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Fuel Economy Regulations and Technology Roadmaps of China and the US: Comparison and Outlook

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Abstract

In order to address the increasing energy and environmental concerns, China and the US both launched the fuel economy regulations and aim to push the development of technology. In this study, the stringency of CAFC and CAFE regulations and the technology development of two countries are compared. Besides, the optimal technology pathways of America and automakers for the compliance of CAFE regulations are calculated based on the modified VOLPE model, and the results are used as reference for China. The results indicate that the annual regulation improvement rates of China is higher than America and the AIR of China 2015-2020 regulation reaches 6.2% and is the most stringent phase in 10 years from 2015 to 2025. From the perspective of technology, there are still big gaps between China and the US in the applications of advanced fuel saving technologies. For both countries, engine still will plays the biggest role in the technology roadmap through 2025 and the contribution rates of electrification and vehicle assembly technologies will increase quickly. The 2020 targets can be reached by the improvement and optimization of existing fuel saving technologies, and 70% hybridization technologies should be introduced for the compliance of the 2025 regulation. The penetration of PHEV/EVs will be 2-3% of the passenger car fleet in MY 2025 and FCV is not necessary for the compliance of US 2025 CAFE target. However, new energy products still need to be prepared in China because of the implementation of dual-credit regulations of CAFC and NEV.

Introduction

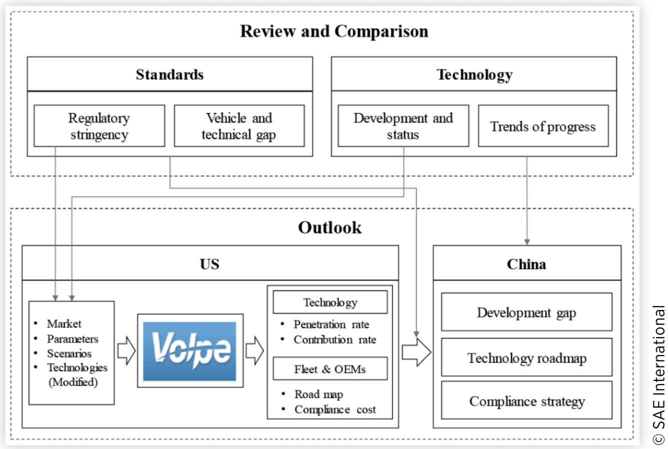
Over the past decades, China's automobile market has been growing in a high speed. From the perspective of industrial scale, China's automobile sales in 2016 were over 28 million [1] with an annual growth rate of 8% from 2011 to 2016 [2]. The sales have been over 20 million for four consecutive years since 2013 and ranking first in the world for eight consecutive years [2]. Even with a conservative estimation of 4.5% annual growth rate in vehicle sales, the sales of China's vehicle market will achieve 30 million in 2020 [3].

However, China is also facing severe energy and environmental problems at the same time [4]. Over the past few years, China's external dependence of crude oil kept increasing. It has exceeded 50%, the international safety warning line, in 2009 and reached 65.4% in 2016 [5], which was far exceeding the international safety warning line. Meanwhile, many cities and regions have experienced long-time chemical smog or haze and particulate matter (PM) is gradually becoming a focus of wide concerns for the entire society [6]. Influenced by the boom of the automobile market, China has replaced the US as the world's largest emitter of carbon dioxide since 2006, and 27.6% of the world's carbon dioxide emissions come from China [7]. In the 2015 Paris climate summit, China proposed the target reducing 60%-65% emissions per unit GDP in 2030 than that of 2005 [8]. Since the capacity of environment to absorb these pollutants is limited, environmental protection will become more and more important and taken as an indispensable assessment criterion for the automotive industry [9, 10].

Under the great pressure of energy and environmental problems, Chinese government has implemented three phases of the passenger car fuel consumption standards from 2005-2015 and implement the fourth phase corporate average fuel consumption (CAFC) standard from 2016, which further tightens the single automobile limit value and specifies a fleet-wide target value [11, 12]. The fourth phase CAFC standard sets the national CAFC target as 5.0 L/100 km in 2020, which aims to further promote the development and application of advanced energy saving technology and continue to reduce vehicle fuel consumption [13]. However, according to the data issued by China Ministry of Industry and Information Technology (MIIT), the corporate average fuel consumption of passenger cars in 2016 is 6.56 L/100 km [14], which is far from the 2020 5 L/100 km target. So it is more challenging for OEMs to comply with the standards as it goes more stringent. Under this background, it is of great importance and strategic significance to identify the future development trend of technology and formulate the long-term energy saving technology route based on the regulations.

As the former world's largest car market, the United States also faces serious energy and environmental problems. From 2004 to 2012, the federal government and California introduced a series of fuel economy and greenhouse gas emissions

FIGURE 1 Research framework of this study.



regulations, which speeded up the application of advanced energy-saving technology of light-duty vehicles, especially the issue of 2012-2016 light-duty vehicle fuel economy and greenhouse gas emission standards [15, 16]. In order to further promote the development of the national energy saving technology and improve the fuel economy level in the new era, American Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA) jointly issued the 2017-2025 light-duty vehicle fuel economy and greenhouse gas emission standard in 2012 and pointed out the direction for the development of technology. Conversely, the actual development of technologies can give reference to the revision of standards [17].

America has been leading the development of global regulatory standards and advanced vehicle technology over the past years and the future development of regulation and technology have great reference for China and other countries. In order to give detailed comparison and outlook for the fuel economy regulations and technology development of China and the US. This study firstly reviews the development of CAFC and CAFE regulations and compares the stringency of future regulations from the perspectives of absolute target value, annual improvement rates, vehicle features and technology starting point. Then the technology development and the gaps of two countries in the past 8 years are compared and summarized. Based on the modified VOLPE model shown in methodology section, technology roadmaps of American passenger car fleet and automakers for the compliance of CAFE regulation are analyzed. Furtherly, this study proposes the policy implications for China based on the aforementioned analysis and concludes the whole study.

Methodology and Data

Standard Conversion and Technology Evaluation

Most governments of countries take differing approaches to design regulations, and use different underlying driving cycles and test procedures to certify that a vehicle complies with the standards. Converting the standard values between different regulations involves not only converting physical units, but also accounting for the impacts of differences in test cycles. So in order to compare the standards of China and the US, the values of CAFE regulation are converted into values with a unit of L/100 km from CAFE drive cycle to NEDC cycle based on the conversion tool [18] developed by the International Council on Clean Transportation (ICCT). Meanwhile, the relative stringency of different standards are measured in the way of annual improvement rates (AIR), which also mean the annual decrease rate of target values underlying the Chinese standards. The annual improvement rate is calculated and compared by using Eqs. (1).

$$AIR = \left(1 - \sqrt[k]{\frac{V_k}{V_0}}\right) \times 100\% \quad (1)$$

Where V_k is the standard target of year k; V_0 is the target value for first year.

