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TECHNOLOGY ROADMAP TO COMPLY WITH CHINA'S CORPORATE AVERAGE FUEL CONSUMPTION STANDARDS: A CASE STUDY

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ABSTRACT– China's Phase IV Corporate Average Fuel Consumption(CAFC) Standards has been issued, which requires the fleet-wide average fuel consumption rate(FCR) to decrease from 6.9L/100km to 5L/100km by 2020. In order to comply with the standards, one original equipment manufacturer(OEM) must select several sets of fuel-efficient technologies strategically from its arsenal to apply to the assortment at the best cost. In this study, an intermediate volume OEM is selected as a case to explore the technology roadmap. The result shows that average compliance cost of CAFC target in 2020 is 4100.5 yuan. Gasoline technologies with a small proportion of diesel and hybrid electric vehicle (HEV) technologies are adequate to satisfy the standards. HEV, plug-in HEV and battery electric vehicles (BEV) do not need to be introduced extensively in the near term.

ABBREVIATIONS

AD	Advanced diesel
ADR	Aerodynamic drag reduction
AT	Automatic transmission
BEV	Battery electric vehicle
CD	Cylinder deactivation
CVT	Continuous variable transmission
CVVL	Continuous variable valve lift
DCP	Dual camshaft phasing
DCT	Dual clutch transmission
DS	Downsizing
DVVL	Discrete variable valve lift
EFR	Engine friction reduction
EPS	Electric power steering
FCV	Fuel cell vehicle
GDI	Gasoline direct injection

HEV	Hybrid electric vehicle
IA	Improved accessories
ICE	Internal combustion engine
ICP	Intake camshaft phasing
LDB	Low drag brakes
LFL	Low friction lubricants
LRRT	Low rolling resistance tires
MHEV	Mild hybrid electric vehicle
MR	Mass reduction
NEV	New energy vehicle
P2	Parallel 2 clutch system
PHEV	Plug-in hybrid electric vehicle
PS	Power split system
SAD	Secondary axle disconnect
SHEV	Strong hybrid electric vehicle
SS	Start-stop
TGDI	Turbocharging and gasoline direct injection
VVL	Variable valve lift
VVT	Variable valve timing

INTRODUCTION

Improving fuel economy and mitigating greenhouse gas(GHG) emissions are the most concerned problems in automotive industry. The carbon dioxide emissions from passenger cars account for 8.7% of global energy-related carbon dioxide emissions in 2013[1]. In China, the GHG emissions from passenger cars are roughly 5% of national total GHG emissions [2]. China has been the largest passenger car producer and market for seven consecutive years. In 2015, 21.08 million and 21.15 million passenger cars are produced and sold in China [3]. The growth of China's passenger car market even accounts for 81.54% of worldwide market growth in the past decade [4]. The explosively increasing vehicle market of China is estimated to bring a 606 million vehicle stock by 2050[5], which significantly raised the concern over China's air environment and energy security. Since 2004, China has issued four phases of standards to regulate the fuel consumption rate (FCR) of passenger cars. The latest Phase IV standards specifies a fleet-wide FCR target as well as FCR limit of each vehicle version [6, 7]. Vehicle versions fail to comply with the FCR limit could not get the license to be sold in domestic market. Automotive original automotive manufacturers (OEM) violating the fleet-wide FCR target, which is defined by the standards as Corporate Average Fuel Consumption(CAFC), would be confronted with a bunch of punishment measures.

It is more challenging for OEMs to comply with the standards as it goes more stringent. To achieve the national fleet-wide FCR target of 5L/100km in 2020, OEMs have to improve the FCR by 6.3% annually [8]. Several studies have explored the potential fuel-efficient technologies to meet fuel economy standards [9-12]. Some studies took a specific category of technologies into consideration and simulated OEMs' response to the fuel economy standards

[13,14]. However, the problem that OEMs most concerned about is how to comply with the challenging standards with appropriate fuel-efficient technologies. In this paper, we take account of all fuel-efficient technologies that are considered available by 2020. By using optimization method, genetic algorithm is employed to solve the technology combination (TC) problem under 2020 CAFC target. Then the simulation result is analyzed from the perspective of compliance cost, variations of standard related parameters and technology roadmap. Finally, we draw conclusions and give some recommendations on technology roadmap to comply with the fuel economy standards in 2020.

