple model is established. Given a manufacturer with only one vehicle model product and one technology eligible for the super credit policy, of which the FCR reduction effect and incremental cost are respectively e_{sc} and c_{sc}, three assumptions are made. First, technology implementation does not change a vehicle model's curb weight, so that the CAFC target does not change before and after. Second, production volume is continuous, so that vehicles using super credit preferential technology can be partitioned continuously. Third, the technology implementation state does not change except for the proportion using super credit technology. Based on Equation (1), these parameters are derived as

$$\begin{cases} CAFC_0 = \dfrac{f\cdot\prod\limits_i(1-x_{i,0}e_i)[(1-e_{sc})p_0+(1-p_0)]\cdot s}{p_0 s+(1-p_0)s} \\ CAFC_{sc} = \dfrac{f\cdot\prod\limits_i(1-x_{i,sc}e_i)[(1-e_{sc})p_{sc}+(1-p_{sc})]\cdot s}{w_{sc}p_{sc}s+(1-p_{sc})s} \\ T_{CAFC_0} = T_{CAFC_{sc}} \\ r_C = \dfrac{C_{sc}}{C_0} = \dfrac{\sum\limits_i x_{i,sc}c_i+p_{sc}c_{sc}}{\sum\limits_i x_{i,0}c_i+p_0 c_{sc}} \end{cases}, \tag{7}$$

where the subscripts 0 and sc represent two scenarios with and without the super credit policy, respectively. f is the FCR of the vehicle model $e_i \in (0,1]$. and c_i are the FCR reduction effect and the cost of technology i. $x_{i,0}, x_{i,sc} \in \{0,1\}$ are the implementation states of technology i. p_0 and p_{sc} are the proportions of production using super credit-eligible technology. r_C represents the total cost reduction ratio, and C_{sc} and C_0 are the total compliance cost under the two scenarios. w_{sc} is the calculation multiplier of the super credit policy. According to the assumptions made above, denote the total cost of conventional fuel-efficient technologies as $\sum\limits_i x_{i,0}c_i = \sum\limits_i x_{i,sc}c_i = TC_{con}$. Equation (7) can be further transformed into Equation (8).

$$r_C = \frac{TC_{con} + \frac{e_{sc}p_0}{w_{sc}(1-e_{sc}p_0)+e_{sc}(1+p_0)-1}\cdot c_{sc}}{TC_{con}+p_0 c_{sc}} \tag{8}$$

Three factors determine the cost reduction under the super credit scheme, namely, attributes of the eligible technologies, super credit scheme specifications and stringency of the CAFC regulation. $TC_{con}$and p_0 reflect the stringency of the CAFC regulation. If the CAFC regulation is strengthened over time, the total cost using conventional technologies and the proportion using the promising costly technologies will increase even without a super credit scheme. w_{sc}, e_{sc}, and c_{sc} account for the impact of scheme specification and technology attributes on cost reduction. $\frac{\partial r_C}{\partial w_{sc}}$, $\frac{\partial r_C}{\partial e_{sc}}$ and $\frac{\partial r_C}{\partial c_{sc}}$ can be derived as constantly negative, positive and negative. Therefore, when w_{sc} and c_{sc} increase or e_{sc} decreases, the cost

Table 3
Assumptions and settings of various scenarios.

Super credit scheme	Targeted Vehicles	Targeted technologies	Super credit multipliers	Year	CAFC target	AER of BEV
NEV	BEV and PHEV	BEV and PHEV	{1.5,2,2.5,3,3.5,4,4.5,5,5.5,6}	2020	5 L/100 km	160 km
				2025	4 L/100 km	240 km
FEV	Any vehicle with FCR<2.8 L/100 km	HEV and other highly fuel-efficient technologies	{1.5,2,2.5,3,3.5,4,4.5,5,5.5,6}	2020	5 L/100 km	160 km
				2025	4 L/100 km	240 km

reduction ratio decreases.

Outside of a great technology breakthrough, e_{sc} would mostly remain the same over time. Nevertheless, w_{sc} is set by policymakers, and c_{sc} could also change over time as a consequence of learning by doing and economies of scale. Because of the assumption that the portfolio of conventional technologies does not change, if p_0 is zero under less stringent regulation phases, r_C remains 1.

To illustrate the effects of c_{sc} and w_{sc} on r_C, r_C results under the CAFC target of 3 L/100 km (potentially in 2030) are simulated, where p_0 is not zero. TC_{con} and p_0 are set using the benchmark results of the selected case. The results are illustrated in Fig. 3.

As shown in Fig. 3, r_C decreases from 1 to 0.76 given $w_{sc} \in [1, 10]$ and $c_{sc} \in [50000, 100000]$. As $\frac{\partial^2 r_C}{\partial w_{sc}^2}$ is positive, r_C declines rapidly when w_{sc} is small. The increase of c_{sc} also contributes notably to the cost reduction. Thus, the more super credit policies target high cost technologies, the more costs can be reduced when eligible technologies are used. Note that under the assumptions described above, the cost reduction effect would be underestimated. First, implementing advanced technologies usually leads to an increase in vehicle curb weight; then, CAFC target increases under the curb weight-based FCR target function, which would further decrease the compliance cost. Second, holding the implementation state of conventional technologies constant would restrict the solution domain considerably. As super credit policies cut down on the relative equivalent cost of those advanced technologies, automakers would use conventional technologies less and policy-eligible technologies more often. Thus, relaxing this assumption would further decrease r_C.

3.2. Cost-effectiveness frontier analysis

By taking technology incompatibilities into consideration, over 81.8 million TCs are generated. Note that some technologies may overlap in terms of fuel FCR reduction potential, so they are assumed to be incompatible in the real-world decision-making process. In this frontier deriving process, the effect of overlapping is not taken into consideration.

The cost and FCR reduction effect attributes of these combinations are compared using the cost-effectiveness method. TCs with a higher cost are eliminated from the set at each level of FCR reduction potential. Finally, the combination set is cut down from 81.8 million to 1142 throughout all feasible FCR reduction effects. The remaining TCs are defined as the cost-effectiveness frontier, which defines the boundary at which the greatest FCR reduction is achieved with the least incremental cost, as presented in Fig. 4. The blue points are the most cost-effective TCs. The yellow crossings, many of which overlap with the blue points, illustrate the cost-effectiveness frontier of the combinations including PHEV. By employing polynomial curve fitting, combinations are fitted into the conventional technology frontier and the PHEV frontier curves, as shown by the green and red lines.

For a benchmark vehicle model, this frontier also represents the best technology roadmap to follow to satisfy the regulation despite technology accessibility. The cost leaps when less cost-effective technology enters the combination. Based on the dataset, lightweighting technologies are discrete in mass reduction; thus, the cost leaps when 15%, 20% and 25% mass reduction enter the combination. The red dot illustrates the initial technology implementation state of the selected case. All vehicle models and versions are reversed backward to the benchmark state and then compared with the current state. The results show that the current technology implementation state is above the cost-effectiveness frontier. In other words, under the condition that all fuel-efficient technologies in our dataset are accessible to this automaker, greater FCR reduction could be achieved by switching to more cost-effective technologies without increasing the cost.

