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A game theoretic approach for analyzing electric and gasoline-based vehicles' competition in a supply chain under government sustainable strategies: A case study of South Korea

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ABSTRACT

This study investigates the issue of electric vehicle (EV) pricing, as well as the issue of determining the extent of electric vehicles' technological improvements on gasoline vehicles (GVs). Furthermore, it looks at four important goals in line with government sustainability plans including the number of EVs, CO_2 emissions reduction (ER), revenue seeking (RS), and customer surplus (CS). Two strategies, including a tax optimization strategy (TO-strategy) and a subsidy optimization strategy (SO-strategy), are suggested in this study as ways to reach the four goals by finding optimum values for four decision variables. Two decision variables of the TO-strategy are the determinations of a GV and gasoline taxes. SO-strategy decision variables are the determinations of a manufacturer and consumer subsidies. The cooperation of government in R&D expenditures is considered as a manufacturer subsidy. The EV manufacturer will optimize research and development efforts to improve the level of EV technology and the government will optimize its share of cooperation in expenditure of the manufacturer's R&D programs. The problem under study is solved by a backward induction procedure. The obtained results are challenging and are not straightforward. For instance, if the government seeks to maximize the number of EVs, or wants to minimize pollution, or maximize revenue, it should consider a tax optimization strategy. Under the **TO-strategy**, if the government has RS or CS goals, the government must increase the GV tax and decrease the fuel tax. Under the ***SO-strategy***, the government must increase its manufacturer subsidy and decrease its customer subsidy.

1. Introduction

"The energy supply from fossil fuels grew in nine G20 countries–Australia, Canada, China, India, Indonesia, Russia, South Africa, South Korea, and the U.S.–mainly due to increased fuel usage in transportation and higher electricity demand …. 82% of the G20's energy mix is still fossil fuels. This must fall to at least 67% by 2030 and to 33% by 2050 globally to be 1 .5 °C compatible, and ultimately too much lower levels—and to substantially lower levels without CCS. G20 countries need to cut their current greenhouse gas (GHG) emissions by at least 45% in 2030 (below 2010 levels) …. They must reach net-zero emissions by 2070." [1].

Climate change is broadly confirmed as the biggest worldwide environmental problem and challenge [2,3]. Therefore, climate protection objectives, such as reducing local emissions, and strategically securing energy, are some important reasons why policy makers are interested in reducing the consumption of fossil fuel [4]. Sustainable transportation, clean production of power, and sustainable ("green") buildings are important domains for addressing climate change reduction [5]. Due to the speed of urbanization and the progression of people's living standards, energy consumption has increased rapidly, especially in the transport sector [6]. This sector, as the greatest consumers of energy and producers of greenhouse gas (GHG) emissions, consumes 29% of the world's energy overall, and about 30% of the energy in developed countries [7]. This sector also consumes 65% of the world's oil products and accounts for about 24% of the world's total carbon dioxide emissions [8]. A quarter of CO_2 emissions in China come from transportation [9,10], which is mainly reliant on fossil fuels [11,12]. In this sector, the chief cause of emissions is the large number of

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Abbreviations

ADWSC	Average distance a vehicle can go with a single charge
BEV	Battery electric vehicle
CS	Customer surplus
ER	Emissions reduction
EVs	Electric vehicles
GHG	Greenhouse gas
GVs	Gasoline vehicles
KRW	Korean Republic won
LCVs	Light-commercial vehicles
PHEV	Plug-in hybrid vehicle
PLDVs	Passenger light-duty vehicles
R&D	Research and development
RS	Revenue seeking
SO-strategy	Subsidy optimization strategy
TO-strategy	Tax optimization strategy

