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Heuristic method for automakers' technological strategy making towards fuel economy regulations based on genetic algorithm: A China's case under corporate average fuel consumption regulation

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HIGHLIGHTS

- Technology combination problem is formulated and proven NP-hard.
- The proposed heuristic algorithm can decrease the compliance cost by 14.1%
- The commonly used method overvalues the effectiveness of mass reduction technology.
- Conventional technologies are more cost-effective to meet China's 2020 regulation.

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ABSTRACT

The vehicle fuel economy standards have been implemented worldwide. However, it is quite difficult for the automakers to secure an optimal portfolio of fuel-efficient technologies which complies with these strengthened standards and minimizes the overall cost at the same time. In this paper, a genetic-algorithm-based heuristic method is proposed for technological strategy planning. In particular, a case study of the Corporate Average Fuel Economy standards in China is presented. Moreover, the mathematical model is constructed with the considerations of the technology cost, effect of reducing fuel consumption and technology physical weight. Problem complexity is analyzed and proven NP-hard. Moreover, a comparison analysis of performance is carried out between the elaborated genetic algorithm and the greedy algorithm that is currently used by most automakers to determine the technological strategies in China. The results imply that genetic algorithm outperforms the common method because it provides more economical and reasonable strategies. In addition, the incremental cost under the greedy algorithm is 16.4% higher than that under genetic algorithm. Due to the counteractive effect under the weight-based standards in China, the mass reduction technologies should be given lower priorities compared with current strategies. To satisfy the standards by 2020, automakers should implement more conventional engine and transmission technologies instead of the hybrid electric vehicle technologies. It is recommended that automakers should develop heuristic algorithms to make strategic decisions more reasonably.

1. Introduction

Since the Corporate Average Fuel Economy (CAFE) was first established in the United States in 1970s, the standards to improve the vehicle fuel economy have been spreading worldwide. Especially in the past decade, 9 countries and regions have initially issued or updated their fuel economy standards. Table 1 presents the fuel economy targets and standards structures in the main vehicle markets [1]. As the fuel

Abbreviations: ABC, Artificial bee colony; AT, Automatic transmission; ANN, Artificial neural network; AWD, All wheel drive; BEV, Battery electric vehicle; CAFC, Corporate average fuel consumption; CAFE, Corporate average fuel economy; CVT, Continuous variable transmission; DCT, Duel clutch transmission; DOHC, Double overhead camshaft; EGR, Exhaust gas recirculation; FCR, Fuel consumption rate; FCV, Fuel cell vehicle; GA, Genetic algorithm; GDI, Gasoline direct injection; HEV, Hybrid electric vehicle; ICE, Internal combustion engine; MPG, Mile per gallon; NP-complete, Nondeterministic polynomial-time complete; NP-hard, Nondeterministic polynomial-time hard; OEM, Original equipment manufacturer; PDA, Partial discrete approximation; PHEV, Plug-in hybrid electric vehicle; PSO, Particle swarm optimization; SA, Simulated annealing; SOHC, Single overhead camshaft; TC, Technology Combination problem; TCAFC, Target of corporate average fuel consumption; TIES, Technology identification, evaluation and selection; TRS, Three rows of seats; TS, Tabu search; V6, V engine six cylinders

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Table 1
Fuel economy regulations and structures in main automobile markets.

Country or Region	Target year	Standard type	Fleet target/ Measure	Converted fleet target (g/km)	Structure	Test cycle
EU	2021	CO2	95 gCO2/km	95	Weight-based corporate average	NEDC
China	2020	Fuel consumption	4.9 L/100 km	117	Weight-class based per vehicle and corporate average	NEDC
U.S.	2025	Fuel economy	56.2 mpg	97	Footprint-based corporate avg.	U.S. combined
Canada	2025	GHG	56.2 mpg	97	Footprint-based corporate avg.	U.S. combined
Japan	2020	Fuel economy	20.3 km/L	122 (exceeded by 2013)	Weight-class based corporate average	JC08
India	2021	CO2	113 g/km	113	Weight-based corporate average	NEDC
South Korea	2020	Fuel economy	24.3 km/L	97	Weight-based corporate average	U.S. combined

economy targets are getting more stringent, technology strategy satisfying the standards will become the main subject in automobile industry. It should be noted that China is the main contributor in the growing vehicle market. In particular, the automotive industry has been developed dramatically in China over the past 15 years. By the end of 2015, the vehicle stock has increased tenfold to 172.2 million [2]. Hao et al. estimated that by 2050, the vehicle population would reach 606.7 million [3]. Subsequently, the on-road vehicles have become the major CO_2 emitters and oil consumers as the result of the booming automotive industry.