As the PHEV cost-effectiveness frontier shows, if PHEVs are essential in the combination, this frontier represents the best technology roadmap to follow. The crossings that do not overlap with blue points are not cost-effective in the total search domain. Therefore, these points are eliminated and could not even be considered without a super credit policy. TCs at the cost-effectiveness frontier are divided into two parts: combinations with and without PHEV.

Taking PHEV, a super credit-eligible technology, as an example, Fig. 5 illustrates the principle of a NEV super credit under China's super credit policy. To apply the fitted cost-effectiveness frontier curve, all vehicle models and versions produced by our selected automaker are reversed backward to the benchmark model. The benchmark CAFC, where no fuel-efficient technology is used on any of the models in the fleet, is calculated and set as the initial CAFC state. The cost and CAFC are calculated when the fleet is entirely implemented with TCs at the conventional and PHEV cost-effectiveness frontier curves, as the red and blue lines shown in Fig. 5. To take advantage of the super credit policy, a portion of vehicles would use PHEV technology and acquire super credit while leaving others at the conventional technology frontier. Assume that the number of vehicles in the fleet is continuous and can be divided into two parts: vehicles that implement super credit-eligible technologies and those that do not. In this case, vehicles using PHEV technology would be at the PHEV frontier and those using

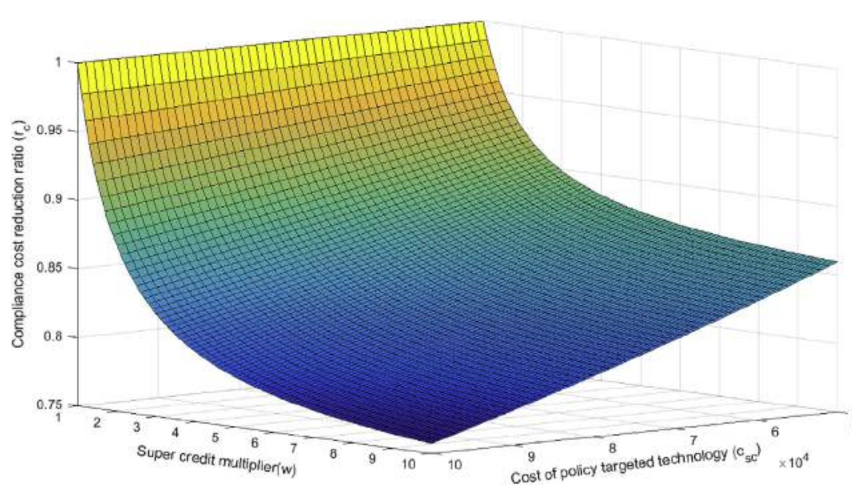


Fig. 3. Cost reduction effect on the eligible technology cost and super credit multiplier.

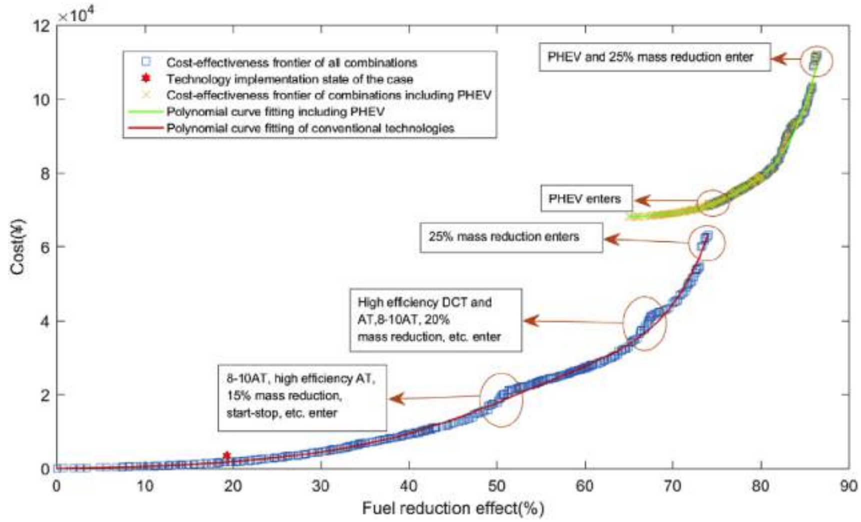


Fig. 4. Cost-effectiveness frontier of feasible technology combinations.

conventional technology at the conventional frontier. Given one technology implementation state at each frontier, $(CAFC_{con}, C_{con})$ and $(CAFC_{PHEV}, C_{PHEV})$, respectively, and the proportion at the PHEV frontier p, the total cost C and $CAFC$ after the decision-making could be derived as

$$\begin{cases} C = (1-p)\cdot C_{con} + p\cdot C_{PHEV} \\ CAFC = \dfrac{(1-p)\cdot CAFC_{con} + p\cdot CAFC_{PHEV}}{w\cdot p + (1-p)} \end{cases} \tag{9}$$

where w is the super credit multiplier.

Given $p \in [0, 1]$, the green line in Fig. 5 presents the linear feasible solution results for cost and CAFC when no super credit policy is formulated and $w = 1$. Other solid lines connecting the $(CAFC_{con}, C_{con})$ and C_{PHEV} dashed lines stand for the scenarios when various super credit multipliers are used.

To satisfy the CAFC target, the minimum incremental cost is the cost at the intersection of the green and the dashed yellow lines, which is notably higher than that at the intersection with the blue frontier curve. Therefore, if no super credit policy is issued, any portion of vehicles using TCs at any point on the PHEV frontier curve would achieve a higher cost intersection with the CAFC target line. The optimal decision is to follow the conventional technology frontier curve to minimize the incremental cost. Holding these two points fixed, the feasible solution curve shifts towards the left side as w increases, while the cost of the intersection with the CAFC target line decreases. Under super credit policies, when the super credit multiplier is sufficiently high to drop the optimal cost of using a combination of policy targeting technology and conventional technology below the cost at the conventional technology frontier curve, the intention in promoting the technology is fulfilled. In this case, when $w = 3, 4, 5, 6$, the cost is lower. In addition, the horizontal gaps between the green benchmark line and the other feasible solution lines represent the gap between the calculated CAFC under the super credit policy and the actual CAFC. The higher the super credit multiplier, the wider the gap between calculated and actual CAFC.

