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The impact of stepped fuel economy targets on automaker's light-weighting strategy: The China case

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ABSTRACT

In China's fuel consumption rate regulation for passenger vehicles, the vehicle curb weight-based fuel consumption rate targets are specified in a stepped pattern, which is supposed to have considerable impact on automaker's light-weighting strategy. In this study, this impact is quantitatively evaluated based on China's domestic automotive market data. From the cost-effectiveness perspective, this paper firstly demonstrate that under stepped fuel consumption rate targets, automakers have strong incentives to manipulate curb weights to get qualified for more favorable targets. Then China's 2010–2014 domestic vehicle models are examined. A significantly imbalanced curb weight distribution is observed, with a considerable number of vehicle models bunching on the targets-preferred end of each weight class. By establishing multiple criteria, the vehicle models which are mostly likely to have been manipulated with curb weights are identified, which account for around 10% of all vehicle models. With an assumed shift from stepped targets to smooth targets, these affected vehicle models would have an average of 17.92 kg mass reduction and 0.073 L/100 km fuel consumption rate improvement. Our analysis suggests that the stepped targets have thwarted automakers from applying light-weighting technologies. China should consider shifting from stepped targets to smooth targets in the next phase of regulation.

1. Introduction

China's vehicle market has grown explosively over the past decade, with an average growth rate of 17.5% since 2000. China's vehicle sales have ranked first globally for 6 successive years. The domestic vehicle sales reached 23.5 million [5], which constituted 29.8% of the global sales in 2014 [36]. Accordingly, vehicle stock rose to 154.5 million (including 9.7 million low-speed trucks and 3-wheel vehicles) and 113 vehicles per thousand people by the end of 2014 [6], 8 times higher than the level in 2000. However, compared to the vehicle ownership of over 500 vehicles per thousand people in the US, Japan and EU, there is still great growth potential in China's vehicle market. Vehicle stock was projected to reach 184.8, 363.8 and 606.7 million by 2020, 2030 and 2050 respectively [14]. Along with the booming auto industry, concerns over CO_2 emissions and energy security have been raised.

Fuel economy standard is one of the most potential transportation energy saving approaches [18]. In order to enhance the vehicle fuel economy and mitigate the rising oil dependence, China's government has issued several compulsory national standards, such as FCR (fuel consumption rate) labeling and the phase-in implementation of FCR standards. The Phase I standards, issued in 2004 by GAQSIQ (General Administration of Quality Supervision, Inspection, and Quarantine of China) and SAC (Standardization Administration of China), specified the FCR limits of vehicles divided into different weight classes. Vehicle models failing to comply with the limits could not be administratively licensed to be sold in China's domestic vehicle market [9]. The Phase III standards established a sales-weighted CAFC (corporate average fuel consumption) standards structure, and specified preferential FCR targets and calculation methods to promote fuel efficient vehicles and new energy vehicles [10]. In China, fuel efficient vehicles are vehicles with FCR of lower than 2.8 L/100 km, and new energy vehicles include PHEVs (plug-in electric vehicles), BEVs (battery electric vehicles) and FCVs (fuel cell vehicles). In 2014, the Phase IV FCR standards were released, with the aim of reducing the national average FCR of passenger vehicles to 5.0 L/100 km by 2020 [11], in which the FCR targets of Phase III are set as mandatory FCR limits in

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Nomenclature

BEV	Battery electric vehicle
CAFC	Corporate average fuel consumption
FCR	Fuel consumption rate
FCV	Fuel cell vehicle
ICE	Internal combustion engine
NEDC	New European driving cycle
PHEV	Plug-in hybrid electric vehicle

Phase IV [12]. As shown in Fig. 1, the fleet-wide average FCR has decreased by over 12% during the 9 years since Phase I standards took into effect [22]. Nevertheless, it is still a formidable challenge for automotive manufacturers to achieve the fleet-wide target of 5 L/100 km in 2020.

Fuel economy targets are normally dependent on the vehicle attributes, such as curb weight, footprint and engine size, which could considerably diminish the disparity of different vehicles in regulatory stringency [3]. For vehicles with comparable types of powertrains, the weight attribute influences the fuel economy inherently [31]. The fuel economy targets of China, EU and Japan are based on vehicle weight, while the fuel economy targets of the US and Canada are set as footprint-proportionate. Light-weighting had proven the largest potential for energy saving expect for battery electric vehicle [32]. However, weight-based targets standards provide less incentives to apply advanced light-weighting materials and light-weighting designs, which may adversely impact consumer utility and safety [23]. In comparison, footprint-based targets would create an incentive to reduce the footprint-to-weight ratio or even motivate vehicle manufacturers to increase the size of vehicles [37].

Two methods are mainly employed to determine the fuel economy targets. The US, Canada and EU use smooth targets, which consequently derives continuous targets based on the vehicle attributes. By contrast, the FCR targets and limits in China and Japan are in stepped pattern, vehicle models are divided into 16 and 9 weight classes with different targets, as China's stepped FCR targets illustrated in Fig. 2. The concepts of China's CAFC and US CAFE (corporate average fuel economy) are very similar, the calculation methods of which are both fleet-wide fuel economy of corporate level. The basic schemes of typical fuel economy standards shown in Table 1 [2], and the scheme comparison of typical light-duty vehicle taxes are shown in Table 2 [17].

The characteristic of targets steps with pivot-points are common in many tax and subsidy structures, such as the US Gas Guzzler Tax based on fuel economy and China's new energy vehicle subsidy based on battery capacity. Evidence has been provided that in the multiple pivot-points featured stepped Gas Guzzler Tax structure, automotive manufacturers in the US would slightly modify the fuel economy of a vehicle model to get qualified for more favorable treatment, which accordingly brings negative net social benefits [34]. An analogy could be made between the tax system and the stepped FCR targets. The footprint attribute is related to a platform that could be shared by several vehicle models. In comparison, a vehicle's curb weight and fuel economy attributes are less integral to the vehicle's design, which could be altered easily between model years at less cost. Thus it is reasonable for vehicle manufacturers to manipulate these attributes to shift the vehicle models to other classes with favorable targets. For automotive manufacturers under the stepped targets of China's FCR standards, the wasteful manipulation of curb weights would be inefficient and costly. However, to the best of our knowledge, no research has provided such evidence relevant to the impacts of stepped FCR targets.

In this study, by employing cost-effectiveness analysis method, the impacts of stepped FCR targets on an automotive manufacturer's short-term and long-term light-weighting strategies are analyzed. The abnormal distribution of passenger car curb weights in China's domestic market between 2010 and 2014 is described. In order to describe the impacts of stepped FCR targets, by using the indicators and criteria defined, the vehicle models which are affected by the stepped FCR targets are identified and redistributed under an assumed smooth FCR targets scenario. The fleet-wide FCR and curb weight changes under the smooth FCR targets are compared with that under the stepped ones.