Parameters

α	Market base for the vehicle
β	Vehicle demand's sensitivity to vehicle price (i.e., self-price elasticity (vehicle/currency))
β_f	Sensitivity of the GV demand to fuel price (vehicle/currency)
γ	Vehicle demand's sensitivity to price of other vehicles (i.e., cross-price elasticity (vehicle/currency))
γ_f	Sensitivity of the EV demand to fuel price (vehicle/currency)
$\zeta^{\cdot}$	Upper bound of the decision variable
ζ^{EV}	The government's lower bound of the number of EVs
ζ^{ER}	The upper bound of the government's CO_2 emissions reduction goal
ζ^{RS}	The lower bound of the government's revenue-seeking goal
ζ^{CS}	The lower bound of the government's consumer surplus goal
λ	Amount of EV demand's growth if the average distance a vehicle can go with a single charge (ADWSC) is increased by 1%
ω	Market share for gasoline-based vehicles
e	Fuel consumption of GV during useful life (unit of volume/unit of time)
k_1	GV pollution (unit of CO_2/vehicle)
k_2	EV pollution (unit of CO_2/vehicle)
p_f	Fuel (for example gasoline), price (currency/unit of volume)

Decision variables

δ	Manufacturer subsidy (dimensionless)
σ	Percentage of ADWSC improvement (%)
p_1	Selling price of GV (currency/vehicle)
p_2	Selling price of EV (currency/vehicle)
s	Customer subsidy for buying an EV (currency/vehicle)
t	The tax of GV (currency/vehicle)
t_f	The tax of fuel (currency/unit of volume)

Demand and profit functions

π_1	The profit of Manufacturer 1′ for total production (currency)
π_2	The profit of Manufacturer 2 for total production (currency)
π_g^{CS}	Government function of government's consumer surplus goal (distance unit/time unit)
π_g^{ER}	Government function for government's CO_2 emissions reduction goal (volume unit/time unit)
π_g^{EV}	Government function for government's number of EVs goal (vehicle)
π_g^{RS}	Government function for government's revenue-seeking goal (currency/time unit)
D_1	Demand for the GV (vehicle)
D_2	Demand for the EV (vehicle)

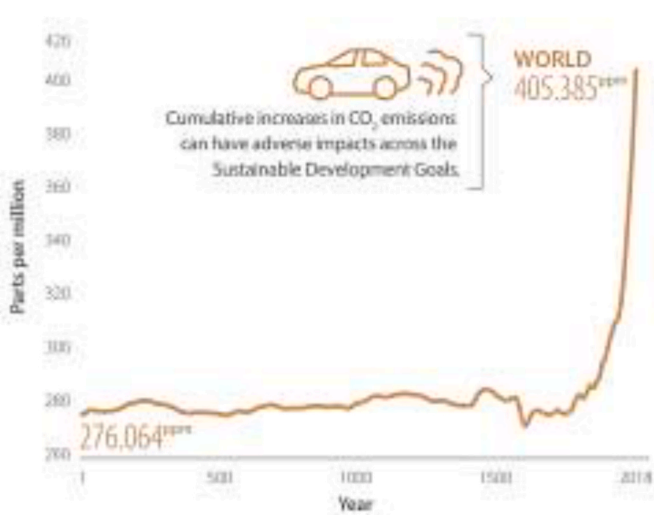

Fig. 1. CO_2 emissions trend [20].

vehicles driven by people (see Fig. 1). Bearing this out is the statistic that more than 0.6 billion vehicles currently exist in the world [13]. To reduce global warming, the ratio of low-carbon fuels would need to increase roughly tenfold by 2050 in the G20's transport fuel mix. Therefore, it is essential to identify critical challenges in the transport sector and to address opportunities to avoid environmental problems, especially carbon emissions [14]. Hybrid and electric vehicles (EVs), as the ideal mode of transportation [15], are a suitable approach for ensuring improvements in emission reductions and fuel saving [15–19].