Fig. 6 illustrates the principle of FEV super credit. The points at the frontier curve to the left of the red dashed line, which defines the 2.8 L/100 km threshold, are eligible for FEV super credit policies. To take advantage of this policy, a portion of vehicles need to be

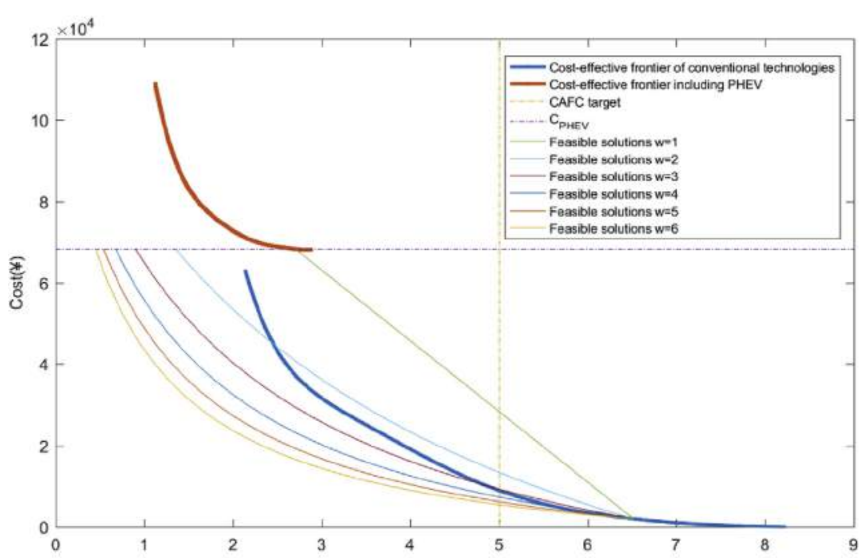


Fig. 5. The principle of the NEV super credit policy.

designed with FCR to the left of the threshold line. Analogously, the given line shows the linear feasible solution results when no super credit policy is formulated and $w = 1$.

The compliance attributes follow analogous patterns under the FEV super credit. Compared with the NEV super credit policy, the optimal cost decreases more rapidly. Additionally, using the same multiplier, the same calculated CAFC could be arrived at under the FEV super credit policy at a much lower compliance cost.

4. Simulation results

If the automaker produces only one model, the optimal cost could be achieved by searching two points along the frontier curves to acquire a cost at the intersection of the feasible solution curve and the CAFC target line that is lower than that at the conventional technology frontier curve. However, in the real world, an automaker usually produces a variety of vehicle models and versions. Production volume cannot be continuously partitioned to be implemented with several different powertrains. These features increase the difficulty in making strategic decisions while satisfying the CAFC regulation. A genetic algorithm is employed to solve the portfolio of technologies that minimize the compliance cost under the assumed multiplier of super credit scenarios, and the results are presented in this section.

4.1. Compliance parameters

The results for the compliance parameters of the NEV super credit policy scenarios under 2020 and the assumed 2025 CAFC regulations are presented in Fig. 7. The multipliers of various NEV super credit scenarios are set from 1 to 6 at intervals of 0.5. In Fig. 7, the left axis shows the initial CAFC before the optimization, the actual and calculated CAFC after the optimization and the CAFC target. The right axis shows the compliance cost reduction trend of the solid red line.

As shown in Fig. 7 (a), in the 2020 NEV super credit scenario, the compliance cost declines by 70.9% from ¥7435 to ¥2163 as the super credit multiplier increases to 6. On the other hand, the increase in the multiplier dilutes the calculated CAFC and leads to an increase in the actual CAFC. The actual CAFC for complying with the regulation increases from 5.14 L/100 km to 6.35 L/100 km while the CAFC target remains almost unchanged, which impairs the fleet-wide fuel saving target from 4.5% to 81.0% as the multiplier increases from 2 to 6. Because of the assumption concerning powertrain compatibility that all production under one vehicle model needs to be entirely converted to another powertrain, an automaker needs to produce a minimum volume of vehicles equipped with super credit-eligible powertrains to take advantage of the super credit policy. Therefore, if the super credit multiplier is not high enough to achieve a benefit from this policy, the automaker would disregard this policy and follow the conventional technology roadmap. In the 2020 NEV super credit policy scenario, the compliance cost and actual CAFC remain almost the same when the multiplier $w = 1, 1.5, 2$.

As shown in Fig. 7 (b), in the 2025 NEV scenario, the conventional technologies implemented to satisfy the 2025 CAFC target are less cost-effective than those in the 2020 scenario. Thus, even when the multiplier is small, the cost of replacing conventional technology with advanced powertrains is less than the cost saving benefit achieved by diluting the calculated CAFC. Compliance cost decreases by 42.5% from ¥19951 to ¥11479. More conventional technologies that add curb weight are implemented when following conventional roadmaps to comply with CAFC targets in 2025. Thus, under the NEV super credit policy in 2025, although a small portion of vehicles implemented with PHEV powertrains may see an increase in curb weight, more conventional technologies will be removed from the fleet. This effect leads to a fleet-wide curb weight decrease and consequently strengthens the CAFC target indirectly. As presented in Fig. 7 (b), while the CAFC target decreases from 4.19 to 4.09 L/100 km, the actual CAFC increases from 4.19 to 5.01 L/100 km, impairing the energy saving target by 36.5% as the super credit multiplier increases.

Fig. 8 (a) and 8 (b) present FEV super credit policy scenarios in 2020 and 2025. The multipliers of the various FEV super credit scenarios are set from 1 to 6 at intervals of 0.5. In Fig. 8, the left axis shows the initial CAFC before the optimization, the actual and calculated CAFC after the optimization and the CAFC target. The right axis shows the compliance cost reduction trend of the solid red line.

Along with the increase in the super credit multiplier, the decline in the compliance cost flattens, which is similar to the pattern of the conventional frontier curve in Fig. 6. As the multiplier increases, the calculated CAFC is diluted, and conventional technologies are removed in order from the least to the most cost-effective. As shown in Fig. 8 (a), in 2020, the compliance cost decreases from ¥ 7436 to ¥ −852, while the actual CAFC needed to satisfy the regulation increases from 5.14 to 6.64 L/100 km, which

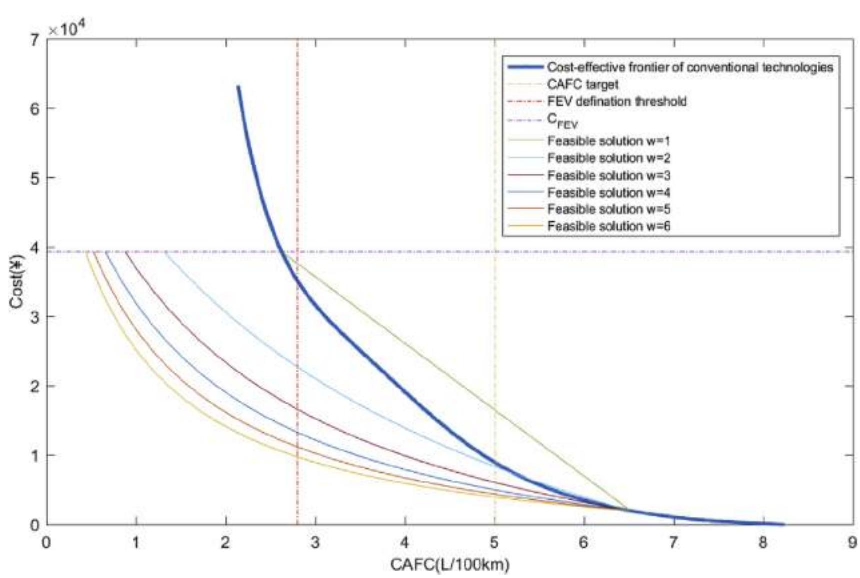


Fig. 6. The principle of the FEV super credit policy.