As for the evaluation of technology, Eqs. (2-4) show the overarching methodology in this study.

$$FE_{new} = FE_{orig} \times \frac{1}{\left(1 - \mathrm{FC}_0\right)} \times \frac{1}{\left(1 - \mathrm{FC}_1\right)} \cdots \times \frac{1}{\left(1 - \mathrm{FC}_n\right)} \times \frac{S_{orig}}{S_{new}} \quad (2)$$

Where FE_{orig} denotes the original fuel economy for the vehicle; FE_{new} denotes the resulting fuel economy for the same vehicle; $FC_{0,\,1,\,\ldots n}$ denote the fuel consumption improvement factors attributed to the *0-th* to *n-th* technologies; S_{orig} denotes the synergy factor associated with technology state before application of any of the *0-th* to *n-th* technologies; S_{new} denotes the synergy factor after the application of technologies.

$$PR_i = \frac{N_i}{N_{all}} \times 100\% \quad (3)$$

$$FCR_i = \frac{FC_i \cdot PR_i}{\sum_{\mathrm{i=1}}^{\mathrm{n}} FC_i \cdot PR_i} \times 100\% \quad (4)$$

Where PR_i denotes the technology penetration of technology i; N_i denotes the sales of passenger cars which are deployed technology i; N_{all} denotes the sales of all passenger cars; FCR_i denotes the fuel-saving contribution rate of technology i.

Modifications to the VOLPE Model

In order to evaluate the influence of the Corporate Average Fuel Economy (CAFE) regulations and estimate the technology roadmap and incremental cost of manufacturers for the compliance of standard, NHTSA developed the VOLPE model and simulated the different scenarios of compliance [17, 19]. The VOLPE model uses a decision tree method and defines technology pathways for grouping and establishing a logical progression of technologies on a vehicle. The decision trees include the following sub-systems: engine; transmission; powertrain electrification; hybridization; light-weighting; aerodynamics; rolling resistance and dynamic load reduction [20]. The technologies involved can be reclassified into four categories: engine, transmission, electrification and vehicle assembly. The compliance simulation applies technologies to each manufacturer's product line based on the CAFE program described by the current scenarios and after evaluating all paths, the model select a most effective solution among all pathways. A flow chart for the decision making process of VOLPE is shown in Appendix A.

It is worth mentioning that the simulation results of VOLPE show the pathways which can meet the regulations with lowest technology cost for each manufacturer, but it doesn't mean that OEMs will exactly take these pathways in reality. The VOLPE model contains the following key assumptions in the compliance simulation loop:

- The technical threshold is not considered;
- The effectiveness and cost of each technology are the same to all manufacturers;
- Due to the standards for MYs 2025-2030 haven't been established by now [21], the standards are assumed to remain constant at the MY 2025 level through MY 2030 in the model.

Considering the timeliness and tendencies of the input data of VOLPE, some modifications was made to the VOLPE input technology and market files in this study in order to compare the results with China suitably. The following sections describe the modifications and the data used in this study.

Technology Fuel Consumption Factors Modifications

Equivalent Fuel Consumption Improvement Modifications. In the analysis work of NHTSA, for non-liquid fuel types such as CNG, electricity and hydrogen, the FC improvement and the resulting fuel economy are assumed to be specified in gasoline equivalents of energy use [20]. In China, the fuel consumption of BEV and FCV are set zero and although the government is able to convert electricity consumption into gasoline or diesel consumption based on the equivalents of energy use, the measures are predicted won't be implemented by 2020. So in order to get referential results for China and investigate the influence of equivalent fuel consumption improvement, the technology inputs of new energy vehicle, which is considered as PHEV, BEV and FCV, are modified and kept consistent with China. The fuel consumption reduction and costs of technology for passenger car used [22, 23] in this study are shown in Table A.1.

CVT Fuel Consumption Improvement Factors Modifications. According to the technology input of VOLPE, the fuel consumption improvement factors of CVT are all negative which means there is a prejudice against CVT technology in the model. Actually, the incremental fuel consumption reduction of CVT is definitely positive relative to 6AT according to the assessments of Environmental Protection Agency (EPA), NHTSA and National Research Council (NRC) [17, 23]. So the input effectiveness of CVT are modified into positive value and the comparisons between the original and the new results are taken.

Sales Modifications The latest model is based on the market data of year 2015 and the predictions of future market deviate from the actual situation. So the sales of the passenger car market are modified based on the actual market sales in 2015 and 2016 [24] . The sales of passenger car in this study are used and also shown in Figures 10 and 12.

Regulations and Technology Development Comparisons between China and the US

Stringency of CAFC and CAFE Regulations

The fuel consumption regulations of China and the US were more and more stringent in the past decades and will definitely stay that way in the near future. Chinese government proposed the target that the fuel consumption of new passenger car should reach 5 L/100 km by 2020 in the "energy saving and new energy automobile industry development plan" and proposed the 4 L/100 km target by 2025 in the "Chinese manufacturing 2025" firstly. Similarly, America requires the fuel economy of new passenger car should reach 44.8mpg by 2020, which is equal to 5.4 L/100 km in NEDC driving cycle, and reach 56.2mpg by 2025 [21], which is equal to 4.2 L/100 km in NEDC driving cycle.

Actually, the absolute target value of the US are smaller than China's from 2015 to 2018, which means the standards of the US is more stringent than China. After that, the absolute target values of China are smaller than the target of the US and the status will be kept. The fuel consumption targets of China and the US in 2020 are 5.0 L/100 km and 5.5 L/100 km (normalized to NEDC) respectively and China is 8% stricter than the US. As for 2025, The fuel consumption targets of China and the US are 4.0 L/100 km and 4.2 L/100 km

FIGURE 2 Passenger car fuel consumption of China and the US, normalized to NEDC driving cycle.

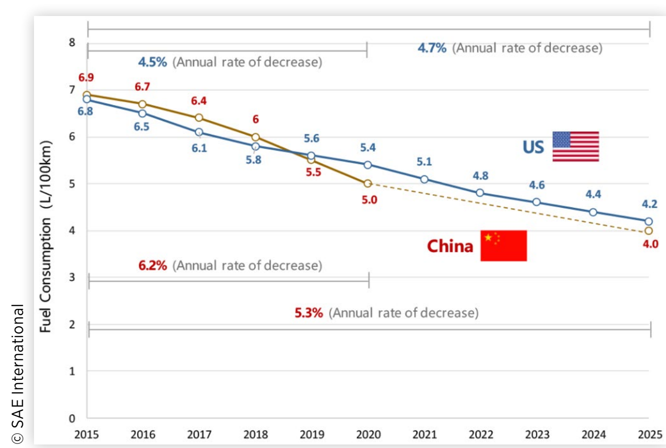


TABLE 1 Comparisons of average passenger car features between the US, China and Europe [25].

Features	US	China	Europe
Curb weight (kg)	1611	1280	1172
Footprint (m^2)	4.22	3.79	3.75
Engine displacement (L)	2.6	1.7	1.4
Horsepower (kW)	156	86	77

(normalized to NEDC) respectively and China is 5% stricter than the US.