EVs, as environmentally friendly technologies, offer improvement in air quality as well as other advantages, such as minor noise pollution, cheaper recharge options, lower maintenance fees [21,22], and higher energy efficiency [23–25]. They are, for those reasons, sound options for moving toward sustainability [26–30]. Therefore, EVs have received wide acceptance worldwide [31] and have become more and more popular in developed or developing countries [32]. In conclusion, countries are looking to replace GVs with EVs to draw on these benefits, and have implemented numerous support programs to help them do so [33]. In keeping this strategy, EV manufacturers in the Far East such as China, Japan, and South Korea have managed to overcome obstacles of commercialization of EVs for more than two decades [34].

In its most recent global perspective on energy, the International Energy Agency stated that the need for EVs will reach 875 million by 2040 [35]. The market share of these types of vehicles is increasing; in China, for example, the number of EVs sold in 2015, 2016, and 2017 was 331,000, 507,000, and 777,000, respectively [29]. The EV30@30 Campaign that launched in June 2017 seeks to attain a 30% market share of EVs by 2030; members of such campaigns are significant

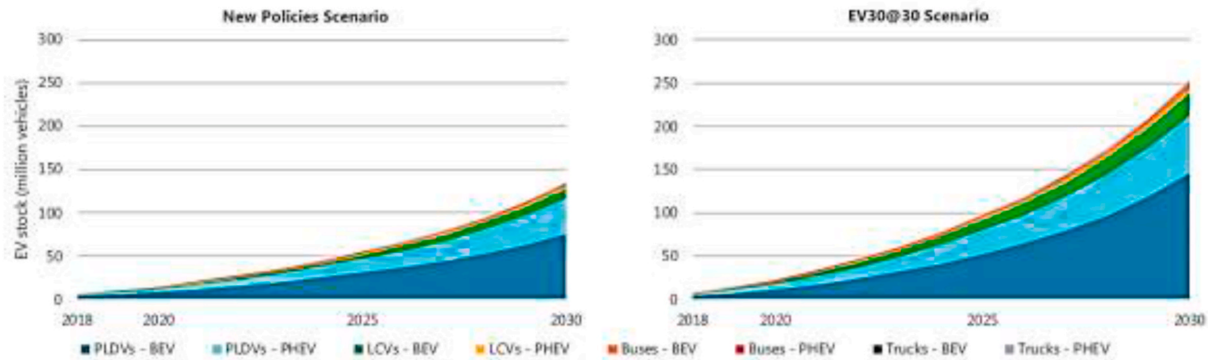

Fig. 2. Future of EV stock by two scenarios, 2018–30 [38]. Note: PLDVs = passenger light-duty vehicles; LCVs = light-commercial vehicles; BEV = battery electric vehicle; PHEV = plug-in hybrid vehicle.