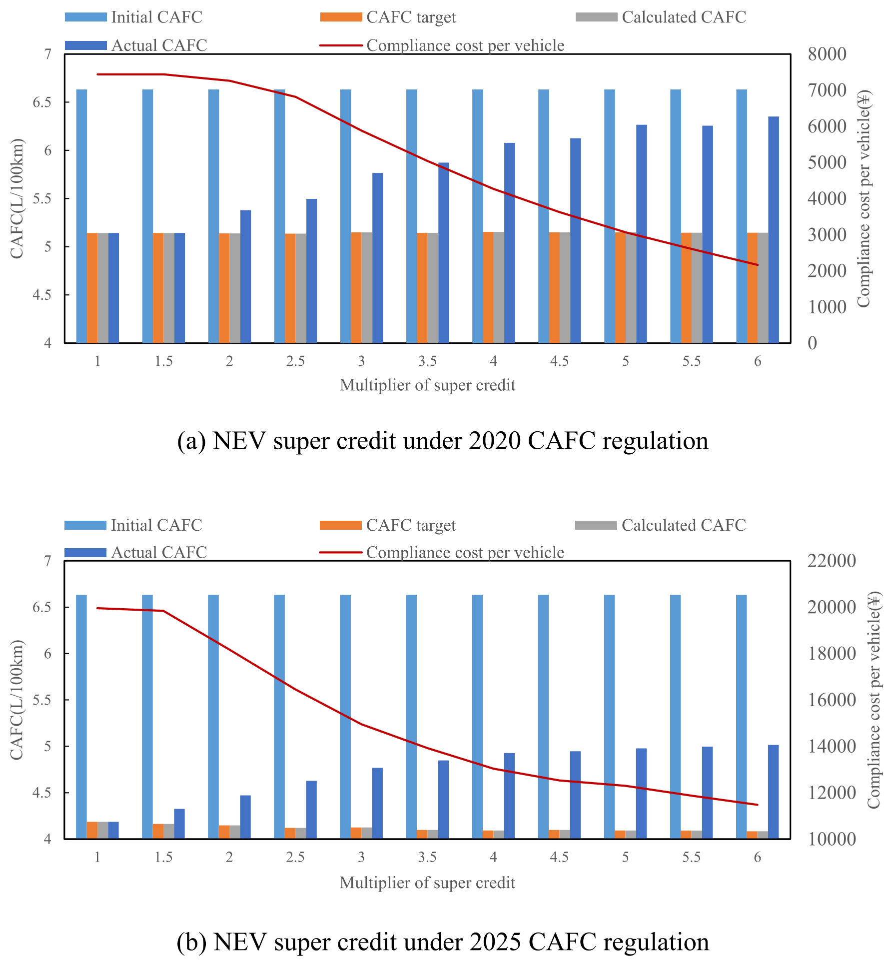


Fig. 7. Compliance parameters under various NEV super credit scenarios.

impairs the CAFC target by 11.6%–100.8%.

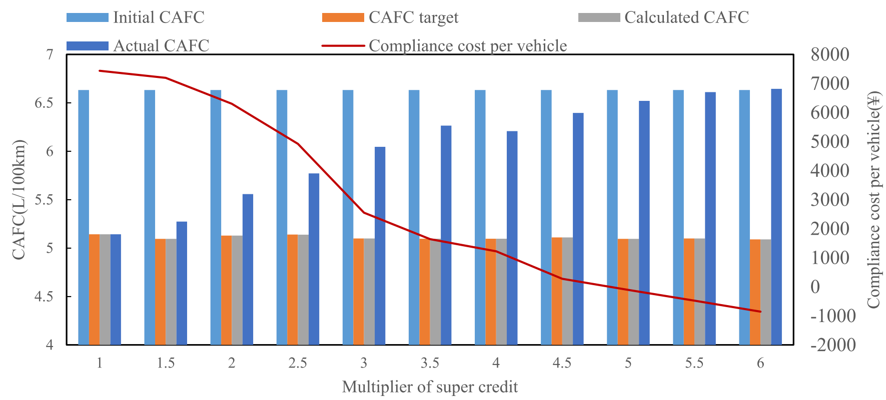
In 2025, the compliance cost decreased by 52.3% from ¥19951 to ¥9506, while the actual CAFC increased from 4.19 to 5.10 L/100 km, which impairs the CAFC improvement target by 14.4%–40.3%. According to Equation (9), to acquire the same calculated CAFC, a less fuel-efficient policy-eligible technology would need to represent a higher proportion $p \in [0, 1]$, which further dilutes the calculated CAFC and in turn further weakens the CAFC target. Additionally, if both NEV and FEV policies are issued at the same level as the super credit multiplier, implementing PHEVs and BEVs would generally lead to an FCR far below the FEV definition threshold, which is 2.8 L/100 km throughout 2020. As a result, it will cost more than simply following conventional technology roadmaps to take advantage of the FEV super credit. Therefore, in comparison with the effects of the NEV super credit, the FEV super credit policy brings greater cost reduction and greater CAFC target impairment.

4.2. Powertrain structure of the vehicle fleet

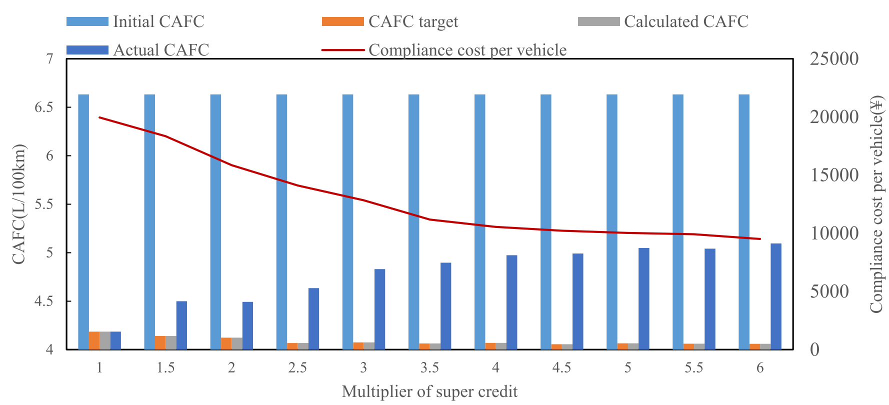
Figs. 9 and 10 illustrate the proportion of different powertrains in the fleet as the NEV and FEV super credit multiplier increases. The overall trend can be observed under the 4 scenarios as the super credit multiplier increases. Some fluctuations in fleet proportions also exist due to the assumption that a vehicle model must convert to another powertrain entirely and the assumption that the sale and product structure of each model remain the same.

As shown in Fig. 9 (a) and (b), under both NEV scenarios for the 2020 and 2025 CAFC targets, BEVs do not account for any proportion in the fleet, which contradicts the intention of the NEV super credit policy. However, PHEVs assume the lead position and benefit from this policy. Under the 2020 CAFC target, the PHEV powertrain enters the fleet when the multiplier increases to 2 and peaks at a 6.0% proportion when the multiplier is 2.5. Under the more stringent 2025 CAFC target, PHEVs enter the fleet as soon as the super credit policy takes effect and peak at 8.2%, again when the multiplier is 2.5. HEV technology plays an important role in satisfying the regulation throughout all super credit multiplier scenarios. Nevertheless, as the super credit multiplier increases, the effect of diluting the calculated CAFC dominates compliance with the CAFC target, and the proportion of PHEVs decline. Note that the AER of BEVs in 2020 and 2025 are assumed to be 160 km and 240 km, respectively. The cost reduction rate for the BEV battery is still not sufficient to satisfy the AER expectation or lead BEVs to outweigh PHEVs in terms of cost-effectiveness.