METHODOLOGY

TC Problem Framework

The TC problem is defined as selecting a portfolio of fuel-efficient technologies to be implemented on the vehicle product assortment of an OEM, so that the OEM's target could be optimized subjecting to specific constraints. Under the CAFC standard, OEM's target is to minimize the technology incremental cost used to comply with the standard, and the constraints are specified by the standards.

We assume there is an OEM with n vehicle versions in this market and m feasible fuel-efficient technologies. The objective function is to minimize the technology incremental cost without violating the constraints, which is formulated as:

$$\min \sum_{j=1}^{n} s_j \sum_{i=1}^{m} (x_{ij} - \tilde{x}_{ij})\, c_i \tag{1}$$

subject to:

1） CAFC constraint
2） FCR limit
3） Technology compatibility

where $x_{ij} \in \{0,1\}$ is the implementation state of fuel-efficient technology i on vehicle version j, while $\tilde{x}_{ij}$ is the initial technology implementation state. c_i is the incremental cost of technology i. s_j is the sales of vehicle version j.

Under the fuel economy standards of China, CAFC is required to be complied with. The CAFC constraint is described as:

$$\begin{cases} t_i = StT(m_j) \\ TCAFC = \dfrac{\sum_{j=1}^{n} s_j t_j}{\sum_{j=1}^{n} s_j} \\ CAFC = \dfrac{\sum_{j=1}^{n} s_j f_j}{\sum_{j=1}^{n} s_j w_j} \\ CAFC \leq TCAFC \end{cases} \tag{2}$$

where t_j and f_j are the FCR target and FCR of vehicle version j. t_i is determined by the step function $StT(m_j)$ according to its curb weight. $CAFC$ and $TCAFC$ are CAFC and CAFC target of the OEM, respectively. w_j is the CAFC calculation weight specified by the standards. When a vehicle model's powertrain configuration is BEV, FCV or PHEV and several criterion are met, "super weight" is adopted to calculate the OEM's CAFC. For example, the "super weight" of BEVs is 5, 3, 2 in year 2016~2017, 2018~2019, 2020, respectively, while for traditional ICE models, the weight is 1 [6].

Meanwhile, all vehicle versions to be sold domestically should comply with the FCR limit constraint, which is described as:

$$\begin{cases} l_j = StL(m_j) \\ f_j \leq l_j \end{cases} \tag{3}$$

where l_j is the FCR limit of vehicle version j which is determined by a step function $StL(m_j)$.

Additionally, technology compatibility is another type of constraints that determines whether several fuel-efficient technologies should be implemented concurrently from the perspective of the standards and technology physical features. Technologies from the same category, for example, 5% mass reduction and 10% mass reduction could not be used at one time. Technologies with almost the same fuel saving principle are not cost-effective to be applied together. Furthermore, technologies that are particularly implemented on different powertrains, for example, GDI and diesel technologies could not be implemented concurrently. This type of constraints is described as:

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

where α and β are incompatible technologies.

<u>Case Selected and Data Input</u>

In this study, we select an intermediate domestic OEM in China, whose sales in 2015 is around 600,000. There are 8 passenger vehicle models and 36 vehicle versions in its assortment. We collect the data of available fuel-efficient technologies by 2020, including the direct manufacturing cost, the reduction rate of FCR and the effect on vehicle curb weight, from several fuel-efficient technology assessment report [15-17]. 54 fuel-efficient technologies are taken into consideration, which consist of 20 ICE technologies, 13 transmission technologies, 15 vehicle technologies and 8 NEV technologies. We make the assumption that one vehicle model, which may include several vehicle versions with different technology allocations, is equipped with one ICE configuration. All vehicle versions belong to the same vehicle model are equipped with same fuel-efficient technologies except transmission technologies and accessory technologies.

RESULT ANALYSIS

The overall combinational optimization problem is solved by an elaborately designed genetic algorithm. Specialized solution structure, decoders and penalty functions are utilized in the designed genetic algorithm. In this case, the solution length is 524 bits. We set a 20,000 population size and 300 generations. The final results are analyzed as follows.

Standard-related Parameters

As illustrated in Figure 1, while the initial CAFC of the selected OEM is 6.63L/100km, the final CAFC reaches 5.18L/100km. This OEM's CAFC declines 28% during the Phase IV time horizon (2016~2020). The annual declining rate is 5.1%. Considering the final CAFC target, the OEM fully satisfies the requirement.