2. Cost-effectiveness analysis on automaker's light-weighting strategy

2.1. Cost-effectiveness definition

Cost-effectiveness analysis is a normal method to compare different projects by providing the justification and feasibility. For example, Noori investigated current reflective cracking mitigation methods by employing life cycle cost analysis, which provided policy makers a method of exploring the most cost-effective mitigation technique [29]. In the field of energy analysis, marginal abatement costs of different measures can be derived by employing cost-effectiveness method [25]. With the remarkable innovation

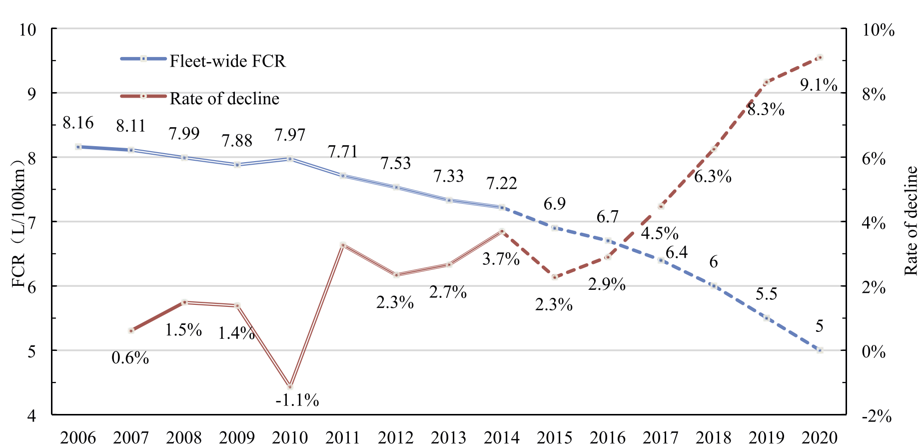

Fig. 1. China's fleet-wide FCR of light duty vehicles. *Note*: dotted line is estimated according to the phasing in of CAFC Phase IV.

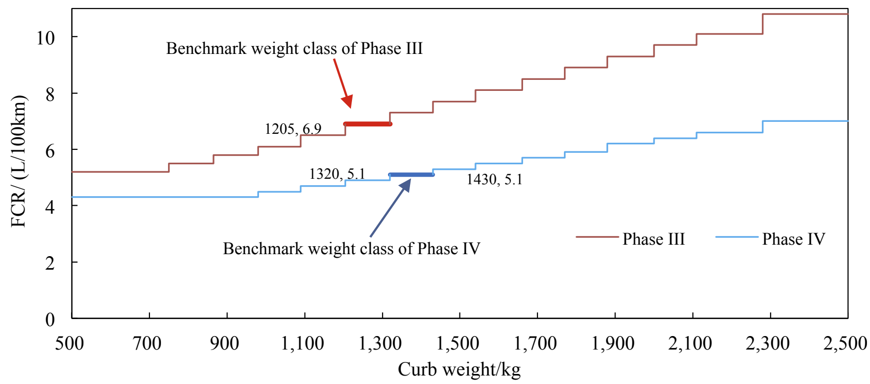

Fig. 2. China's stepped FCR targets of Phase III and Phase IV.

and improvement of automotive fuel economy technologies in the past decade, researchers also employed the method to assess vehicle advanced technologies, light-weighting technologies and especially electrification. The energy saving effectiveness of Al intensive light-weighting technology is evaluated by using life cycle assessment [8]. The life cycle cost, environmental emission and water footprint were assessed considering uncertainties with Exploratory Modeling and Analysis, according to which the ideal combination of various vehicle powertrains was optimized for the US [30]. Another study examined the competitiveness of 5 hybrid electric vehicles from the perspective of life cycle cost [26]. Peterson and Michalek compared the cost-effectiveness of increased battery capacity and electric vehicle charging infrastructure installation of different vehicle types in the US [33]. Brooker and Thornton evaluated several potential cost-effective vehicle electrification approaches by employing this method [4]. Markel and Simpson compared the cost and benefits of PHEV with that of conventional and hybrid electric vehicles [28]. To analyze the light-weighting strategy of automotive manufacturers under stepped FCR targets, cost-effectiveness method can be employed to describe the relationship between light-weighting relative cost and effect.

Under China's CAFC Standards, when implementing light-weighting strategy, the gap between a vehicle's real FCR and the FCR target is narrowed, which indicates the effect of light-weighing strategy. Consequently the cost-effectiveness is defined by Eq. (1)

$$CE = \frac{C}{(FC - T) - (FC' - T')} \tag{1}$$

where, CE is the cost-effectiveness; C is the cost of applying light-weighting technologies to a specific degree; T and FC are initial FCR target and the real FCR without applying light-weighting technologies; T' and FC' are FCR target and the real FCR after the application of light-weighting technologies.

2.2. Vehicle model selection and assumptions

The NHTSA (National Highway Traffic Safety Administration) conducted a comprehensive assessment on 2011 Honda Accord in the US market [35], the maximum feasible weight reduction with corresponding technology roadmap and cost were determined, as presented in Fig. 3.

To apply the data into cost-effectiveness analysis, two counterpart vehicle models in China's domestic market are selected. The specifications are shown in Table 3.

For automotive manufacturers, technology implementation strategy can be considered in two dimensions, short term and long term. Automotive product development program generally spans at least 15 years. Short-term feasible light-weighting technologies are those that could be implemented in the re-skin or re-style of a vehicle model every 2–4 years without substantial changes to vehicle primary systems [13]. Vehicle systems which could be redesigned without affecting the design of primary load bearing structures are broadly classified as non-structural vehicle systems, such as interior trim, lighting, seats, safety systems, instrument panel etc. [35]. Light-weighting designs of non-structural systems, application of advanced materials on closures and fenders could be taken into consideration in short-term light-weighting strategy. In long-term strategy, such as re-engineering and re-design of vehicle's platform every 4–6 years, secondary mass saving (mass compounding) potential would bring additional mass reduction when implementing more significant changes to powertrain, chassis and body structure [1].

The curb weight of the selected 2012 Accord 2.4L LX is 1515 kg, close to the right end of the 1430–1540 kg weight class, while 2012 Accord 2.4L SE weighs 1547 kg, close to the left end of 1540–1660 kg weight class.

By employing linear interpolation method between adjacent engineering solution points in Fig. 3, the mass reduction potential and corresponding cost are assumed to be continuous. Curb weights are reduced by implementing advanced materials and light-weighting designs with incremental costs. In contrast, in short-term strategy scenario, when using less advanced materials and adopting simplified machining processes, a vehicle's curb weight would increase with a cut in cost. For a specific model, an

Table 1
Scheme comparison of typical light-duty vehicle fuel economy standards.

Region	Structure	Targets type	Measure	Test cycle
United States	Foot-print	Continuous	mpg	CAFE combined
China	Curb weight	Stepped	L/100 km	NEDC
Japan	Curb weight	Stepped	km/L	NEDC
European Union	Curb weight	Continuous	g/km(CO_2)	JC08

Table 2
Scheme comparison of typical light-duty vehicle taxes.