However, the average curb weight of the US passenger cars is 25.3% heavier than China and the average footprint is 11.3% larger than China. So the future regulations of China are not more stringent than the US considering the gap of vehicle.

In other aspects, the annual improvement rates of the US regulations from 2015 to 2020 and from 2015 to 2025 are 4.5% and 4.7% respectively. As for China, the annual improvement rates from 2015 to 2020 and from 2015 to 2025 are 6.2% and 5.3%. The results show that the 2020-2025 regulation stringency of America is stricter than the 2015-2020 regulation. Meanwhile, the 2015-2020 regulation of China is the most stringent in 10 years from 2015 to 2025. Generally speaking, the annual regulation improvement rates of China is higher than America. However, the current technologies deployed in American cars are more advanced than that of China. So the upgrading difficulty and cost are much higher than China, which is also an important aspect that need to be considered.

So in the next 10 years (based on the year 2015), the absolute target values and annual improvement rates of Chinese CAFC regulation are both more stringent than the US CAFE regulation. But the US passenger cars are much larger, heavier and higher-performance than the Chinese cars on average. Meanwhile, the technology starting point of the US cars (2015) is much higher than China. So taken together, the stringency of Chinese CAFC regulation is very similar to the US CAFE regulation over the same period. Therefore, the current technology development and future trends of American passenger car are definitely great references for China.

Technology Development and Trends

The technology development and trends of the Chinese and American passenger cars from 2009 to 2016 are shown in Figures 3-5 [26, 27]. The reason this study chose the 2009 as the starting point is that the fuel economy regulations of American light-duty vehicle almost kept stop for a long time before 2009 and California started the stringent light-duty vehicle greenhouse (GHG) gas emissions standards. Meanwhile, federal government, California and all manufactures came to an agreement about the federal regulations and prepared for the "2012-2016 light-duty vehicle greenhouse gas emissions standards" during 2009-2010. After that, the American light-duty vehicle technologies were faced with a rapid development [15].

FIGURE 3 Technology development of Chinese passenger cars from 2009-2016.

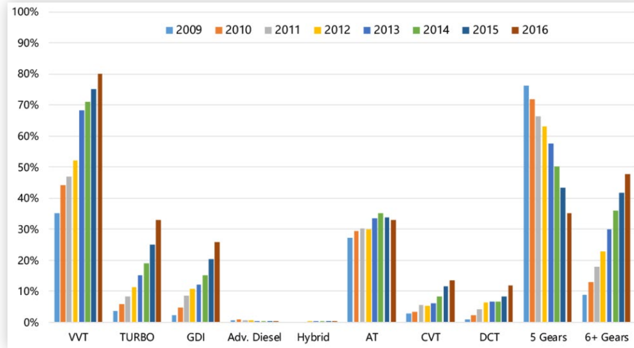


FIGURE 4 Technology development of American cars from 2009-2016.

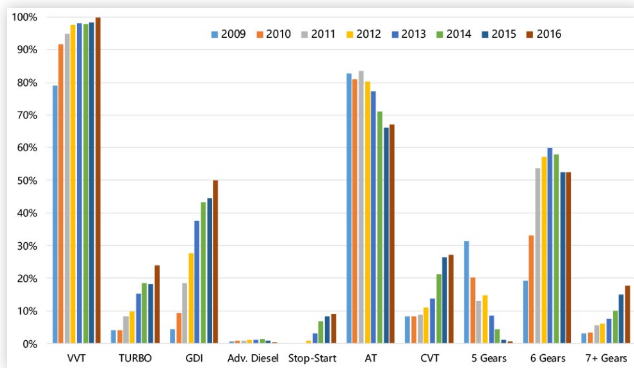
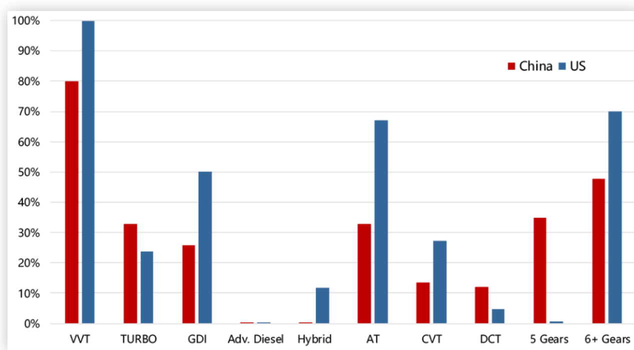


FIGURE 5 Comparison between the Chinese and American passenger cars technology penetrations in 2016.



As is clearly shown in Figure 3, the penetration of advanced fuel-saving technologies of China such as VVT, turbocharging, GDI, multi-gears transmission improved obviously from 2009 to 2016. Among which, VVT technology was installed with a sharp increase from 35% in MY 2009 to nearly 80% in MY 2016. Similarly, turbocharging technology penetration rate increased from 3.48% to 32.9% and GDI penetration rate increased from 2.1% to 25.7%. Meanwhile, transmission technologies have been rapidly evolving in new passenger cars and there is a significant trend of multi-gears, which is clearly shown in the decrease of five speed transmission and the increase of six speed transmission. However, six speed transmissions may peak in the near future, as transmissions with more than six speeds, CVTs and DCTs have begun to expand quickly. However, although automatic transmissions are increasing production shares, manual transmissions are still installed in over 40% of all new passenger cars in China.

As for diesel cars, the market share is very small and decreased year by year from 0.6% in 2009 to merely 0.1% in 2016. The sales of hybrid electric vehicle (HEV) is increasing in recent years, but the total market share is still very small with 0.3% in the latest 2016. According to the “Energy saving and new energy technology roadmap”, the hybrid passenger cars will reach 8% of all new passenger cars in 2020 and there is still a long way to go for China.

Similarly, the penetration rates of advanced fuel saving technologies in American passenger cars also show an obvious increasing trend. Among which, GDI technology was installed with a sharp increase from 4.2% in MY 2009 to 50% in MY 2016. The penetration rate of turbocharging technology increased from 4% to 23.8% and VVT technology penetration rate increased from 79.1% to nearly 100%. Meanwhile, transmission technologies have been rapidly evolving in new passenger cars and there is a more significant trend of multi-gears than China. 5 speed transmissions were never the leading transmission technology in terms of production share and 6 speed transmissions became the most popular transmission and gain 60% market share in MY 2013. However, 6 speed transmissions also already have peaked and transmissions with more than six speeds and CVTs expand quickly. CVTs were installed in 27.2% of all new passenger cars in MY 2016 and transmissions with 7 or more speeds increased quickly and reached 17.6% market share in MY 2016.

Meanwhile, the market share of automatic transmissions decreased recent years with the rapid increase of CVTs. The penetration rate of Stop-Start expanded quickly from 0.9% in MY 2012 to 9.1% in MY 2016. Similar to China, the diesel engines take a small market share of passenger cars in America and merely 0.1% in MY 2016, which were greatly influenced by the emission standard and the expansion of electric technologies.