From the perspective of CAFC target, the national fleet-wide FCR target would not be fully achieved in this case. The standards divide the curb weight passenger vehicles into 16 categories, each of which has one FCR target and FCR limit. Vehicles are specified with FCR target and limit based on their curb weights. The national expected fleet-wide average curb weight is in the category of 1205-1320kg, whose FCR targets are 6.9L/100km and 4.9L/100km in Phase III and Phase IV, respectively. In order to achieve the national fleet-wide 5L/100km target by 2020, the government is trying to control the curb weight and promote light-weighting during the Phase IV period. However, in this case, when making the strategic decision to minimize the compliance cost, the OEM's average vehicle curb weight increases from 1324kg to 1383kg. Accordingly, the CAFC target increases from 5.01L/100km to 5.18L/100km.

There are two reasons resulting in this outcome. Almost all the fuel-efficient technologies would increase the vehicle's curb weight expect light-weighting and ICE turbocharging with downsizing. Particularly, diesel ICE, HEV and PHEV technology would increase the curb weight significantly. Another reason is the features of the standards. Under the standards that FCR targets are determined by curb weight, OEMs have less motivation to implement light-weighting technologies [18]. The stepped FCR targets thwart OEMs from applying light-weighting strategies as well [19].

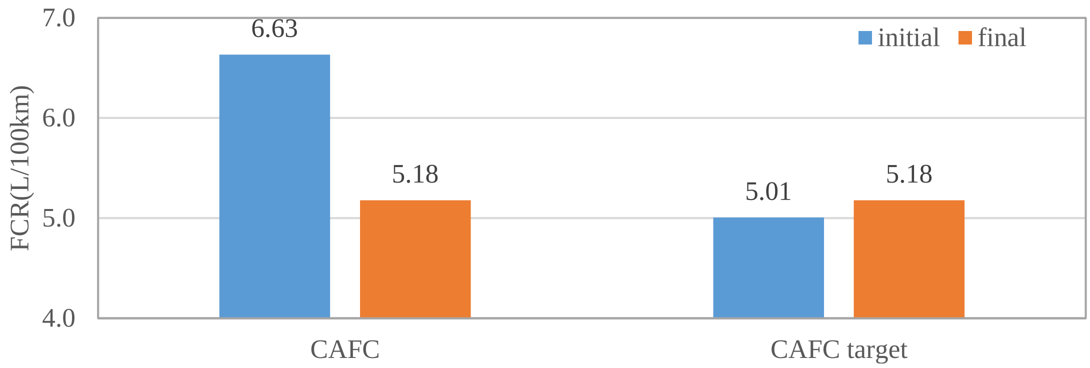


Figure 1: CAFC compliance state

Figure 2 presents the cost, FCR and curb weight variation after the optimized TC decision. All vehicle models' curb weight increase on account of the reasons discussed above. As for the FCR, while 89% of vehicle versions increase their FCR to comply with the 2020 CAFC target, 11% of vehicle versions decrease their FCR a little bit. Since an OEM need to both comply with the standards and keep the product diversity to some extent, this outcome is quite similar to the real product assortment of an OEM.

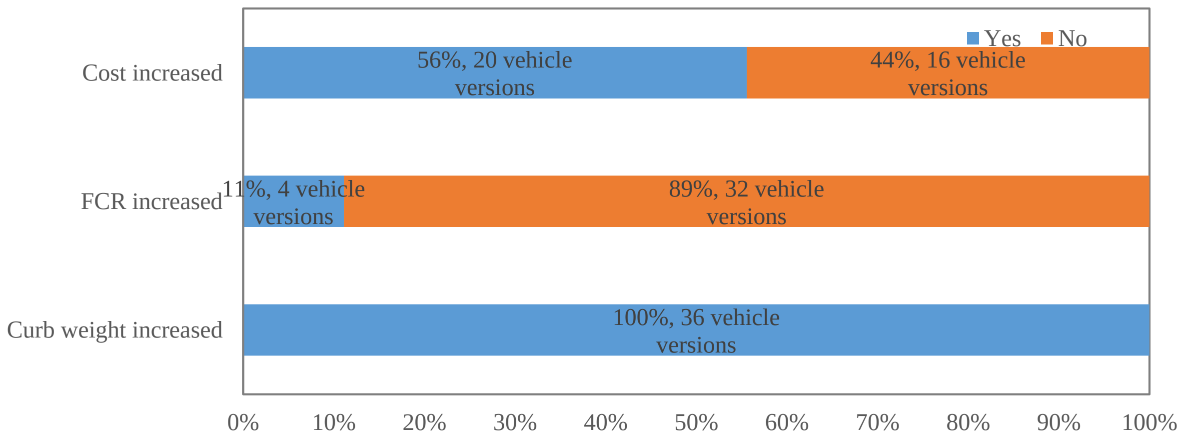


Figure 2: Cost, FCR and curb weight variation

<u>Compliance Cost</u>

Based on the assumption that all the 54 fuel-efficient technologies are available for the OEM at the assessed cost. During the optimization process, some less cost-effective fuel-efficient technologies are replaced by more cost-effective ones. Therefore, as Figure 2 shows, while 56% of vehicle versions increase the technology cost, 44% vehicle versions decrease the cost.