Region	Tax	Targets type	Methods	Measure	Test method
United States	Guzzler tax	Stepped	Fuel economy	mpg	CAFE combined
China	Acquisition tax	Stepped	Engine size	L	N/A
	Excise tax	Stepped	Engine size	L	N/A
Japan	Acquisition tax	Stepped	Engine size	L	N/A
	Tonnage Tax	Stepped	Engine size	L	N/A

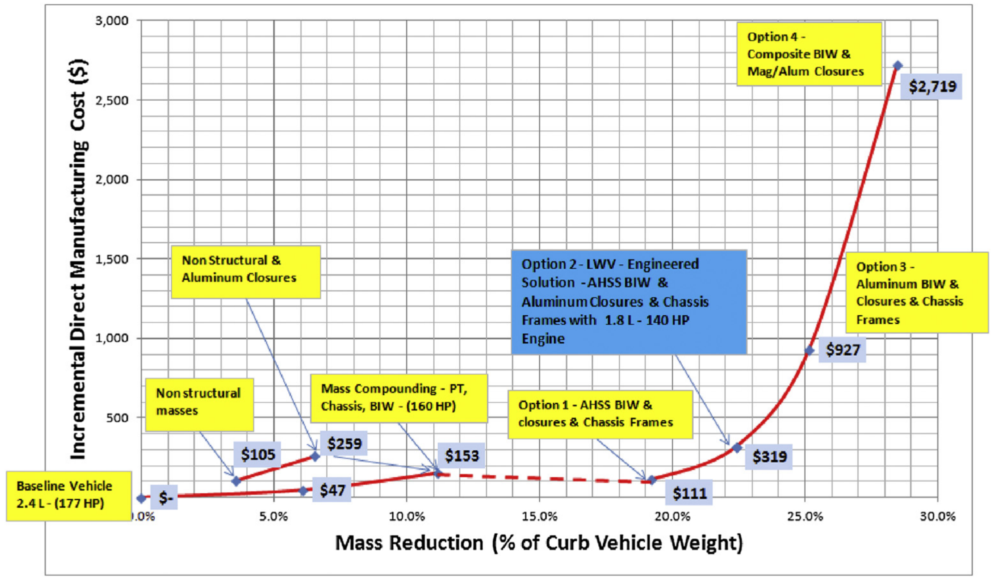

Fig. 3. Light-weighting technology roadmap and cost of 2011 Honda Accord (adapted from Ref. [35]).

assumption is made that the cost of adding curb weight is the negative cost of short-term light-weighting technologies.

2.3. Cost-effectiveness of light-weighting technologies

In the 2–4 years short-term light-weighting decision scenario, light-weighting could be applied on vehicle models without platform re-design and mass compounding, the maximum light-weighting potential is 6.4% with aluminum material closures and non-structural systems light-weighting designs. Likewise manufacturers could increase vehicle weight to 6.4% at most. Using the Phase III Standards FCR targets, the short-term cost-effectiveness of light-weighting technologies are illustrated in Fig. 4.

For Accord 2012 2.4L SE model, the model close to the left end of a weight class, when a further 7 kg mass reduction is implemented, the curb weight would drop to the lower weight class with a 0.4 L/100 km drop-off of FCR target. Consequently the benefit from applying light-weighting technologies is offset, creating a negative cost-effectiveness value. As presented in Fig. 4, the cost-effectiveness is negative when the degree of light-weighting is between 0.4% and 3.5%, which indicates that the investment on light-weighting technologies actually brings a negative effect in terms of complying with the FCR targets. A rational vehicle manufacturer would choose a light-weighting degree with positive and local minimum cost-effectiveness value to implement light-weighting technologies. However, as a local minimum point, the cost-effectiveness of 6.4% mass reduction is 9600 Yuan per L/100 km, which is considerably high and provides no advantage over other fuel economy technologies. Therefore, in terms of light-weighting to improve fuel economy in the short term, at most 7 kg mass reduction would be implemented on Accord 2012 2.4L SE model, which actually makes little difference of fuel economy.

For Accord 2012 2.4L LX model, the model close to the right end of a weight class, the mass reduction of 0–5.6% with modest cost-effectiveness values should be considered, which would bring a 0.26 L/100 km FCR reduction at most. However, adding curb weight to over 25 kg would cause a 0.4 L/100 km leap in FCR target, which effortlessly narrows the gap between real FCR and target FCR sharply and consequently brings a better compliance state than the initial. Moreover, since mass is added by employing economical materials and simplified machining processes, a negative cost-effectiveness value on the negative axis of mass reduction indicates a cost saving with a compliance improvement. Therefore, in terms of complying with the standards, vehicle manufacturers have strong incentives to get qualified for more favorable targets by slightly modifying vehicle curb weights. As to all vehicle models of this type, instead of promoting light-weighting as officially

Table 3
Specifications of selected Accord models with benchmark Accord model.

Specifications	US 2011 Honda Accord 4DR LX	Guangzhou Honda 2012 Accord 2.4L LX	Guangzhou Honda 2012 Accord 2.4L SE
Engine Number	K24Z2	K24Z2	K24Z2
Engine Type	In-Line 4-Cylinder	In-Line 4-Cylinder	In-Line 4-Cylinder
Displacement (cm^3)	2354	2354	2354
Power @ rpm (kW@rpm)	131@6500	132@6500	132@6500
Torque @ rpm (Nm@rpm)	217@4300	225@4300	225@4300
Compression Ratio	10.5	10.5	10.5
Valvetrain	16-Valve DOHC i-VTEC	16-Valve DOHC i-VTEC	16-Valve DOHC i-VTEC
Transmission	5AT	5AT	5AT
Wheelbase(mm)	2799	2800	2800
Length(mm)	4950	4960	4960
Width(mm)	1847	1845	1845
Height(mm)	1476	1480	1480
Track(mm)	1590	1590	1590
Curb weight(kg)	1487	1515	1547

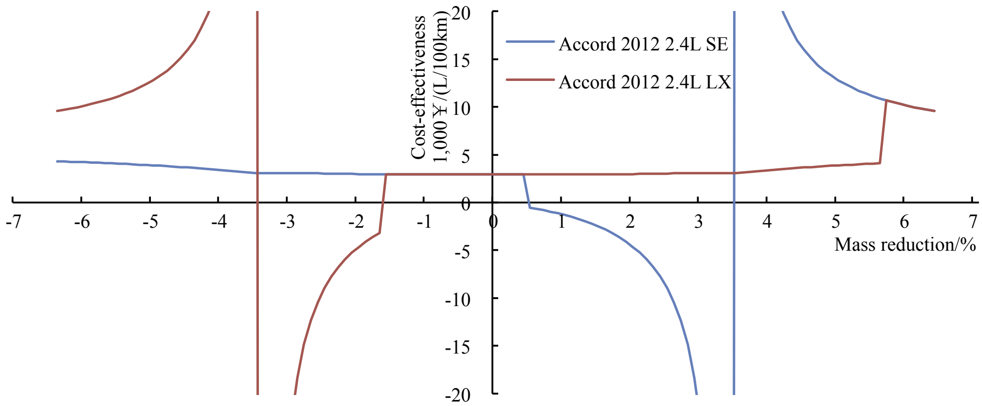

Fig. 4. Cost-effectiveness of light-weighting technologies in the short term.

expected, the stepped FCR targets in the short term are actually discouraging the application of light-weighting technologies.