Although the advanced technologies developed rapidly in China recent years, there was still a big gap with the US, which can be seen from the comparison between China and the US. Especially in the development of VVT, GDI, AT, CVT, HEV and etc., the gap were still approximately 15%-30%. For instance, 5 gears transmission still occupied 35% of the market and America has almost transferred all the transmissions into 6 and 6+ gears transmissions and CVTs in the same time. Meanwhile, the average gear of transmission in America has reached 5.8 in 2016. What is worth mentioning is that the penetration of turbocharging and DCT of China has exceeded the US and reached 25% and 8.1% respectively, which is related to the big market share of the European manufactures such as VW.

Technology Roadmap for the Compliance of CAFE Regulation

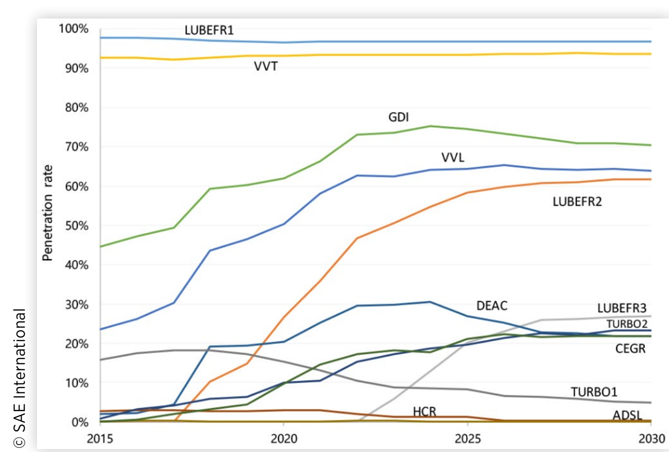
Using the modifications to the VOLPE model and the technology evaluation methods, the penetration rates and the fuel-saving contribution rates of various technologies can be calculated for the American passenger car and light truck fleet between the years 2015-2030 and the future technology roadmap of different manufactures can be predicted. The technologies are classified into four categories: engine, transmission, electrification and vehicle and the results presented in this study are focused on the passenger cars. It is noteworthy that in planning and implementing the introduction of advanced technologies, manufactures must make multi-objective decisions based on series of complex elements. The VOLPE model may simulate the real situations to the greatest extent and show the pathways which can meet the regulations with lowest technology cost for each manufacturer. So the results show the optimal technology application pathways for manufactures but may not the real decisions they will implement.

Engine Technology Roadmap

Conventional engine technologies include gasoline technologies and diesel technologies. The development of key engine technologies of fleet from 2015 to 2030 is shown in Figure 6.

The conventional and classical engine technologies such as LUBEFR1 and VVT will always keep in high penetration rates in the future. GDI, VVL, LUBEFR2 technologies will expand quickly in a “S” curve and gain the fastest speed in MY 2021. LUBEFR3 technology will booms after MY 2021. Meanwhile, TURBO1 technology will transfer into TURBO2 gradually and the total market share of turbocharging technologies will meet a slight decrease in the future. DEAC technology will booms before 2024 and be substituted by other technologies after that. Advanced diesel will continuously keep in a very low penetration rate.

FIGURE 6 Prediction of the development of engine technologies.



Transmission Technology Roadmap

The multi-gears is the most important development trend of the automatic transmission. It is obvious that 6ATs are transferring to 8AT in the US and almost all automakers take automatic transmission as an important fuel-saving technology for the compliance of future regulation. Interestingly, the manual transmission will still take nearly 6% share of the passenger cars and the multi-gears trend also will suitable to manual transmissions and the 5 and 6 speed manual transmission will be transferred into 7 speed manual transmission. Meanwhile, CVTs will expand gradually after the modifications and reach 33% of the passenger car fleet in MY 2030. With the increase of strong hybrid vehicles and new energy vehicles such as PHEV, BEV and FCV, the market share of conventional transmissions is decreasing year by year. However, the automatic transmission still maintain a large share in passenger car market, which is shown in Figure 7.

As for different automakers, there is also great difference in technology roadmaps. Figure 8 chooses a part of automakers to illustrate the different trends. The roadmaps of Japanese and Korean automakers can be divided into 2 categories. The first one is taking AT as core technology and developing CVT meantime, such as Toyota and Hyundai. The other one is taking CVT as the main technology, such as Honda, Nissan, Mitsubishi, Subaru and so on.

The roadmaps of European automakers can also be divided into 2 categories. The first one is focusing on the development of DCTs and the typical representative is VW. The other one is taking AT as the main technology and almost all European automakers excluding VW choose this pathway.

As for American automakers, the main pathway before MY 2021 is developing AT technologies. However, the optimal choice for Ford after MY 2021 is introducing CVTs as the main transmissions to comply with the future regulations based on the product structure of Ford, and this optimal choice is greatly depending on the effectiveness and cost of CVT. On the contrary, the main task for GM is transferring 6 speed automatic transmissions to 8 speed transmissions.

FIGURE 7 Prediction of the development of transmissions.

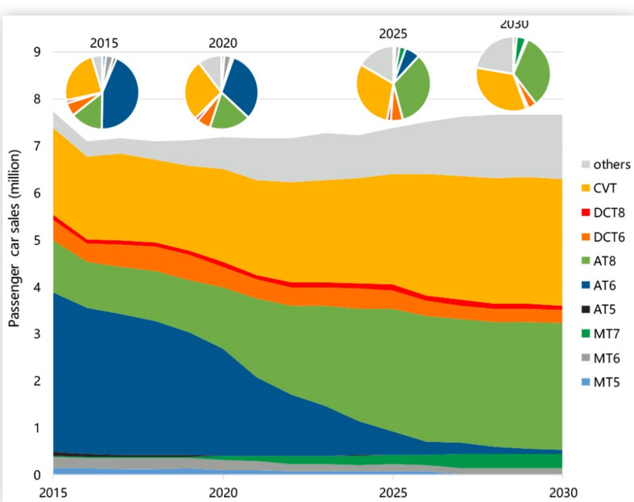
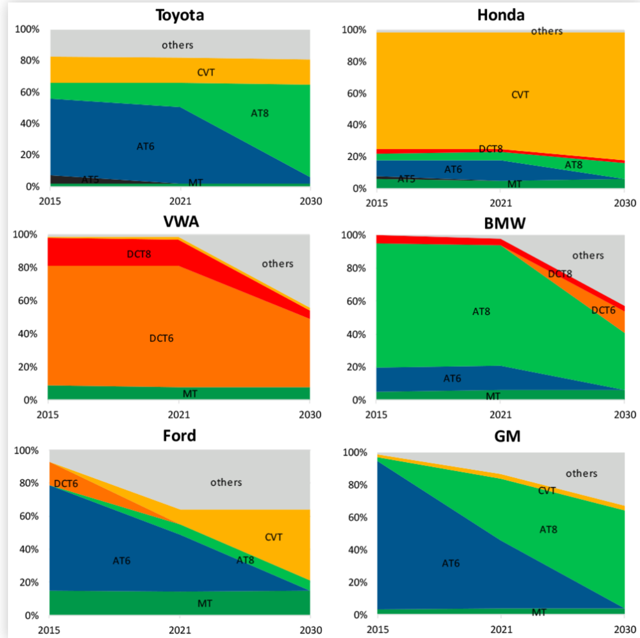


FIGURE 8 Transmission technology roadmaps of different automakers in America.