The average compliance cost of 2020 CAFC standards in this case is 4100.5 yuan. Figure 3 presents the cost distribution of 36 vehicle versions in this case. 66.7% of vehicle versions converge to (-4,4] thousand-yuan section. Vehicle versions in this section are equipped with more cost-effective technologies. The vehicle FCRs in this section vary from -20% to 2%. Meanwhile, the costs of 8 versions, which account for 22.2% of the fleet, range between 46,000 and 56,000. These versions are implemented with diesel or HEV technologies. Along with other fuel-efficient technologies, the FCRs of these versions decrease by roughly 50% to 60%. Therefore, to comply the CAFC target in 2020 with the lowest cost, OEMs should improve the fleet-wide fuel economy as well as produce several vehicle models that are outstandingly fuel-efficient.

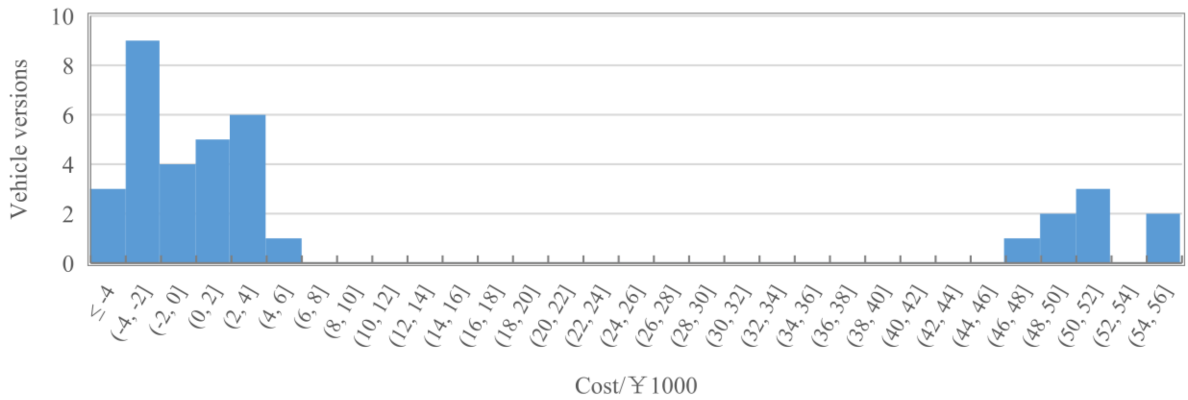


Figure 3: Histogram of compliance cost

<u>Technology Preference</u>

Technology implementation rate is selected to indicate technology preference under 2020 CAFC target, which are defined as:

$$R_k = \frac{N_k}{N_{ck}} \tag{5}$$

where N_k is the amount of vehicles that are implemented with technology k. N_{ck} is defined as the amount of vehicles that are compatible with technology k. As shown in Figure 4, the most favorable fuel-efficient technologies to comply with the 2020 CAFC target are those with the highest implementation rate. Therefore, EFR, VVT and VVL, LRRT are the most preferred technologies by 2020, whose implementation rates are 100%. Additionally, DCT, ADR and IA should also be considered firstly to satisfy the standards. On the contrary, BEV, PHEV, SS, LDB, EPS and etc. are not cost-effective by 2020 with the aim of minimizing compliance cost. Consistent with the light-weighting strategy under China's standards discussed above, vehicles are barely applied with MR technologies.