In the 4–8 years long-term light-weighting decision scenario, currently available technologies provide a 0–28.5% mass reduction potential with mass compounding and advanced materials applying. The maximum degree of 28.5% mass reduction is achieved by using composite body structure with magnesium and aluminum closures, and downsizing the powertrain, chassis and body structure to take full advantage of mass compounding effect. Using the Phase IV Standards FCR targets, the long-term cost-effectiveness of light-weighting technologies is presented in Fig. 5.

For both the LX Model and the SE Model, the maximum mass reduction design option accordingly brings a prohibitive cost-effectiveness value of 32,529￥/(L/100 km). As discussed above, every time a model's curb weight crosses the left end of a weight class as light-weighting technologies implemented, the FCR target sharply drops and the gap between the model's FCR target and real FCR widens. The drop-off of the FCR target creates a step change in cost-effectiveness value, consequently lots of fuel economy gained by light-weighting is offset. A rational vehicle manufacturer would consider mass reduction scales based on 2 criteria. One is the gap between real FCR and target FCR should be narrower than that in the upper weight classes, which means further investment in light-weighting technologies brings further effects in terms of standards compliance. In order to better understand this criterion and explicitly present the appropriate mass reduction scales, the points exactly before a step change of FCR compliance gaps are illustrated by grey axillary lines in Fig. 5. Another criterion is that the mass reduction scales should be with local minimum cost-effectiveness values, which indicates an economical light-weighting strategy in terms of technology cost.

Therefore, for vehicle models distributed close to the left end of weight classes, which are represented by Accord 2012 2.4L SE in this case, limited scales of mass reduction are economical and feasible. For example, the feasible mass reduction scales for Accord 2012 2.4L SE are 5.8–7.5%, 13.5–14.6% and 21.1–22.1%. For vehicle models close to the right end of weight classes, the cost-effectiveness values corresponding to each weight class are flat, as shown red (in web version) in Fig. 5. To compromise with real fuel economy gained by light-weighting, vehicle manufacturers would reduce a model's curb weight to the left end of each weight class. As for Accord 2012 2.4L LX model, the feasible mass reduction scales are 0–5.6%, 9.3–12.8% and 17.1–20.3%.

Additionally, whether in the short or long term, the stepped FCR targets would restrict a vehicle manufacturer's light-weighting strategy to limited mass reduction scales. Many manufacturers have difficulty manipulating the curb weights precisely into the feasible scales with currently available light-weighting technologies. Consequently the light-weighting strategy would be compromised or even be abandoned, which would bring the aim of promoting light-weighting into a more adverse situation. Therefore, the stepped FCR targets are passive for some models in light-weighting implementation with respect to cost-effectiveness analysis.

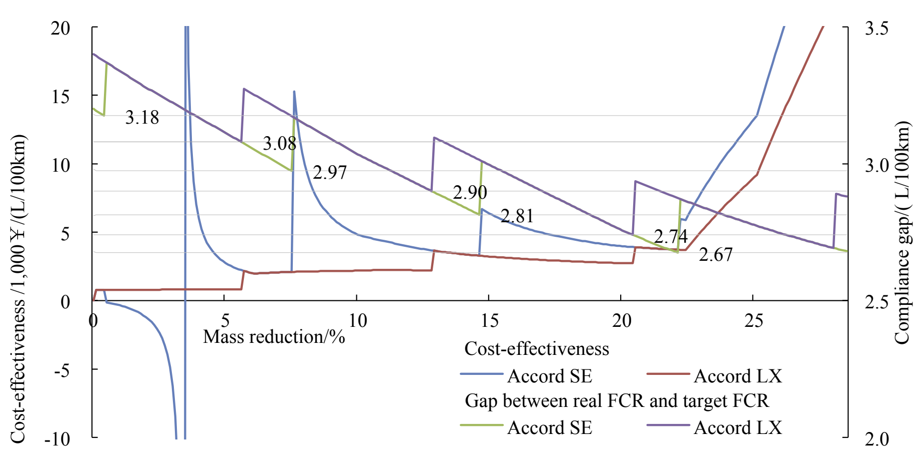

Fig. 5. Cost-effectiveness of light-weighting technologies in the long term.

3. Empirical analysis

3.1. Overarching methodology

In this study, the data of all passenger car models domestically manufactured from 2010 model year to 2014 model year and corresponding specifications are investigated. With the exception of the curb weight and FCR data, which are monthly released on the official website (chinaafc.miit.gov.cn) of Ministry of Industry and Information Technology (MIIT), China does not officially publish vehicle specifications data. Thus the data of other main specifications in our study are collected from yiche.com and autohome.com.cn. The investigated vehicle models are based on China Automotive Industry Yearbook [7], and the data of one model is further divided into different sub-models by transmission types (AT, MT, AMT, DCT) and engine displacements. The numbers of vehicle models which are investigated from 2010 to 2014 are shown in Table 4.

In empirical analysis, 74 vehicle models affected by stepped FCR targets in 2014 are identified and redistributed under an assumed smooth FCR targets scenario. By employing the survival pattern, the factor of real-world FCR and vehicle use intensity corresponding to vehicle age, the impacts of stepped FCR targets on average curb weight, average FCR and the overall lifespan fuel consumption are described. The research framework and calculation process are illustrated in Fig. 6.

To describe the impacts of stepped FCR targets, average curb weight reduction and average FCR reduction under smooth FCR targets are defined by Eq. (2) and Eq. (3).

$$ACWR = \frac{\sum_{i=1}^{n} Sales_i \cdot M_{r_i}}{\sum_{i=1}^{n} Sales_i} \tag{2}$$

$$AFCR = \frac{\sum_{i=1}^{n} Sales_i \cdot f(M_{r_i}, M_i, FC_i)}{\sum_{i=1}^{n} Sales_i} \cdot f_{real} \tag{3}$$

$$f(M_{r_i}, M_i, FC_i) = r_{FCR} \cdot FC_i \cdot \frac{M_{r_i}}{M_i} \tag{4}$$

where, *ACWR* is the average curb weight reduction under smooth FCR targets; *AFCR* is the average FCR reduction under smooth FCR targets; *i* represents the model; $Sales_i$ represents the sales of vehicle model *i*; *n* is the number of vehicle models affected by the stepped FCR targets; f_{real} represents a correction factor from the laboratory FCR to the real-world FCR; $f(M_{r_i}, M_i, FC_i)$ is a function of curb weight M_i, mass reduced M_{r_i} and laboratory FCR FC_i of vehicle model *i*, which indicates the FCR reduction after mass reduction and defined by Eq. (4). r_{FCR} is the ratio of FCR reduction proportionate to mass reduction. In this study, an assumption is made that the FCR reduction ratios are 1.4% and 3.3% corresponding to 2% and 5% mass reduction respectively [13].