Electrification Technology Roadmap

On the one hand, the CAFE regulation will continuously promote the exploration of the potential of advanced fuel saving technologies. On the other hand, the increasing stringency of CAFE will greatly promote the introduction of electrification technologies in the passenger car fleet, which is shown in Figure 9.

As is vividly shown in the figure, the electrification technologies will expand quickly in the near future. Among which, the Stop-Start, ISG and strong hybrid technologies will be the main choices to comply with the more and more stringent regulation and the penetration rates of them will reach 35%,

FIGURE 9 Prediction of the development of electrification technologies.

Notes:

(1) The EPS, IACC technologies that meet sharp increase are also included in electrification technologies and haven't been shown in this figure.

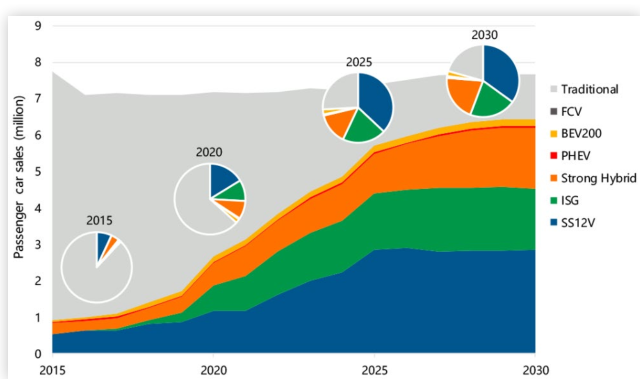
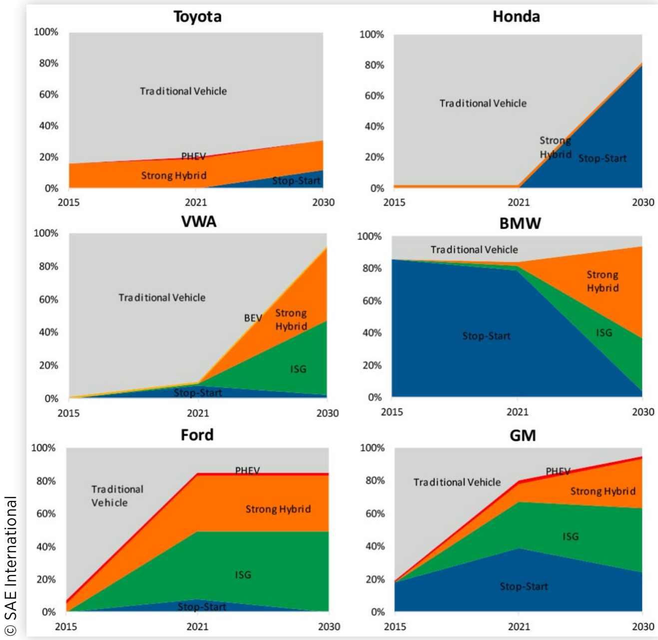


FIGURE 10 Electrification technology roadmaps of different automakers in America.



21% and 21% respectively. Meanwhile, PHEV and BEV are only take 0.5% and 2.3% of passenger car market and there is no need for FCV in the compliance of the US 2025 light-duty vehicle CAFE targets.

By comparing different electrification technology roadmaps of automakers, we can draw the conclusion that the Japanese and Korean automakers can reach the regulations by introducing relatively low penetration of electrification technologies and European and American automakers should introduce large quantities of ISG and strong hybrid technologies for the compliance of regulations. After MY 2021, almost all Japanese automakers should comply with the regulations by the application of the "NA + TGDI+Stop-Start+strong hybrid" technology portfolio. The majority of European automakers should strive to develop ISG and strong hybrid technologies and introduce a small amount of new energy vehicles based on the upgrading of TGDI engine or advanced diesel engine (VW). American automakers will take ISG and strong hybrid technologies as the main electrification technologies and substitute Stop-Start gradually.

Vehicle Assembly Technology Roadmap

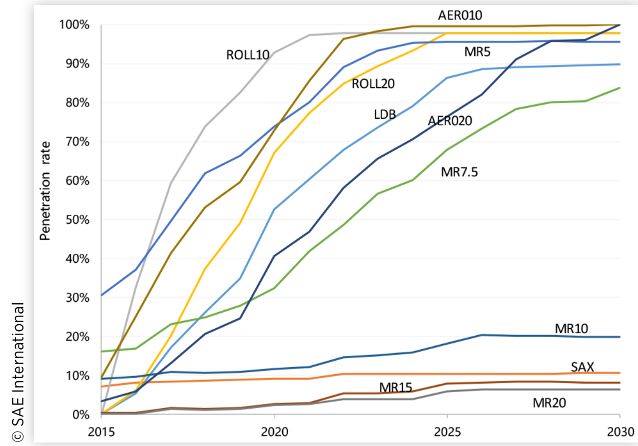
The vehicle technology trends of all manufactures are convergent. The penetration rates of most vehicle technologies, such as ROLL, AERO, LDB, MR technologies and so on are very low. But these technologies have impactful effectiveness and will rapidly applied in the near future with the improvement of technology readiness and cost-effectiveness. The penetration rates of ROLL, AREO, LDB and MR5 will reach nearly 100% in MY 2025, while the penetration rate of MR7.5 will reach over 70%.

The vehicle assembly technologies will be of great importance for the compliance of standards when the potential of conventional powertrain is nearly exhausted. Besides, these fuel-saving technologies are fundamental not only for conventional propulsion systems, but also for new energy vehicles and they will continuously play important parts in the future energy revolution.

FIGURE 11 Prediction of the development of vehicle assembly technologies.

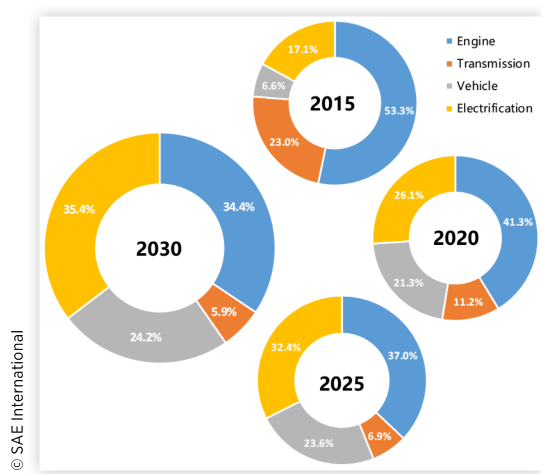
Notes:

(1) All technologies exclude powertrain technologies are included in vehicle technology and illustrated here.