As illustrated in Fig. 10, under FEV super credit scenarios, neither PHEVs nor BEVs enter the fleet under 2020 or 2025 CAFC targets. In 2020, FEV super credit policy promotes the penetration of technologies that are capable of bringing the FCR of one model down to the FEV definition threshold, 2.8 L/100 km. Advanced diesel and HEV technologies benefit the most from the FEV super credit. The proportion of diesel and HEV powertrains peaks at 9.3% when $w = 2, 2.5, 3$. In 2025, the FEV super credit policy did not promote the penetration of advanced technologies beyond diluting the calculated CAFC and reducing compliance costs. The proportion of HEVs in the fleet decreases continuously as the super credit multiplier increases.



(a) FEV super credit under 2020 CAFC regulation



(b) FEV super credit under 2025 CAFC regulation

Fig. 8. Compliance parameters under various FEV super credit scenarios.

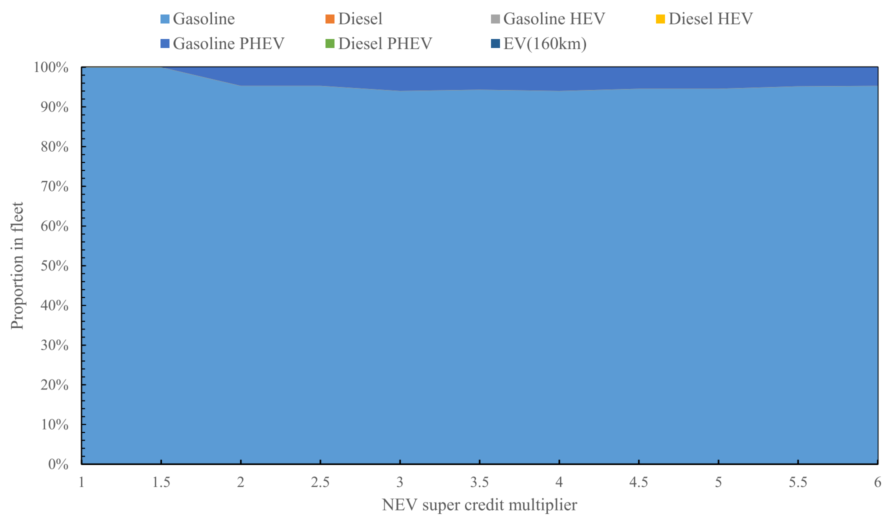
4.3. The effectiveness factor of super credit policy

As defined in Equation (6), Fig. 11 illustrates the effectiveness factor EF_W under the assumed multipliers for the super credit scenarios in the selected case. Because the NEV proportions under the 2020 CAFC target with the multipliers of 1 and 1.5 are zero, the NEV effectiveness factor starts at a multiplier of 2. EF_W decreases from 1.19 to 0.12 as the NEV super credit multiplier increases from 2 to 6. That is, the NEV proportion increases from 1.19% to 0.12% per 1% of CAFC impairment. Under the 2020 FEV and 2025 NEV scenarios, EF_W decreases from 0.60 to 0.06 and from 0.29 to 0.06, respectively. Because the FEV super credit policy actually decreases the market share of the targeted technologiesEF_W, it is negative under the 2025 FEV scenario, which is not presented in Fig. 11.

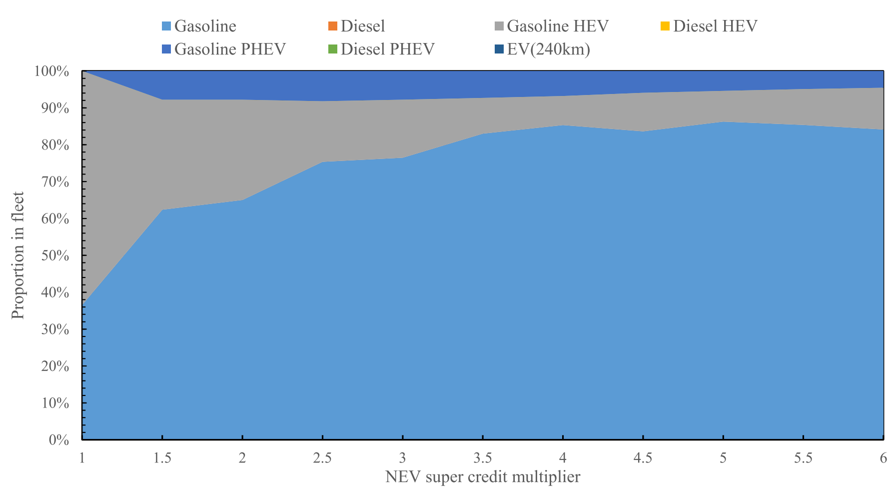
5. Policy implications

As shown in the analysis and simulation conducted and discussed above, adopting different super credit multipliers leads to two main effects. One is the accelerated market penetration of policy targeting technologies, which could be defined by the proportion difference between the baseline and that under the super credit multiplier. Another is the dilution of calculated CAFC, which will lead to impairment of the energy saving target. As presented in Fig. 9, in 2020, the optimal multipliers for the FEV and NEV super credit are 1.5 and 2, respectively. In 2025, the optimal multiplier for the NEV super credit is 1.5. Regarding the FEV super credit in 2025, the optimal super credit multiplier is 1 because the baseline leads to the highest technology penetration ratio without impairing the CAFC energy saving target. In other words, no FEV super credit policy is needed to promote these targeted technologies in 2025.

However, the NEV super credit policy is not effective in promoting BEVs in this selected case. The results demonstrate that using the same super credit multiplier, BEVs are still not more cost-effective than PHEVs. Researchers have found that promoting the electrification of PCs at lower cost and risk requires a balanced mix of BEVs and PHEVs [59]. Because the long-term goal of the policy is to promote BEVs to green the passenger vehicle fleet, several measures could be taken to modify this discrepancy. First, the super credit multiplier could be formulated separately for PHEVs and BEVs. Policymakers could define a ratio for the multiplier between these two powertrain types to balance the targeted proportion of each powertrain in the fleet. The main cost of BEVs is the battery cost, and its cost reduction rate is still highly uncertain owing to technology development or even technology breakthroughs. This ratio should be dynamically issued and adjusted 3–5 years before it takes effect based on an updated battery cost reduction rate. Second, subsidies could continue to be implemented until the cost of BEVs becomes competitive. China is phasing out the NEV subsidy throughout Phase IV CAFC regulation. By 2020, the subsidy from the national government on BEVs would decrease by 40% from the peak of ¥55,000 in 2016 to ¥33,000 [14], while subsidies from the local government would decrease from ¥55,000 in 2016 to at most ¥16,500 in 2020 [60]. China is also planning to cease NEV subsidies after 2020. Under the battery cost reduction rate in our case, policymakers should continue subsidizing BEVs to guarantee that they