Considering the average lifespan of passenger cars, with all affected vehicles sold during the foreseeable valid time period of the Phase III and Phase IV CAFC Standards with stepped FCR targets, the overall fuel conservation and CO_2 mitigation potential under the assumed smooth FCR targets are derived by Eq. (5) and Eq. (6)

Table 4
Number of models investigated each year.

Year	2010	2011	2012	2013	2014
Number of models	297	483	586	670	696

$$OFCR = \sum_j \sum_k VUI_{i,j,k} \cdot \sum_i Sales_{i,j} \cdot f(M_{r_{i,j}}, M_{i,j}, FC_{i,j}) \cdot f_{real} \tag{5}$$

$$OCR = OFCR \cdot f_{co_2} \tag{6}$$

where, *OFCR* is the overall fuel reduction under smooth FCR targets in the lifespan of all affected passenger cars; *j* represents year; *i* represents vehicle model; *k* represents vehicle age; $Sales_{i,j}$ is the sales of vehicle model *i* in year *j*; $f(M_{r_{i,j}}, M_{i,j}, FC_{i,j})$ is the FCR reduction under smooth FCR targets of vehicle model *i* sold in year *j*; $VUI_{i,j,k}$ is the vehicle use intensity in the vehicle age *k* of vehicle model *i* sold in year *j*; *OCR* is the overall CO_2 emission reduction potential under smooth FCR targets, f_{co_2} is a conversion factor of oil to CO_2.

3.2. Curb weight distribution under stepped FCR targets

The CAFC standards establish FCR limits and targets for vehicles divided into 16 curb weight classes. The widths of first ten classes range from 105 to 110 kg, and the widths of last two classes are 170 kg and 230 kg respectively. In order to identify vehicle models affected by the stepped FCR targets, each class is further divided into ten categories equally in width. The number of models distributed in each category is counted, and the distribution trend is illustrated by summing the number of models of corresponding categories in each weight class, as presented by Fig. 7.

As shown in Fig. 7, there are observable abnormal weight distributions in 0–10% category, 80–90% category and 90–100% category. The proportion of 0–10% category increased significantly to 21% in the past 5 years, while the proportions of 80–90% and 90–100% categories decreased to 7% and 6% respectively.

As discussed above, the cutoff points between curb weight classes with different FCR targets would create cost-effectiveness notches when implementing light-weighting technologies, which bring two inducements that lead to the evident abnormal distribution in 0–10% category. One is for the vehicle models initially distributed in the left part of each weight class. Rational manufacturers will barely implement light-weighting technologies to reduce the curb weights to lower weight classes, which would bring more challenging FCR targets to comply with. Consequently the initially left part distributed vehicle models are bunching in 0–10% category of model year 2010–2014. Another inducement is for the vehicle models initially distributed close to the right end of each weight class. In order to be qualified for more favorable FCR targets in the upper weight classes, automotive manufacturers have difficulties complying with CAFC Standards would slightly add weight to these models, which would inevitably induce the shrinkages in categories of 80–90% and 90–100%.

3.3. Identification of vehicle models with manipulated curb weights

There is a strong correlation among vehicle model curb weight, equivalent volume (defined as the product of vehicle length, width and height), type of powertrain, engine power and body type [38]. The linear correlation between equivalent volume and curb weight suggests a vehicle's surrogate density concerning materials applied, while the linear correlation between installed engine power and curb weight indicates the designed power and accelerating performance. A consideration solely based on weight related specifications is not sufficient. Real FCR and target FCR that imply the difficulty for a specific vehicle model to comply with the standards should also be included.

In China's domestic passenger vehicle market, passenger car fleet is dominated by unibody-type gasoline engine vehicles

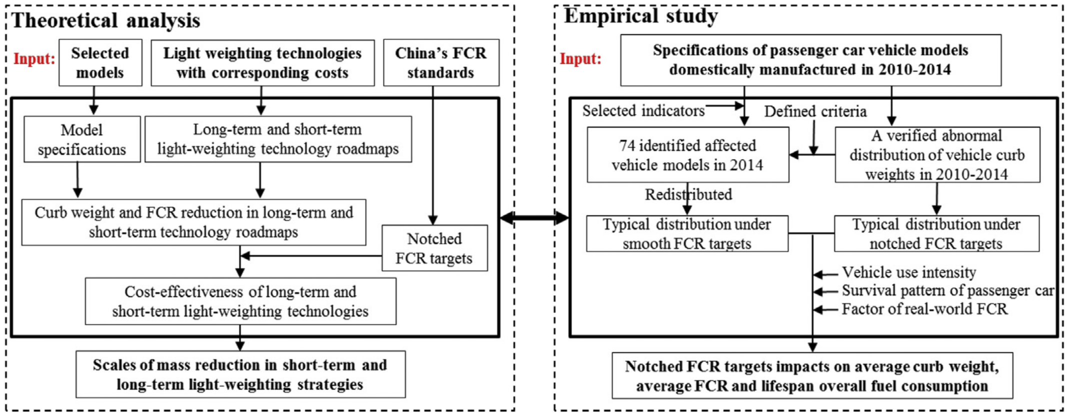

Fig. 6. Research framework and calculation process.

without all-wheel drive systems, while few are hybrid, electric or diesel powered. Therefore, to estimate the indicated curb weight of each vehicle model, equivalent volume and engine power are employed as 2 independent variables in a multiple linear regression model, as shown in Eq. (7)

$$MI = b_0 + b_p \cdot P + b_v \cdot V \tag{7}$$

where, MI is the indicated curb weight estimated by the regression model; P is the engine power; V is the equivalent volume; b_p, b_v and b_0 are the coefficients of engine power, equivalent volume and constant in the regression model. The indicated curb weight is assumed to be a normal curb weight corresponding to each vehicle model's engine power and equivalent volume.

As discussed above, vehicle models in 10–80% categories are unaffected by the stepped FCR targets. 455 unibody-type gasoline powered vehicle models which are distributed in 10–80% categories in 2014 model year are used to estimate the model coefficients. The results are presented in Table 5.

To identify the vehicle models affected by the stepped FCR targets, two indicators are defined, the residual error is defined by Eq. (8) as

$$RE = M - MI \tag{8}$$

where, RE is the residual error between the indicated curb weight MI and real curb weight M, which suggests the light-weighting degree of a specific vehicle model. A positive RE suggests a deficient light-weighting technologies application or a compromise in vehicle power and performance, while a negative RE suggests a sufficient light-weighting technologies application and an emphasis on vehicle power and performance.