China has announced four phases of fuel economy standards concerning the light-duty vehicles. In particular, the Corporate Average Fuel Consumption (CAFC) system has been established since Phase III, which requires Original Equipment Manufacturers (OEM) to meet the fleet average fuel consumption rate (FCR) targets. During the past 9 years after the release of the Phase I regulation, a 14.7% national fleet-wide fuel economy improvement has been achieved [4,5]. However, the strengthening CAFC regulation at the current phase requires OEMs in China to improve the fleet FCR by 4.5 ~ 9.1% annually, as shown in Fig. 1. Therefore, the technological strategy making is of vital importance to comply with the standards. An OEM needs to optimally select several sets of fuel-efficient technologies to its assortment.

2. Literature review

Two strategies for regulation compliance have been widely explored. One strategy is to measure the technology improvements and compromise the trade-offs of vehicle attributes, which mostly includes fuel economy, acceleration time and size. Lutsey and Sperling [6] assessed the standards in terms of technology improvements. Luk, et al. carried out the simulation of tradeoffs among vehicle price, performance and interior volume to meet the 2025 fuel economy target [7]. By measuring the vehicle potential fuel economy improvement with the consideration of vehicle attribute trade-offs, the difficulty complying with next phase standard could be quantified [8]. Another strategy is to evaluate the promising and advanced technology roadmaps. Some studies assessed the potential of improving fleet-wide vehicle fuel economy by setting various scenarios with different policy instruments and penetration rates of the advanced technologies [9,10,11]. Meanwhile, some studies analyzed the availability and potential of fuel-efficient technologies as well as the technology roadmaps to meet current standards and beyond [12,13]. Simmons et al. reviewed the fuel economy technologies that were available in 2014 model year. The results demonstrated OEMs with new insights into what the fuel-efficient technology roadmap would be [14].

There were several methods used in the OEM's decision-making studies. In particular, these methods include the utility function in conceptual and preliminary design stages [15], strategic decisions to improve profitability according to the vehicle production volume in flexible manufacturing system [16], design decisions with demand distributions forecasted by exogenous variables [17], and cost-benefit analysis to minimize the technology cost while complying with the energy-saving requirement [18]. Moreover, the responses of OEMs are examined under various regulation stages and scenarios in other studies. Oh et al. generated several strategies for the main OEMs to satisfy the fuel economy regulations in Korea and made scenario analysis. They found OEMs could only satisfy the standards by employing at least two strategies [19]. Shiau et al. simulated OEMs' responses under low, moderate and high CAFE requirements respectively. They found that improving the CAFE standards should cooperate with the increase of the penalty for violation to guarantee the effectiveness of CAFE [20]. Besides the stringency of the standards, an appropriate regulatory lead-

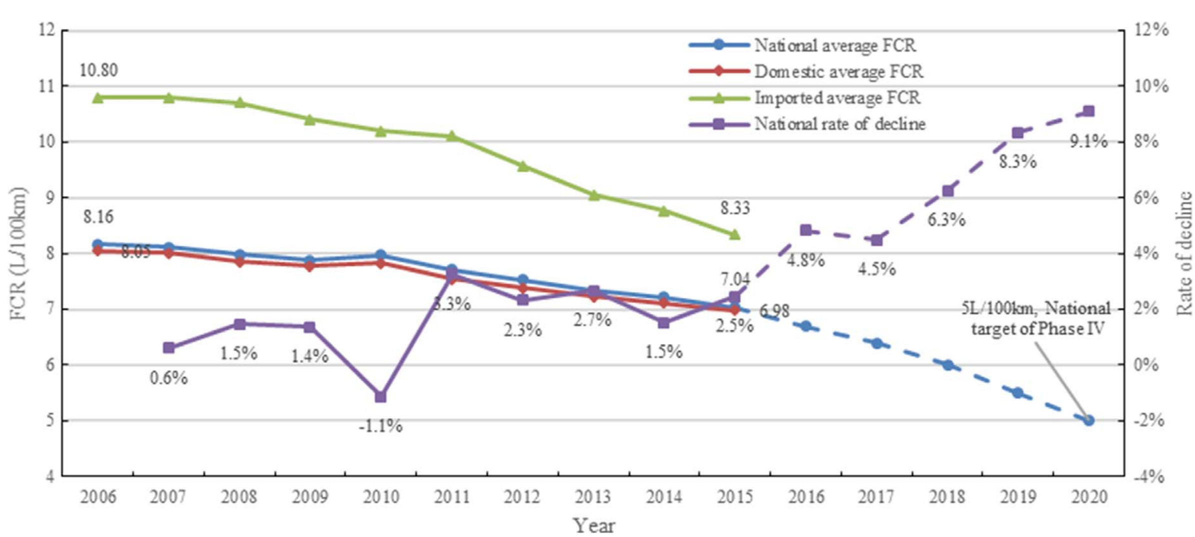

Fig. 1. China's fleet-wide FCR and the future targets. Note: dotted line is estimated according to the phasing in of phase IV CAFC standards.