Using the Eqs. (2-4) introduced before, we can obtain the contribution rates of different technologies for the compliance of CAFE regulations of the MY 2015-2030. It is obvious that engine and transmission technologies take great contribution for the compliance in MY 2015 but the rates decrease year by year. Meanwhile, the contribution rates of vehicle and electrification technologies increase gradually and reach 23.6% and 32.4% in MY 2025 respectively. However, the engine technologies are still important parts for the compliance of regulations through 2030. The vehicle technologies will meet sharp increase and take great contribution for the compliance while the contribution of transmission will decrease and take a smallest contribution after 2020.

FIGURE 12 Contribution rates of different technologies for the compliance of passenger car CAFE regulations of the MY 2015-2030



Overall, the continuously upgrading of conventional powertrain technologies and the application of different hybrid technologies such as Stop-Start, ISG and strong hybrid technologies, as well as the deployment of effective vehicle assembly technologies are the optimal and essential pathways to comply with the US CAFE regulations through MY 2025. Besides, due to the different product features of different automakers, the optimal roadmaps present great difference. Considering the maximum thermal efficiency and the incremental technology cost, the American automakers whose products are mainly medium and large cars, will prefer to explore the potential of NA engine and the Japanese automakers with small cars will prefer to develop TGDI engine and take advantages of latecomers' superiority. Meanwhile, the Japanese automakers can reach the 2030 CAFE target with small amount of strong hybrid technology relying on the superiorities of advanced fuel saving technologies and vehicle type. On the contrary, European and American automakers must employ large quantities of ISG and strong hybrid technologies for the compliance. Generally, the market penetration of PHEV/EVs will be 2-3% of the entire passenger car fleet in MY 2025 and FCVs are not necessary for the compliance of US 2025 CAFE target.

Policy Implications for China

By analyzing and comparing the fuel economy regulations of China and the US from 2015 to 2025, it turns out that the annual regulation improvement rates of China is higher than America and the 2015-2020 regulation of China, which also refers to the China phase IV CAFC regulation, is the most stringent in 10 years from 2015 to 2025. The annual regulation improvement rate of phase IV reaches 6.2% and the closer the date approaches the model year 2020, the more stringent the standards are. So Chinese automakers must employ advanced fuel saving technologies ahead of the late stage of phase IV. Besides, considering the absolute target values and annual improvement rates of China CAFC regulation and the US CAFE regulation, and also the vehicle features and technology starting point of passenger cars in two countries, the stringency of China CAFC regulation is very similar to the US CAFE regulation over the same period. Therefore, the current technology development and future trends of American passenger car are definitely great references for China.

As compared in Figure 5, there are still big gaps between China and the US in the applications of advanced fuel saving technologies. Especially in the development of VVT, GDI, AT, CVT and hybrid technologies, the gaps are still approximately 15%-30% nowadays. Meanwhile, the application rates of advanced technology of self-owned automakers is still far behind the joint venture companies in 2016 [26]. Moreover, from a per-vehicle perspective, technology packages focusing on engine, transmission, accessory efficiency improvement and mass reduction can realize as much as 42-48% fuel reduction and lead to 2.5-3 L/100 km for cars with baseline fuel consumption of 6.2-6.4 L/100 km, which can easily meet the Chinese 5 L/100 km target [15]. Taken together with the technology roadmap research of SAE-China [13], the fuel saving technologies still have a potential of realizing an approximately 40% fuel reduction, which means there is still a big space for the improvement of advanced fuel saving technologies of Chinese passenger cars.

In view of the predictions of American technology trends and roadmaps based on the VOLPE model, the technology strategy is also applicable to China for the compliance of future regulations. Advanced fuel saving technologies such as VVT, VVL, LUBEFR, GDI and CEGR should be employed energetically before 2020. The optimal gasoline engine technology trends for small and large cars may be TGDI and NA-GDI respectively in 2025. The multi-gears is the main trend of automatic transmissions and is the same to manual transmissions, though the pace of manual transmissions is relatively slow. Besides, CVT will also plays an important part in the fuel consumption reduction. Vehicle assembly technologies such as ROLL, AERO, LDB, MR5 and MR7.5, which will realize universal popularization in MY 2025, are crucial to the compliance of future standards. What's more, the vehicle assembly technologies are equally important for conventional propulsion systems and new energy systems. Generally, engine still will plays biggest role in the roadmap through 2025 and the contribution rates of electrification and vehicle assembly technologies will increase gradually. On the contrary, the contribution rates of engine and transmission technologies will decrease year by year. By the improvement and optimization of existing fuel saving technologies, which refer to engine, transmission and vehicle assembly technologies, the 2020 CAFC target can be reached. But large quantities of electrification technologies should be introduced for the MY 2025.

It is worth mentioning that though the 2020 CAFC targets can be reached by means of optimizing the advanced fuel saving technologies, new energy products still need to be laid out in the Chinese market because of the implementation of dual-credit regulations of CAFC and NEV [28, 29]. The advanced fuel saving technologies for conventional propulsion systems and new energy vehicles both should be paid much attention in the long term, especially when the electricity consumption and emission are also included in the regulations.

Conclusions

This paper focuses on the fuel economy regulations and technology development of China and the US and establishes a framework to compare and evaluate the regulations and technologies. By modifying the VOLPE, the study calculates the optimal technology roadmap for the compliance of CAFE regulation and give guidance to the future technology development of China. This study indicates that the absolute target values of China CAFC regulation are more stringent than the target of the US CAFE regulation from 2019 (NEDC cycle) and the annual regulation improvement rates of China is higher than America from 2015 to 2025. Besides, from the perspective of annual improvement rate, the 2015-2020 regulation of China is the most stringent regulation in the future 10 years. The AIR of phase IV reaches 6.2% and the closer the date approaches the model year 2020, the more stringent the standards are. However, considering the vehicle features and technology starting point of passenger cars in two countries, the stringency of China CAFC regulation is very similar to the US CAFE regulation over the same period.

From the perspective of technology, there are still big gaps between China and the US in the applications of advanced fuel saving technologies. Especially in the development of VVT, GDI, AT, CVT and hybrid technologies, the gaps are still approximately 15%-30% nowadays. In the future, advanced fuel saving technologies such as VVT, VVL, LUBEFR, GDI and CEGR should be employed energetically before 2020 and the optimal gasoline engine technology trends for small and large cars may be TGDI and NA-GDI respectively in 2025. The engine still will play the biggest role in the technology roadmap through 2025 and the contribution rates of electrification and vehicle assembly technologies will increase gradually. The multi-gears is the main trend of automatic transmissions and CVT will also plays an important part in the fuel consumption reduction. Vehicle assembly technologies such as ROLL, AERO, LDB, MR5 and MR7.5, which will realize universal popularization in MY 2025, are crucial to the compliance of future standards. By the improvement and optimization of existing fuel saving technologies, namely engine, transmission and vehicle assembly technologies, the 2020 CAFC target can be reached but new energy products still need to be laid out in the Chinese market because of the implementation of dual-credit regulations of CAFC and NEV. Furthermore, 70% hybridization technologies, including Stop-Start, ISG and strong hybrid technologies should be introduced for the compliance of the 2025 regulation. In the long term, the advanced fuel saving technologies for conventional propulsion systems and new energy vehicles both should be paid much attention.