The share of vehicle models affected by the first inducement could to some extent be identified by the RE value. To identify the share affected by another inducement, an assumption is made that vehicle models not in compliance with the FCR targets of the lower weight classes are more liable to be manipulated to an upper weight class. Thus another indicator FC_g is defined by Eq. (9)

$$FC_g = FC_r - T_{lc} \tag{9}$$

where, FC_r is the real FCR of a vehicle model; T_{lc} is the FCR target in the lower weight class; FC_g is the gap between them. A negative FC_g indicates a greater possibility of a manipulated curb weight of a vehicle.

According to the inducements analyzed above, nearly all affected vehicle models are distributed in 0–10% category. An assumption is made that in a smooth FCR targets scenario, vehicle models in different categories are evenly distributed. Therefore, the impact of the stepped FCR targets on the distribution is eliminated by evening the proportion of each category to generally 10%. In order to cut the proportion distributed in 0–10% to approximately 10%, 74 vehicle models should be picked out and redistributed.

To identify the affected 74 vehicle models in 0–10% category, indicators RE and FCR_g are employed to establish the criteria. Criterion 1: affected models are among the models with a negative FCR_g value, which indicates a higher FCR and a greater difficulty complying with the standards; Criterion 2: affected models are among the models with the largest RE value, which indicates the least degrees of light-weighting.

The identified affected vehicle models are shown as red dots (in web version) in Fig. 8. A higher RE value indicates a less degree of light-weighting technologies application. While most RE values of

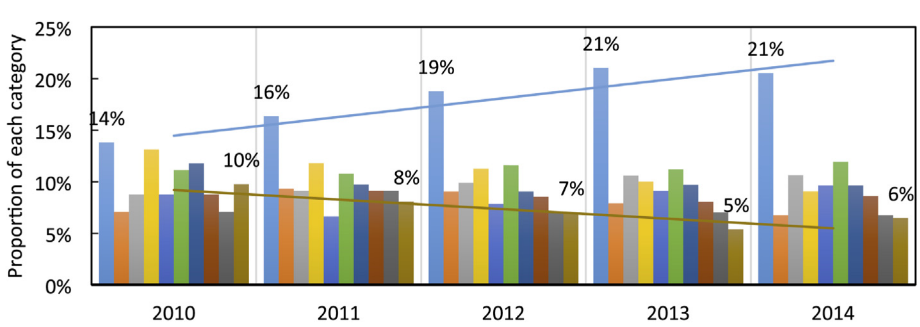

Fig. 7. The overall trend of curb weight distribution in 2010–2014 model years.

Table 5
Coefficients estimation results in the multiple linear regression model.

Model	Unstandardized coefficients		Standardized coefficients	t	Sig.
	b	Std. Error	β		
Constant	−113.503	40.788		−2.78	0.006
Engine power	3.509	0.186	0.476	18.88	0.000
Equivalent volume	92.401	4.440	0.524	20.81	0.000

the 74 identified affected vehicles are positive (above the indicated curb weight plane), some are negative (underneath the plane).

3.4. Curb weight redistribution under smooth FCR targets

As analyzed above, under a smooth FCR targets scenario, automotive manufacturers would further implement light-weighting technologies on the 74 affected models. A consistent light-weighting degree measurement of vehicle models is defined by comparing the *RE* value of one model with the RE_b value of a selected benchmark model, as shown in Eq. (10)

$$M_p = RE - RE_b \tag{10}$$

where, M_p is the ideal weight to be reduced of each affected model, which indicates the light-weighting potential of applying currently available technologies.

Considering the cost-effectiveness of light-weighting and other fuel economy technologies, instead of implementing light-weighting technologies to the most, a rational manufacturer would prefer to comply with the standards by employing a technology portfolio on vehicle models at the best cost. Therefore, to redistribute the vehicle curb weights under smooth FCR targets, affected vehicle curb weights are reduced by weights proportionate to the M_p value, as shown in Eq. (11)

$$M_r = p \cdot M_p \tag{11}$$

where, M_r is the mass reduced of an affected vehicle model under the stepped FCR targets. With the aim of realizing a generally even distribution of vehicle curb weights under the smooth FCR targets, the proportion p is tuned to be 14%.

3.5. Fleet characteristics

This study focuses the analysis on private passenger cars. The average lifespan of affected passenger cars are assumed to be 14.5 years [15]. The passenger car sales in 2010–2014 are based on historical data. China does not officially publish the sales data of each specific vehicle model, thus the sales of each affected model in our analysis are collected from China Automotive Industry Yearbook 2014 [7] and the website of data.auto.sina.com.cn. By employing the survival pattern method [16], the future PPV (private passenger vehicle) sales during the foreseeable valid time period of Phase III and Phase IV China's FCR standards (2015–2020) will increase from 19.53 million in 2015 to 24.76 million in 2020.

Research shows that vehicle use intensity of PPV in China decreased as the PPV ownership increased considerably, and vehicle use intensity also decreases over vehicle lifespan [20], for which an assumption is made that the vehicle use intensity varies based on the vehicle age. Another assumption is that the real-world FCR is generally 15.5% higher than the label FCR [19]. Since gasoline ICE (internal combustion engines) dominate China's vehicle market, and over 99% newly registered vehicles are gasoline powered [15], the f_{co_2} is set as the conversion factor from gasoline to CO_2 to be 2.32 kg/L.

4. Results and discussions

4.1. Curb weight distributions under stepped and smooth FCR targets

By employing the criteria established above, 74 vehicle models are identified, which consist of 2 C-class models (generally defined as vehicles with wheelbase of above 2.9 m in China), 19 B-class

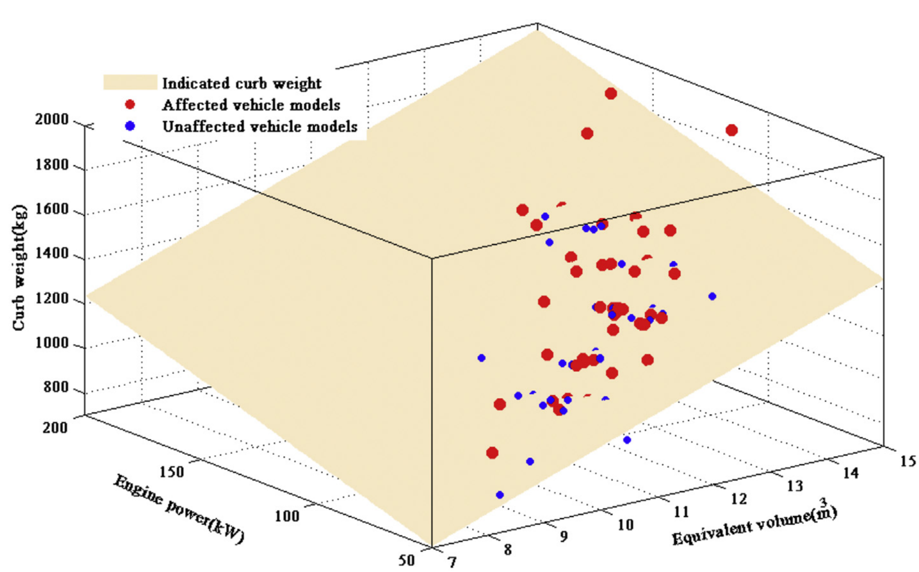

Fig. 8. Identified affected vehicle models in 2014 model year.