(a) NEV super credit under 2020 CAFC regulation



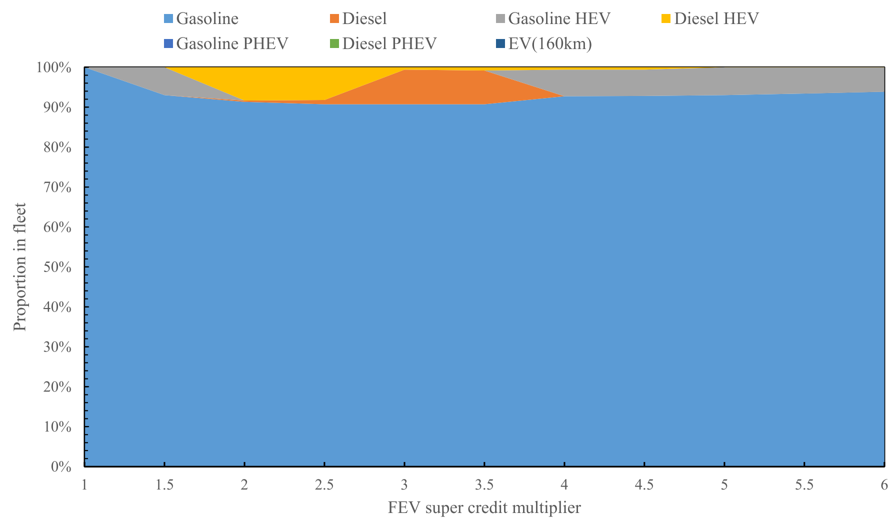
(b) NEV super credit under 2025 CAFC regulation

Fig. 9. Powertrain structure under NEV super credit scenarios.

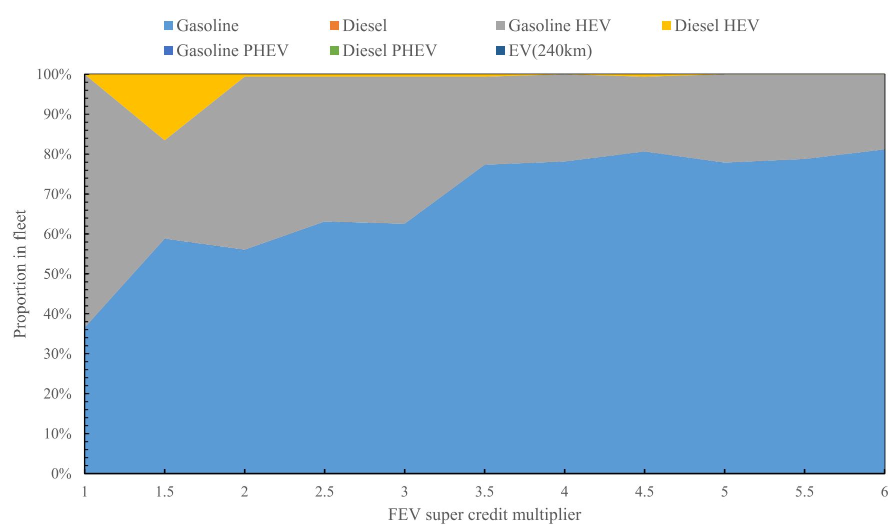
will achieve the targeted proportion in the fleet both in 2020 and 2025. Third, the inferior competitiveness of BEVs compared to PHEVs is conditional on the assumption that the AER of BEVs in 2020 and 2025 are 160 km and 240 km, respectively. Nevertheless, constructing more BEV chargers, charging stations and battery changing stations could reduce consumers' anxiety about AER, which would reduce the AER expectations and the BEV battery cost. Finally, BEV preferential policies could be implemented and quantified. Many policies, for example, free BEV plate registration in plate auction or lottery cities, free parking for BEVs, access to restricted areas in cities, access to HOV lanes, etc., also play a vital role in promoting BEVs. Some of these policies affecting the vehicle purchase and usage phases could be quantified and added into the vehicle equivalent total cost. After quantifying and combining these policies with the super credit, the market shares of BEVs and PHEVs could be more precisely promoted without much sacrifice of the CAFC energy saving target.

As for the FEV super credit policy aiming to promote advanced fuel-efficient technologies, its effectiveness depends on the CAFC target. In the short term, through the 2020 5.0 L/100 km CAFC target, little effects could be achieved at the cost of impairing energy saving target. In the mid to long term through the 2025 4.0 L/100 km CAFC target, the FEV super credit policy would even make a negative contribution to both advanced technology promotion and the CAFC energy saving goal. There are two reasons for this. First, the strengthened CAFC targets in the next phase are promoting less cost-effective but more fuel-efficient technologies. In comparison with the proportion of advanced technologies under the 2020 CAFC target, the proportion of HEVs in 2025 increases to 63.4% even without the FEV super credit policy. The only changed incentive between these two baseline scenarios is the strengthened 4.0 L/100 km CAFC target. Second, compared with the 4.0 L/100 km fleet-wide FCR target, the FEV definition threshold of 2.8 L/100 km is no longer sufficiently fuel-efficient. The FCR distribution of the fleet is illustrated in Fig. 12. The left axis shows the proportion of each FCR bin, and the right axis shows the accumulated proportion.

As shown in Fig. 12, to comply with the 2025 CAFC target under the baseline scenario, 32% of vehicles' FCR must be under 4.0 L/100 km. These models could be readily implemented with more fuel-efficient technologies so that the 2.8 L/100 km FEV definition is satisfied and the super credit benefit is obtained. Then, the calculated CAFC is diluted, so that less advanced technologies are needed to meet the CAFC. Therefore, the FEV super credit policy would impair both the penetration of advanced technology and the energy



(a) FEV super credit under 2020 CAFC regulation



(b) FEV super credit under 2025 CAFC regulation

Fig. 10. Powertrain structure under FEV super credit scenarios.

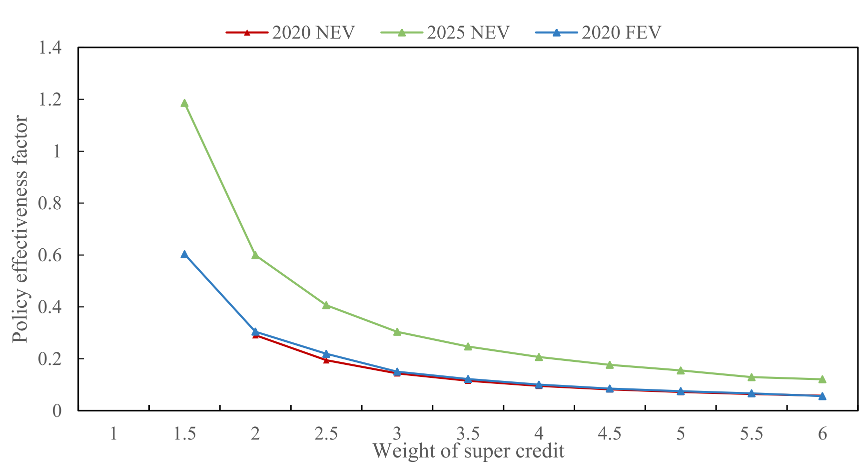


Fig. 11. Effectiveness factor for super credit policy under different scenarios.