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Definitions/Abbreviations

AT - Automatic transmission

ADSL - Advanced diesel

AERO10 - Aero drag reduction 10%

BEV - Battery electric vehicle

CEGR - Cooled exhausted gas recirculation

CVT - Continuously variable transmission

DEAC - Cylinder deactivation

DCT - Dual clutch transmission

EPS - Electric power steering

FCV - Fuel cell vehicle

GDI - Gasoline direct injection

HCR - High compression ratio

HEV - Hybrid electric vehicle

ISG - Integrated starter generator

IACC - Improved accessories

LUBEFR1 - Improved low friction lubricants and engine friction reduction level 1

MR5 - Mass reduction 5%

MT - Manual transmission

NA - Naturally Aspirated

LDB - Low drag brakes

PHEV - Plug-in hybrid electric vehicle

ROLL10 - Low rolling resistance tires 10%

SAX - Secondary axle disconnect

SS - Stop-start

TURBO1 - Turbocharging and downsizing level 1 (18 bar)

TURBO2 - Turbocharging and downsizing level 2 (24 bar)

TGDI - Turbocharging and gasoline direct injection

VVL - Variable valve lift

VVT - Variable valve timing

Appendix

Technology input (partial)

TABLE A.1 The fuel consumption reduction and costs of technology for passenger car

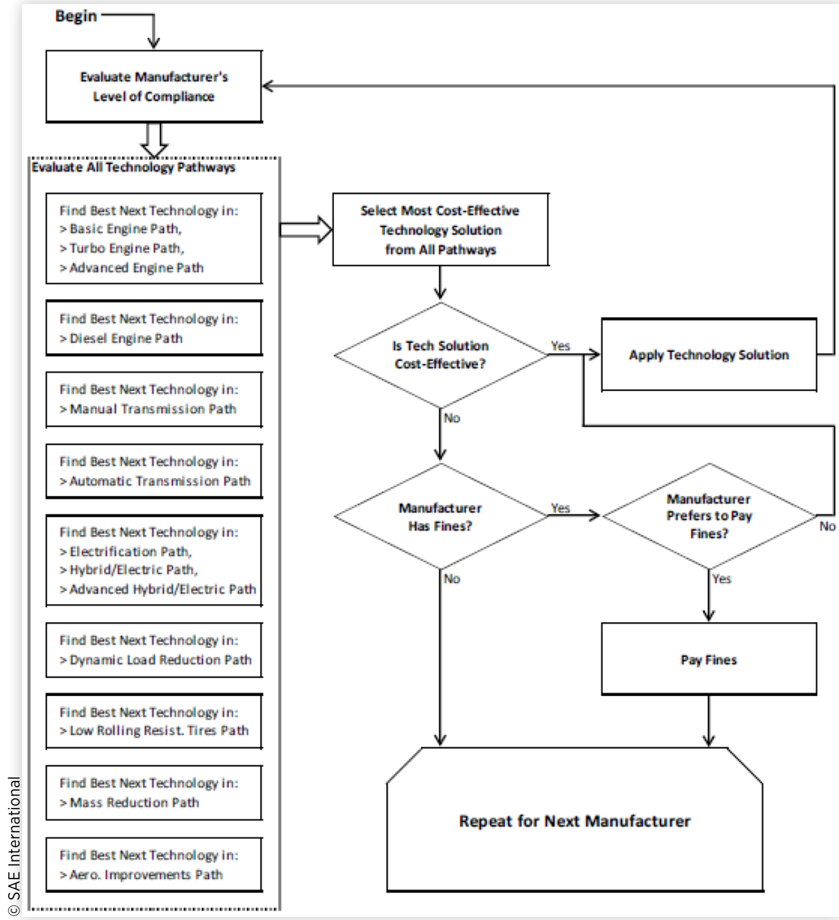
	Small Car					Mid-Size Car					Small SUV				
		Cost ($)					Cost ($)					Cost ($)			
Technology	FC	2015	2020	2025	2030	FC	2015	2020	2025	2030	FC	2015	2020	2025	2030
LUBEFR1	1.6%	60.1	60.14	60.1	60.1	1.6%	80.2	80.18	80.18	80.18	1.6%	100.2	100.2	100.23	100.23
LUBEFR2	0.8%	0.0	11.98	12.0	12.0	0.8%	0.0	15.97	15.97	15.97	0.8%	0.0	20.0	19.97	19.97
LUBEFR3	1.4%	0.0	0.00	20.0	20.0	1.4%	0.0	0.00	26.62	26.62	1.4%	0.0	0.0	33.28	33.28
VVT	4.2%	112.8	100.92	91.2	86.8	4.2%	225.6	201.84	182.45	173.51	4.1%	112.8	100.9	91.23	86.75
VVL	4.3%	230.9	206.60	186.7	177.6	4.3%	307.9	275.46	249.00	236.79	4.0%	384.9	344.3	311.24	295.99
SGDI	2.2%	233.1	208.57	188.5	179.3	2.2%	310.8	278.10	251.38	239.06	2.2%	388.5	347.6	314.22	298.82
DEAC	6.0%	38.6	34.53	31.2	29.7	6.0%	38.6	34.53	31.22	29.69	9.2%	38.6	34.5	31.22	29.69
HCR	3.4%	144.8	124.37	110.1	102.6	3.4%	144.8	124.37	110.14	102.64	2.1%	217.3	186.6	165.21	153.96
TURBO1	6.1%	526.4	470.99	425.7	404.9	6.1%	526.4	470.99	425.74	404.87	1.2%	526.4	471.0	425.74	404.87
TURBO2	3.4%	207.0	185.24	167.4	159.2	3.4%	207.0	185.24	167.44	159.23	2.3%	207.0	185.2	167.44	159.23
EGR	0.2%	349.9	313.06	283.0	269.1	0.2%	349.9	313.06	282.98	269.12	0.4%	349.9	313.1	282.98	269.12
CEGR	1.3%	607.6	543.65	491.4	467.3	1.3%	607.6	543.65	491.42	467.34	−0.2%	607.6	543.7	491.42	467.34
HCR2	3.0%	38.6	34.53	31.2	29.7	3.0%	38.6	34.53	31.22	29.69	3.0%	38.6	34.5	31.22	29.69
CNG	--	158.5	140.28	120.5	108.9	--	158.5	140.28	120.47	108.89	--	158.5	140.3	120.47	108.89
ADSL	14.3%	4,415.5	3,749.15	3,281.8	3,042.4	14.3%	4,128.0	3,485.80	3,034.79	2,806.03	13.3%	4,066.1	3,424.3	2,970.23	2,743.13
TURBODSL	2.5%	28.6	24.59	21.8	20.3	2.5%	28.6	24.59	21.77	20.29	2.5%	28.6	24.6	21.77	20.29
DWSPDSL	2.5%	47.2	40.49	35.9	33.4	2.5%	47.2	40.49	35.86	33.42	2.5%	47.2	40.5	35.86	33.42
EFRDSL	2.5%	107.8	92.56	82.0	76.4	2.5%	107.8	92.56	81.97	76.38	2.5%	107.8	92.6	81.97	76.38
CLCDSL	2.5%	114.5	98.34	87.1	81.2	2.5%	114.5	98.34	87.09	81.16	2.5%	114.5	98.3	87.09	81.16
LPEGRDSL	3.5%	224.0	192.35	170.3	158.7	3.5%	224.0	192.35	170.34	158.73	3.5%	224.0	192.3	170.34	158.73
MT6	3.0%	371.1	332.0	300.1	285.4	3.0%	371.1	332.0	300.1	285.4	1.8%	371.1	332.0	300.1	285.4
MT7	1.0%	327.3	292.9	264.7	251.7	1.0%	327.3	292.9	264.7	251.7	0.9%	327.3	292.9	264.7	251.7
AT6	4.4%	−7.3	−6.3	−5.5	−5.2	4.4%	−7.3	−6.3	−5.5	−5.2	3.9%	−7.3	−6.3	−5.5	−5.2
AT6P	2.7%	0.0	0.0	0.0	0.0	2.7%	0.0	0.0	0.0	0.0	2.7%	0.0	0.0	0.0	0.0
AT8	2.5%	112.5	100.7	91.0	86.5	2.5%	112.5	100.7	91.0	86.5	2.2%	112.5	100.7	91.0	86.5
AT8P	2.0%	309.3	265.6	235.2	219.2	2.0%	309.3	265.6	235.2	219.2	2.0%	309.3	265.6	235.2	219.2
DCT6	6.5%	52.2	44.8	39.7	37.0	6.5%	52.2	44.8	39.7	37.0	7.9%	52.2	44.8	39.7	37.0
DCT8	2.8%	327.3	292.9	264.7	251.7	2.8%	327.3	292.9	264.7	251.7	2.1%	327.3	292.9	264.7	251.7
CVT	4.6%	301.5	258.9	229.2	213.6	4.6%	301.5	258.9	229.2	213.6	3.0%	301.5	258.9	229.2	213.6