models (wheelbase between 2.7 and 2.9 m), 48 A-class models (wheelbase between 2.5 and 2.7 m) and 5 A0-class models (wheelbase under 2.5 m). As A-class vehicle models dominate China's domestic passenger car market, the 48 affected models constitute 75.15% of the total affected models sales, which implies the difficulty of vehicle manufacturers complying with the FCR targets. C-class vehicle models are positioned as limousine and luxury for a minority group of people in the market, which take a relatively small share in the product assortments of vehicle manufacturers. Thus the vehicle models of C-class market segment contribute less to the CAFC target. Besides, in the conception of Chinese customers, high curb weight is a proxy for driving stability and safety. Moreover, the cost of other fuel economy technologies implemented to comply with the FCR targets could be readily covered by the comparatively higher retail price. Therefore, automotive manufacturers would not risk compromising the curb weight of C-class models to earn a negligible number of CAFC credits. As for A0-class models, since the slope of curb weight based FCR targets is flat to promote light-weighting as officially announced, it is less challenging to comply with the standards.

As illustrated in Fig. 9, after the identification and redistribution of affected vehicle models under stepped FCR targets, the curb weights in different weight categories are generally distributed evenly, the proportion in 0–10% category decreases from 21% to 11%, consequently the maximum difference of the proportions among weight categories decreases from over 14% to less than 5%. The 74 affected vehicle models initially distributed in 0–10% weight category are mainly redistributed into the 70–100% weight categories after implementing the assumed degree of light-weighting, which modifies the abnormal distributions in 0–10% and 70–100% weight categories significantly under the assumed smooth FCR targets scenario.

4.2. *The impacts on fleet average curb weight and FCR*

The sales of the 74 identified models are 1.42 million and constitute 11.5 percent of the passenger car overall sales in the 2014 model year. Redistributed under a standards scenario with smooth FCR targets, the curb weights of the affected models decrease by 17.92 kg on average, and in the scope of the 12.38 million passenger cars sold in 2014, the impact of stepped FCR targets on curb weight change is 2.06 kg on average. With respect to the FCR, an average FCR improvement of 0.073 L/100 km is acquired by the 74 models after light-weighting. Nevertheless, under the stepped FCR targets without adequate light-weighting, the average FCR target of the affected models would increase by 0.33 L/100 km. Thus by slightly manipulating the curb weights, automotive manufacturers would gain an average of 0.26 L/100 km relative FCR "improvement" in terms of standards compliance. As to all the models sold in 2014, the average FCR reduction is 0.0084 L/100 km. However, when considering the lifespan real-world accumulative fuel consumption by all the affected vehicle models sold every year, it is meaningful.

Under China's Phase IV FCR standards, since the fleet-wide average of 5 L/100 km FCR target would be phased in year by year, vehicle manufacturers would manipulate the curb weights more in order to comply with the more challenging targets. As shown in Fig. 10. Considering the foreseeable valid time period of the stepped FCR targets, by the time of 2020, the affected vehicles would amount to 20.69 million, the cumulative energy conservation potential in their lifespans is 2.15 million ton gasoline, and the CO_2 mitigation potential is 6.87 million ton.

5. Policy implications

The preceding study points to several lessons for policy. The overall vehicle gasoline consumption by 2020 was estimated to be 223 million ton [16], compared to the 2.15 million ton gasoline conserved under smooth FCR targets, the contribution from this point of view is not significant. However, it is estimated that in 2030, the gasoline passenger vehicles would still amount for 76% of China's passenger vehicle market even in the integrated policy scenario, which indicates that in the near future from 2015 to 2030, alternative energy powered vehicles would still take a small share of the new vehicle market in China [27]. . For ICE powered vehicles, the 5 L/100 km fleet-wide FCR target of China's Phase IV FCR standards is considerably restrictive. A 1.9 L/100 km fleet-wide FCR target gap between the Phase III and Phase IV standards would be phased in from 2016 to 2020. During this period time, as estimated by China's government, 35 million ton fuel would be conserved [21]. By contrast, the estimated 2.15 million ton gasoline conserved by shifting the regulation from the stepped to continuous targets accounts for a meaningful 6.1% of the fuel conservation potential of Phase IV CAFC standards. Moreover, automotive manufacturers would manipulate the curb weights more with more stringent targets implemented in China's Phase V and Phase VI FCR standards in the future, with a larger vehicle market size in China, there would be a greater energy conservation potential.

The stepped FCR targets create several gaming opportunities, automotive manufacturers make very minor modifications to vehicles that shift the models to the weight classes with more favorable treatment, or implement insufficient light-weighting technologies to maintain vehicle models on the FCR targets preferred sides. The automotive manufacturers benefit from the stepped FCR targets ostensibly. However, an automaker has no

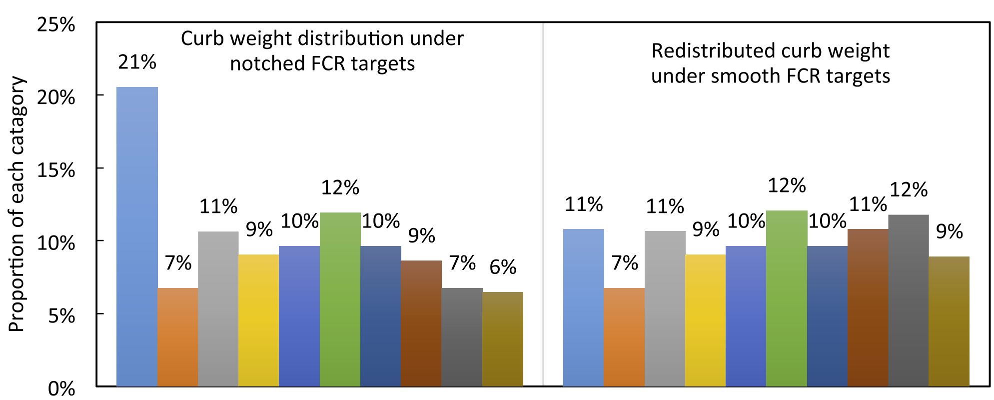

Fig. 9. Comparison of vehicle curb weight distributions under stepped and smooth FCR targets.