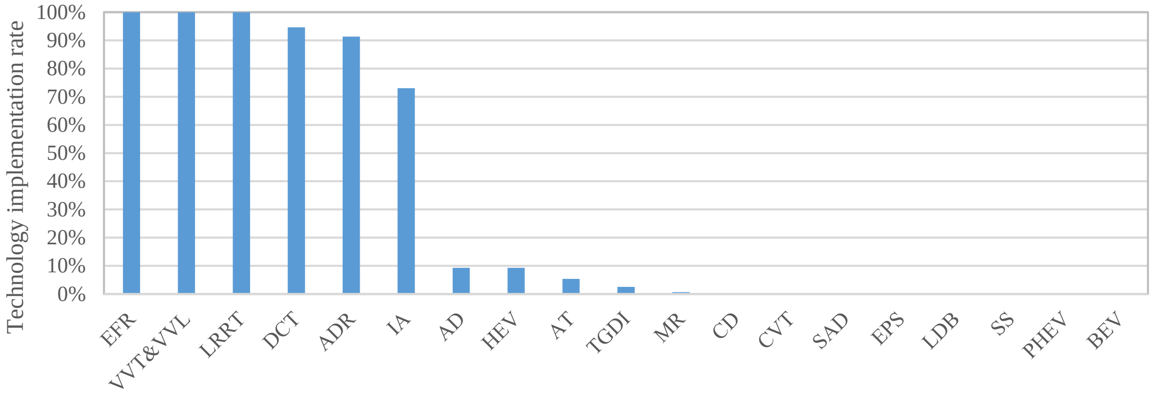
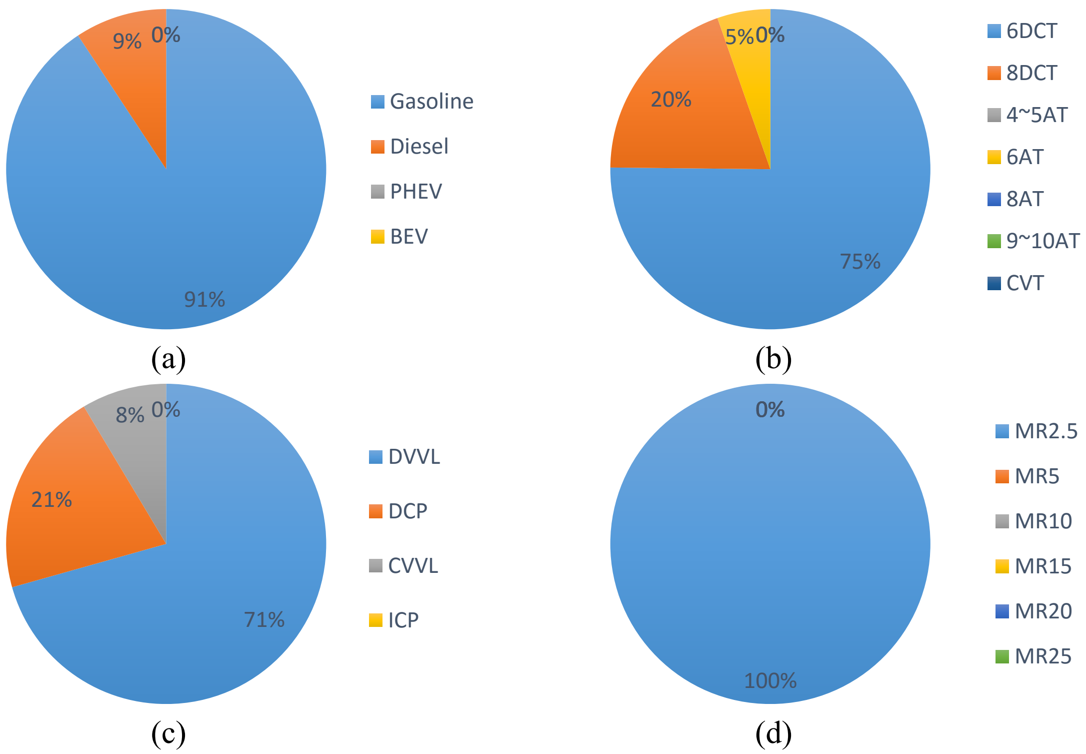
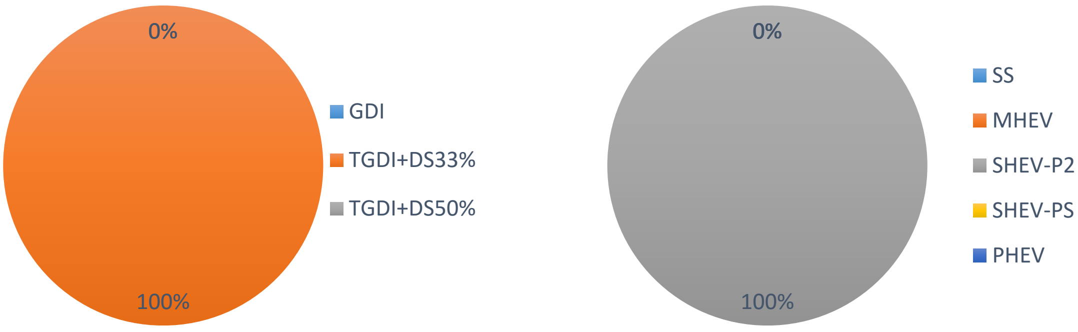