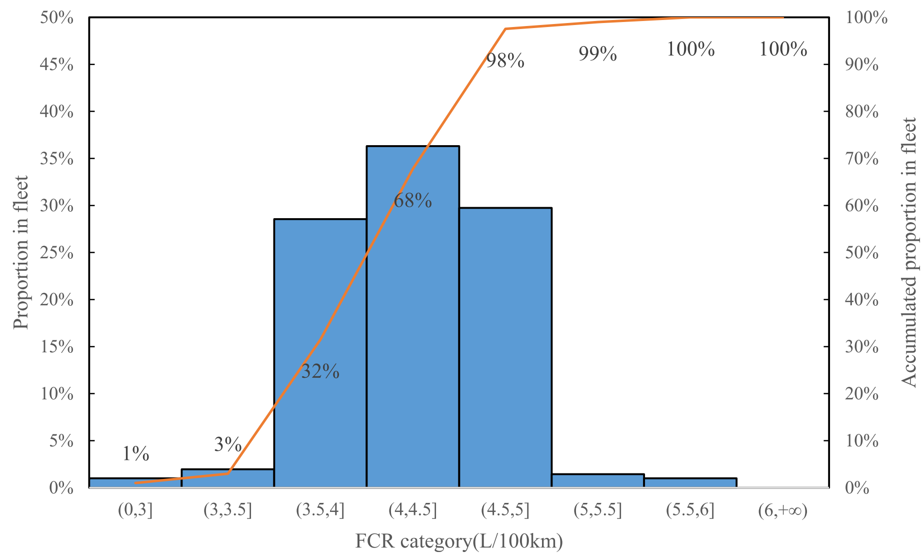


Fig. 12. Histogram of fleet FCR complying with the 2025 CAFC target.

saving goal of CAFC regulation. To further promote advanced technologies, the threshold should be strengthened along with the fleet-wide FCR target.

6. Conclusions

Several lessons are learned from this research. The theoretical results show that given a CAFC target, the impact of the super credit on compliance cost reduction is determined mainly by three factors: the super credit multiplier, the FCR reduction effect and the cost of the targeted technology. First, the super credit multiplier affects the rate of compliance cost reduction more when the multiplier is small, as Fig. 7 shows that compliance cost drops more rapidly when w is small. This result differs from the simulation results partially due to the difference in assumptions and the real-world decision-making process in the simulation. Second, the less fuel-efficient the targeted technology is, the greater the compliance cost reduction achieved. The simulation results showing that the FEV super credit reduces compliance cost more than the NEV super credit under the same multiplier level confirms that result as well. As for the cost of the policy targeting technology, the more that super credit policies target high cost technologies, the greater the cost reduction realized when eligible technologies are used.

From the perspective of the simulation results, the technology promotion effect does not always increase as the super credit multiplier increases. An overreaching super credit multiplier even has a negative influence. Additionally, it is noteworthy that while super credit policy contributes to the market penetration of targeted technologies, it may significantly impair the energy saving goal by diluting the calculated CAFC. If PHEVs and BEVs are defined as NEV super credit policy targeting technologies, HEVs and advanced diesel are defined as FEV super credit targeted technologies. The optimal super credit multipliers are, respectively, 2 and 1.5 for NEVs in 2020 and 2025, 1.5 and 1 for FEVs in 2020 and 2025. Under these multipliers in the selected case, the targeted technology could be promoted most without sacrificing the CAFC energy saving goal too much.

In addition, some discrepancies in super credit policies are observed in the simulation results. Though the long-term target of the super credit policy is to promote BEVs, under the current battery cost reduction rate, BEVs are not competitive with PHEVs under any multiplier in the super credit scenarios in 2020 or 2025. Several measures, including continuing BEV subsidies, separately and dynamically formulating and controlling the PHEV and BEV super credit multipliers, implementing and quantifying BEV preferential policies in the usage phase, and accelerating the construction of BEV chargers and charging stations across the nation, could be taken to modify this discrepancy. In terms of the FEV super credit, the effect of promoting advanced technologies is superseded by continuously strengthening the CAFC regulation in the future. To further promote advanced technologies, the 2.8 L/100 km threshold should be reduced or the FEV super credit policy could cease in 2025.

Acknowledgements

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Appendix. The input data of the attributes of fuel-efficient technologies[1]

[1] Technologies that the abbreviations stand for in this table: LUB1, low friction lubricants-level 1; EFR1, engine friction reduction – level 1; LUB2+EFR2, low friction lubricants-level 2 and engine friction reduction-level 2; ICP, intake cam phasing; DCP, dual cam phasing; DVVL, discrete variable valve lift; CVVL, continuously variable valve lift; DEACD, Cylinder deactivation; SGDI, stoichiometric gasoline direct injection; TRBDS1, TRBDS2, turbocharging and downsizing-level 1, level 2; CEGR1, CEGR2, cooled exhaust gas recirculation-level 1, level 2; ADSL, advanced diesel; LPEGR, low pressure exhaust gas recirculation; CLCC, closed loop combustion control: INJ, injection pressure increased; DS, down-speeding with increased boost pressure; FR, friction reduction; IATC, improved automatic transmission controls; 6AT, 8AT, 6-speed, 8-speed automatic transmission; 10SPD, 9–10 speed transmission; HEG1, HEG2, HEG3, high efficiency gearbox-level 1, level 2, level 3; SHFTOPT, shift optimizer; 6DCT, 8DCT, 6-speed, 8-speed dual clutch transmission; DCT-HEG, high efficiency gearbox (DCT); CVT, continuously variable transmission; CVT-HEG, high efficiency gearbox(CVT); SAX, secondary axle disconnect; EPS, electric power steering; IACC1, IACC2, improved accessories-level 1, level 2; MR2.5, MR5, MR10, MR15, MR20, MR 25, 2.5%, 5%, 10%, 15%, 20%, 25% mass reduction; ROLL1, ROLL2, rolling resistance reduction level 1, level 2; AERO1, AERO2, aerodynamic drag reduction level 1, level 2; LDB, low drag brakes; SS, stop start; MHEV, integrated starter generator; SHEV-PS, strong hybrid (power-split); SHEV-P2, strong hybrid (parallel 2 clutch); PHEV56, plug-in hybrid electric vehicle (56 km all-electric range); EV160, EV240, 160 km, 240 km electric vehicle.