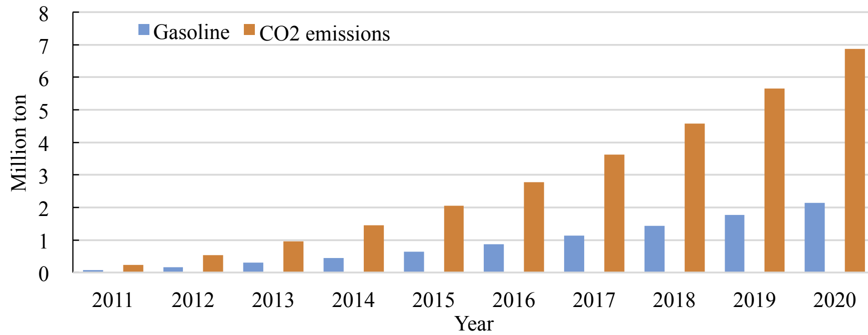

Fig. 10. Accumulative energy conservation and CO_2 mitigation potential.

advantage over another who manipulates the curb weights as well. Moreover, the additional curb weights manipulation is costly to automakers and without necessarily reducing fuel consumption to contribute to the national targets of reducing fossil fuel reliance,

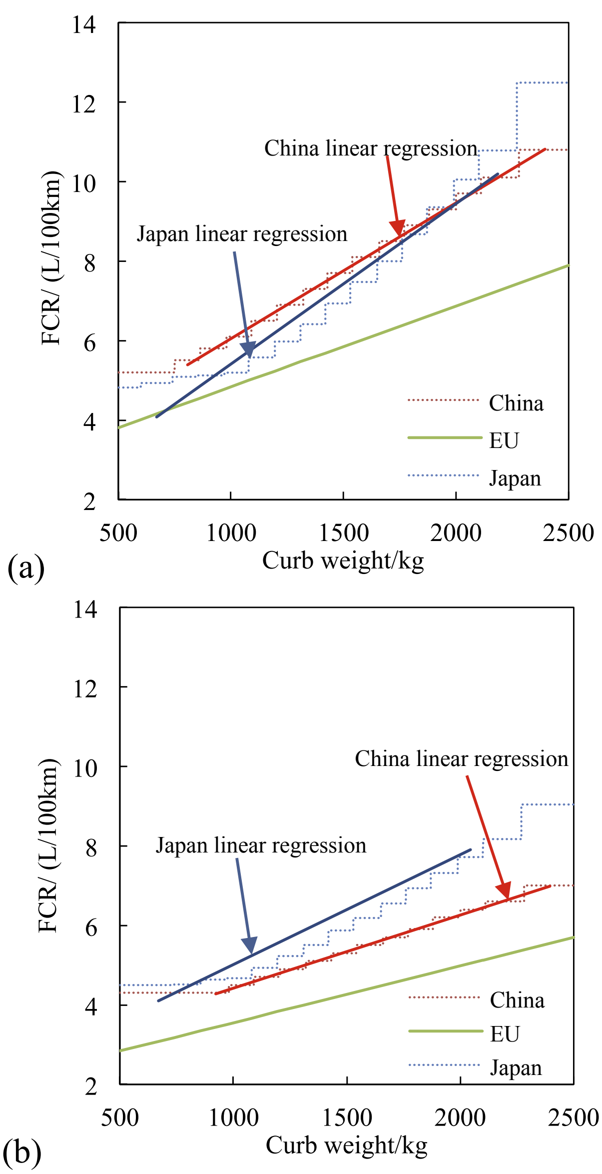

Fig. 11. Comparison of the slopes in curb weight-based standards worldwide (a) 2012–2015 (b) 2016–2020.

improving local air quality and mitigating global climate change, thus it increases the cost to society. In addition, for the policy makers, reforming the present stepped structure of FCR targets with smooth targets requires little administrative costs. Therefore, policy makers should give the smooth FCR targets due consideration to eliminate the liabilities discussed above.

Under the standards with smooth FCR targets, the slope of curb weight-based FCR targets is a parameter of vital importance, which reflects the degree of promoting light-weighting technologies. Considering the smooth FCR targets, the FCR targets structure among China, EU and Japan are compared. The slopes of China's and Japan's FCR targets under NEDC test cycle is obtained by employing linear regression analysis and test cycle conversion factors [24], as displayed in Fig. 11. The NEDC equivalent weight-based targets slopes of China, EU and Japan during 2012–2015 are 0.34, 0.20 and 0.40 (L/100 km)/100 kg respectively, compared to the slopes during 2016–2020, which are 0.18, 0.14 and 0.28 (L/100 km)/100 kg, China, EU and Japan have decreased the slopes by 46.2%, 26.9% and 31.7% in the next phase FCR standards respectively. Although China's FCR targets slope has decreased the most, which indicates the government's significant determination to promote light-weighting technologies as officially announced, nevertheless, compared to the 0.14(L/100 km)/100 kg in EU's smooth FCR targets standards, it is still higher.

In order to promote light-weighting and improve the fuel economy in China's light-duty vehicle fleet, policy makers should consider using a smooth FCR targets structure as well as flattening the FCR targets on the basis of curb weight.

6. Conclusions

First, the light-weighting strategies in the short term and long term are analyzed by employing the cost-effectiveness method. The results show the strategy preference of automakers. In the short term, as a vehicle's curb weight could be tuned by making very minor modifications, vehicle manufacturers have strong incentives to shift vehicle models to the weight classes with more favorable FCR targets. In the long term, further light-weighting is available through means of mass compounding. Since vehicle platform and body-in-white structure could not easily be altered between model years, when implementing light-weighting strategy, the curb weights of vehicle models tend to be bunching on the FCR targets preferred sides.

Second, an empirical analysis is conducted by using the data of 2010–2014 vehicle models in China's domestic market. The distribution shows that the curb weights are bunching in the left 10% of each weight class and the phenomenon is evident as the standards phased in year by year. By using the defined criteria, 74 vehicle models affected by the stepped FCR targets are identified and redistributed, which constitute 11.5 percent of passenger car sales in 2014.

Third, in terms of energy conservation and CO_2 mitigation potential, the impacts of stepped and smooth FCR targets are compared. The results show that a further average of 17.92 kg light-weighting should be implemented on the affected models, which would create a 0.073 L/100 km FCR improvement on average. Under the smooth FCR targets, the affected vehicle models, sold during the Phase IV CAFC Standards with stepped FCR targets from 2016 to 2020, would create 1.50 million ton gasoline consumption and 4.81 million ton CO_2 emissions reductions in their lifespans, which accounts for 4.3% of the officially estimated fuel conservation potential of China's Phase IV CAFC Standards. Moreover, in addition to the CO_2 emissions reduced, other vehicle emission pollutants would be reduced proportionally as well, for example, CO, NO_x, SO_x, etc.

Should the policy makers desire to continue the FCR standards based on curb weight, they could improve the efficiency of the standards by being attentive to the responses of automakers. The wasteful gaming and fuel consumption could be eliminated by using smooth FCR targets instead of the stepped ones. In addition, policy makers should also consider flattening the FCR targets in order to improve fuel economy and promote light-weighting in China.

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