Figure 4: Implementation rate of fuel-efficient technologies under 2020 CAFC target

Figure 5 presents the specific preference of fuel-efficient technologies in the same category. 91% of vehicles are still using gasoline ICEs by 2020, which indicates that gasoline fuel-efficient technologies are still adequate to satisfy the standards in the near future. With higher thermal efficiency, diesel ICEs are equipped to 9% of vehicles to improve the fleet-wide fuel economy. According to Figure 5(b), 95% of vehicles are using 6-speed or 8-speed DCT, while only 5% vehicles are using 6-speed AT. It implies that DCT has observable advantage over CVT and AT with more than 6 speeds. As for the valve train technologies, DVVL and DCP are more favorable than CVVL and ICP. Among the vehicles applied with light-weighting, GDI with turbocharging and downsizing and HEV technologies, 2.5% MR, GDI with turbocharging and 33% downsizing, SHEV-P2 are the dominating technologies by 2020.





(e) (f)

Figure 5: Technology preference under 2020 CAFC target

There are five technologies with 2 implementation levels. Level 2 is the technology with higher cost and FCR reduction potential. As illustrated in Figure 6, EFR, LFL and ADR are more cost-effective at level 1 by 2020. Meanwhile, IA and LRRT are more favorable when being implemented at level 2.

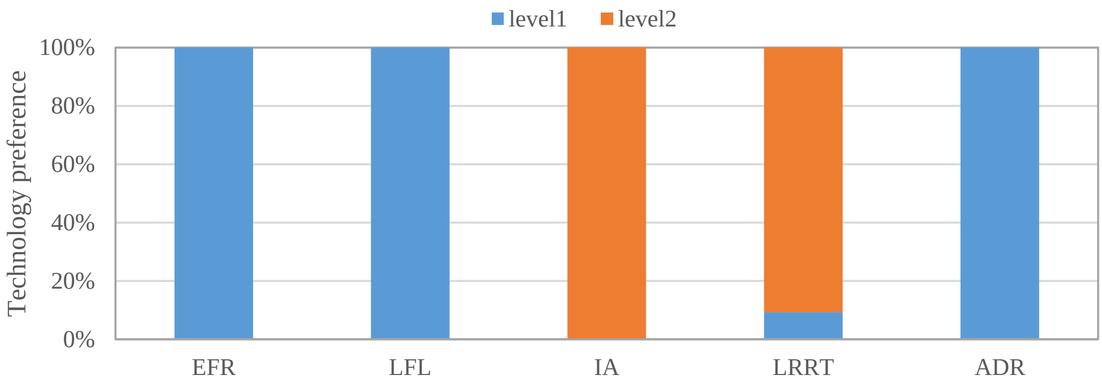


Figure 6: Preference of 2 level technologies under 2020 CAFC target

CONCLUSION

From the perspective of an OEM, to comply with the CAFC standards by 2020, the product assortment should be elaborately planned and fuel-efficient technologies be strategically implemented. In the selected case, with the aim of minimizing compliance cost, the fuel economy of almost all vehicle versions are improved. Meanwhile, 9.3% of vehicles are designed with outstanding fuel economy. The average compliance cost of 2020 CAFC is 4100.5 yuan.

From the perspective of technologies, EFR, VVT, VVL, LRRT, DCT, ADR and IA are the most favorable fuel-efficient technologies by 2020. Considering the CAFC target in 2020, technologies of gasoline engines are still adequate to satisfy the standards in the near term, while HEV, PHEV and BEV technologies would not be extensively introduced in this phase standards.

From the perspective of policy makers. Under the standards based on vehicle curb weight with stepped features, light-weighting technologies are barely used in this case. Meanwhile, the implementation of fuel-efficient technologies would lead to an increase of the fleet-wide curb weight, which would consequently bring up the CAFC target and preclude the national fleet-wide FCR target from being achieved by 2020. Therefore, we recommend policy makers reconsider the curb weight features of the standards.

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