Abbreviations	Fuel consumption reduction effect(%)			Curb weight effect(%)	2020 Costs (2010$)			2025 Costs (2010$)			Relative to	Compatibility
	I4	V6	V8		I4	V6	V8	I4	V6	V8		
LUB1	0.7	0.8	0.7	0.0	3	3	3	3	3	3	Baseline	Incompatible
EFR1	2.6	2.7	2.4	0.0	48	71	95	48	71	95	Baseline	
LUB1+EFR1	3.3	3.5	3.1	0.0	51	74	98	51	74	98	Baseline	
LUB2+EFR2	4.5	4.8	4.2	0.0	102	149	197	102	149	197	Baseline	
ICP	2.6	2.7	2.5	0.1	38	76	38	34	68	34	Baseline	Incompatible
DCP	5.0	5.3	4.8	0.2	69	147	76	63	133	67	Baseline	
DCP + DVVL	8.5	9.0	8.1	0.5	186	317	N/A	169	287	N/A	Baseline	
DCP + CVVL	9.4	9.9	8.9	0.5	245	470	N/A	222	424	N/A	Baseline	
DEACD	0.0	0.7	5.5	0.0	N/A	131	147	N/A	118	133	Baseline	N/A
SGDI	1.5	1.5	1.5	0.1	181	273	328	164	264	296	Baseline	Incompatible
SGDI + TRBDS1	9.4	8.9	8.4	−0.5	473	172	1246	428	173	1121	Baseline	
SGDI + TRBDS2	12.4	12.1	11.4	−0.8	645	344	1535	583	328	1382	Baseline	
SGDI + TRBDS2+CEGR1	15.3	15.0	14.4	0.5	844	543	1734	763	508	1562	Baseline	
SGDI + TRBDS2+CEGR2	16.4	16.2	15.4	0.5	1187	886	2313	1073	818	2085	Baseline	
ADSL	29.4	30.5	29.0	8.0	2845	3356	3571	2572	3034	3228	Baseline	N/A
LPEGR	3.5	3.5	3.5	0.0	125	157	157	113	141	141	ADSL	N/A
CLCC	2.5	2.5	2.5	0.0	64	96	96	58	87	87	ADSL	N/A
INJ	2.5	2.5	2.5	0.0	23	25	25	20	22	22	ADSL	N/A
DS	2.5	2.5	2.5	0.0	26	26	26	24	24	24	ADSL	N/A
FR	2.5	2.5	2.5	0.0	60	91	91	54	82	82	ADSL	N/A
IATC	2.8	2.8	2.8	0.0	46	46	46	42	42	42	Baseline	Incompatible
6AT	4.9	4.9	4.9	1.0	34	34	34	31	31	31	Baseline	
8AT	1.8	1.8	1.8	1.0	89	89	89	81	81	81	6AT	Incompatible
10SPD	2.0	2.0	2.0	1.0	160	160	160	146	146	146	6AT	
HEG1	2.5	2.5	2.5	0.0	113	113	113	102	102	102	6AT	Incompatible
HEG2	5.1	5.1	5.1	0.0	296	296	296	267	267	267	6AT	
HEG3	6.6	6.6	6.6	0.0	437	437	437	395	395	395	6AT	
SHFTOPT	0.8	0.8	0.8	0.0	24	24	24	22	22	22	6AT	N/A
6DCT	4.0	4.0	0.0	2.0	55	55	55	50	50	50	6AT	N/A
DCT-HEG	2.0	2.0	2.0	0.0	141	141	141	127	127	127	6DCT	N/A
8DCT	1.8	1.8	1.8	1.0	167	167	167	152	152	152	6DCT	N/A
CVT	4.0	4.0	0.0	2.0	64	64	N/A	58	58	N/A	6AT	Incompatible
CVT-HEG	6.9	6.9	0.0	0.0	181	181	N/A	165	165	N/A	CVT	
SAX	2.2	2.2	2.2	0.0	94	94	94	86	86	86	Baseline	N/A
EPS	1.3	1.1	0.8	0.0	82	82	82	74	74	74	Baseline	N/A
IACC1	1.2	1.0	1.6	0.0	67	67	67	60	60	60	Baseline	Incompatible
IACC2	3.6	3.6	3.8	0.0	107	107	107	97	97	97	Baseline	
MR2.5	0.8	0.8	0.9	−2.5	11	14	20	11	14	20	Baseline	Incompatible
MR5	1.6	1.6	1.7	−5.0	44	57	77	44	57	76	Baseline	
MR10	6.1	6.1	4.5	−10.0	281	361	496	277	356	487	Baseline	
MR15	9.2	9.2	6.7	−15.0	596	766	1048	581	746	1015	Baseline	
MR20	12.2	12.2	9.0	−20.0	1201	1544	2107	1124	1445	1980	Baseline	
MR25	15.3	15.3	11.2	−25.0	2512	3229	4421	2267	2914	3857	Baseline	
ROLL1	1.9	1.9	1.9	0.0	5	5	5	5	5	5	Baseline	Incompatible
ROLL2	3.9	3.9	3.9	0.0	51	51	51	36	36	36	Baseline	
AERO1	2.3	2.3	2.3	0.0	37	37	37	33	33	33	Baseline	Incompatible
AERO2	4.7	4.7	4.7	0.0	147	147	147	133	133	133	Baseline	
LDB	0.8	0.8	0.8	0.0	59	59	59	59	59	59	Baseline	N/A
SS	2.1	2.2	2.1	0.5	299	334	363	250	280	304	Baseline	Incompatible
MHEV	8.5	8.5	5.0	3.0	1383	1475	1531	1203	1282	1330	Baseline	
SHEV-P2	31.3	32.0	28.5	8.0	2604	2941	3124	2315	2748	2775	Baseline	
SHEV-PS	33.3	33.1	0.0	8.0	2954	3196	N/A	2671	2889	N/A	Baseline	
PHEV56	81.3	82.0	0.0	18.0	10454	14183	N/A	8954	12109	N/A	Baseline	
EV160	100.0	100.0	0.0	6.2	11482	14492	N/A	9486	11971	N/A	Baseline	Incompatible
EV240	100.0	100.0	0.0	11.4	14954	17737	N/A	12264	14567	N/A	Baseline	

Nomenclature

Abbreviations

AER	All Electric Range
AT	Automatic Transmission
BEV	Battery Electric Vehicle
CAFC	Corporate Average Fuel Consumption
CAFE	Corporate Average Fuel Economy
CVT	Continuously Variable Transmission
EV	Electric Vehicle
FCR	Fuel Consumption Rate
FCV	Fuel Cell Vehicle
FEV	Fuel-Efficient Vehicle
HOV	High Occupancy Vehicle
LCV	Light Commercial Vehicle
PC	Passenger Car
PHEV	Plug-in Hybrid Electric Vehicle
ICE	Internal Combustion Engine
NEV	New Energy Vehicle
NP-hard	Nondeterministic Polynomial-time hard
TC	Technology Combination
ZEV	Zero Emission Vehicle

Symbol

$c_{i,t}$	technology incremental cost

C_{sc}	overall incremental cost
$CAFC$	Corporate Average Fuel Consumption
e_i	reduction effectiveness of fuel consumption rate
EF_w	effectiveness factor
r_c	total cost reduction ratio
r_I	impairment ratio
f_j	fuel consumption rate
l_j	fuel consumption rate limit
m_j	vehicle mass
p_w	proportion of the policy targeting technology
s_j	vehicle sales
StL	standards function of fuel consumption rate limit
StT	standards function of fuel consumption rate target
t_j	fuel consumption rate target
T_{CAFC}	target of Corporate Average Fuel Consumption
w_j	super credit multiplier
$x_{i,j,t}$	implementation state of fuel-efficient technology
$\tilde{x}_{i,j,0}$	initial technology implementation state of fuel-efficient technology

Subscripts

0	baseline
a	actual
b	baseline
c	calculated
C	overall incremental cost
con	conventional
i	technology number
in	initial
I	impairment
j	vehicle number
m	the amount of fuel efficient technologies
n	the amount of vehicle models
sc	super credit
t	model year
w	super credit multiplier

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