TABLE A.1 (Continued) The fuel consumption reduction and costs of technology for passenger car

	Small Car					Mid-Size Car					Small SUV				
		Cost ($)					Cost ($)					Cost ($)			
Technology	FC	2015	2020	2025	2030	FC	2015	2020	2025	2030	FC	2015	2020	2025	2030
EPS	1.5%	143.8	128.6	116.3	110.6	1.5%	143.8	128.6	116.3	110.6	1.2%	143.8	128.6	116.3	110.6
IACC1	1.2%	116.9	104.6	94.6	89.9	1.2%	116.9	104.6	94.6	89.9	1.0%	116.9	104.6	94.6	89.9
IACC2	1.9%	72.2	64.6	58.4	55.5	1.9%	72.2	64.6	58.4	55.5	1.7%	72.2	64.6	58.4	55.5
SS12V	3.8%	410.2	363.2	311.9	281.9	3.8%	450.4	398.8	342.4	309.5	3.6%	483.8	428.3	367.8	332.4
BISG	5.7%	1156.2	725.8	609.8	538.5	5.7%	1116.0	690.2	579.2	510.9	4.9%	1082.7	660.7	553.9	488.0
CISG	12.6%	2438.7	1884.4	1335.5	1194.5	12.6%	3243.1	2524.5	1813.7	1626.8	9.9%	3227.2	2508.9	1798.9	1613.3
SHEVP2	20.0%	2032.5	1889.3	1722.0	1650.3	20.0%	3261.3	2917.0	2636.6	2507.2	21.1%	2332.4	2139.2	1944.2	1858.3
SHEVPS	27.2%	750.0	730.6	996.3	994.3	27.2%	1134.2	1082.7	1402.1	1391.3	21.3%	187.9	290.9	699.2	732.9
PHEV30	60.0%	14861.9	8731.7	7395.1	6659.3	60.0%	24338.6	14527.0	12264.9	11031.2	59.5%	17186.5	10087.7	8521.3	7660.3
PHEV50	75.7%	6720.0	4172.6	3638.1	3336.1	75.7%	11397.6	6567.6	5554.1	4981.4	75.7%	7760.5	4705.4	4064.3	3702.0
BEV200	100%	13767.4	6352.1	5027.5	4242.9	100%	13407.6	5825.5	4492.1	3681.8	100%	17019.1	7603.2	5932.7	4944.7
FCV	100%	5601.9	10868.7	10056.5	9402.9	100%	−9781.3	1650.7	2356.1	2528.8	100%	1936.8	8730.0	8281.9	7827.9
LDB	0.8%	93.0	93.0	93.0	93.0	0.8%	93.0	93.0	93.0	93.0	0.8%	93.0	93.0	93.0	93.0
SAX	1.4%	128.4	114.8	103.8	98.7	1.4%	128.4	114.8	103.8	98.7	1.4%	128.4	114.8	103.8	98.7
ROLL10	1.2%	8.5	8.5	8.5	8.5	1.2%	8.5	8.5	8.5	8.5	1.4%	8.5	8.5	8.5	8.5
ROLL20	1.3%	100.2	80.2	56.8	50.8	1.3%	100.2	80.2	56.8	50.8	1.4%	100.2	80.2	56.8	50.8
MR1	1.1%	0.5	0.4	0.4	0.4	1.1%	0.5	0.5	0.4	0.4	1.2%	0.5	0.4	0.4	0.3
MR2	0.5%	1.3	1.1	1.0	0.9	0.5%	1.4	1.2	1.0	1.0	0.6%	1.2	1.0	0.9	0.8
MR3	2.8%	2.3	2.0	1.8	1.7	2.8%	2.5	2.1	1.9	1.8	3.0%	2.9	2.5	2.2	2.0
MR4	2.6%	3.0	2.6	2.3	2.1	2.6%	3.1	2.6	2.3	2.2	2.4%	4.0	3.4	3.0	2.8
MR5	1.9%	1.6	1.4	1.3	1.2	1.9%	1.4	1.2	1.1	1.0	2.5%	2.7	2.3	2.1	1.9
AERO10	2.0%	64.3	57.5	52.0	49.4	2.0%	64.3	57.5	52.0	49.4	2.0%	64.3	57.5	52.0	49.4
AERO20	2.0%	192.8	172.5	156.0	148.3	2.0%	192.8	172.5	156.0	148.3	2.1%	192.8	172.5	156.0	148.3

Compliance simulation algorithm

FIGURE A.1 Compliance simulation algorithm of VOLPE model



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