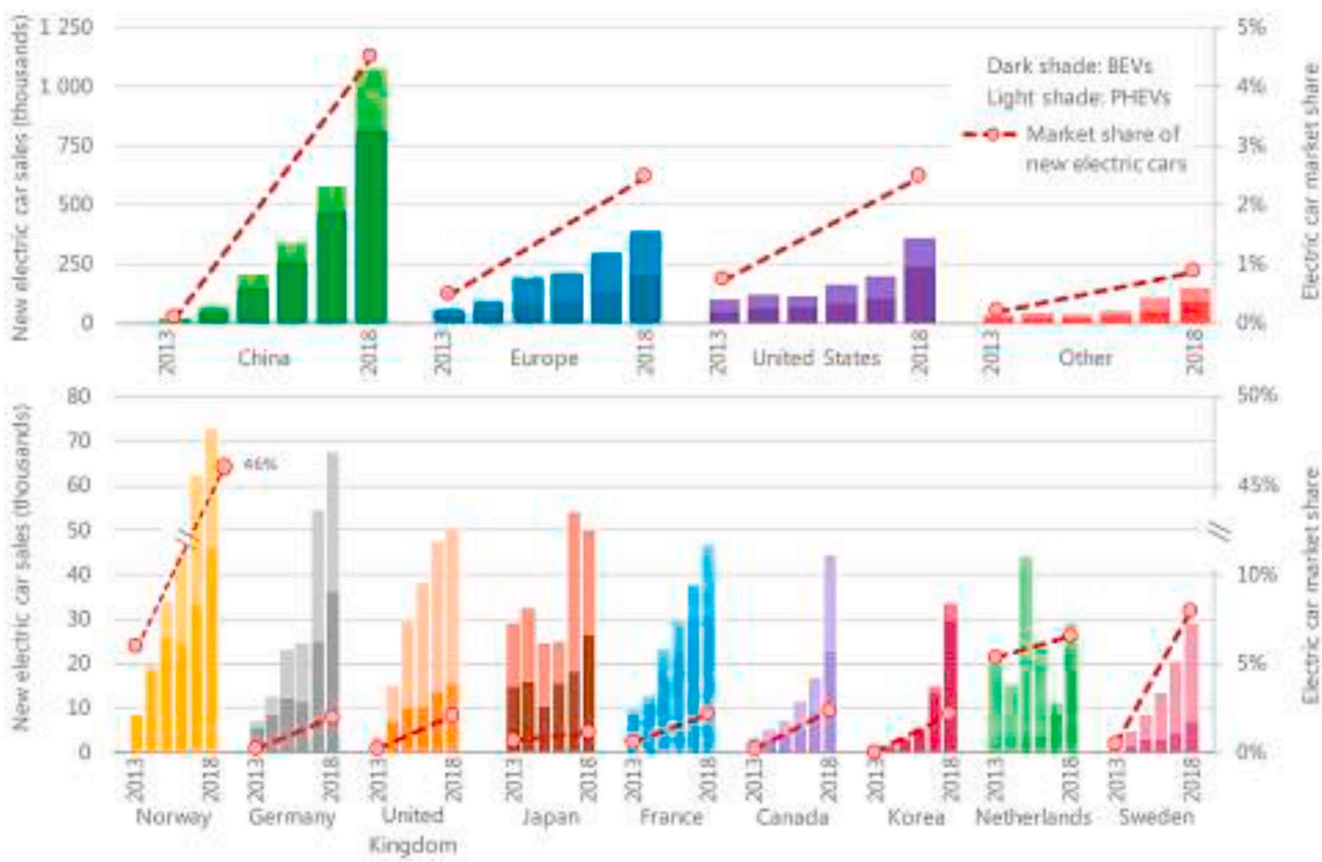

Fig. 3. Market share and car sales of global EVs, 2013–2018 [38]. Note: BEV = battery electric vehicle; PHEV = plug-in hybrid vehicle.

economies such as China, Japan, and India [36,37]. Fig. 2 shows that the global EV stock, according to the new policies scenario, will be more than 130 million by 2030. In the EV30@30 scenario, EV stock will be more than 250 million. In 2030, the projected share of EVs in India will be 29%, more than 30% than it will be in the United States and Canada, more than 37% of what it will be in Japan, and more than 22% of what it will be in all other countries, in aggregate [38]. South Korea designed a plan to increase the domestic sale of EVs from 2.5% in 2019 to 33% of Korea's new vehicle sales by 2030 [39]. Fig. 3 shows the market share trend and the number of sales of EVs for some countries [38].

This study analyzes the competition between two vehicle supply chains—a gasoline-consuming vehicle (GV) and an electric-consuming vehicle (EV)—by 2030—by addressing a case study from South Korea. The findings were analyzed with regard to South Korean government policies, and the suggestions, based on the results, are aimed at achieving sustainable development goals in the field of EV manufacturing. Given the importance of government decisions in the field of sustainability [40], four goals include maximizing the number of EVs (EV goal), minimizing CO_2 emission (ER goal), maximizing government revenue (RS goal), and maximizing consumer surplus (CS goal) as one of the indicators for social welfare. To reach these goals, two types of strategies, a TO- and SO-strategies, are discussed. Therefore, in this study, eight scenarios for the South Korean government are studied. GV and fuel taxes are considered for the TO-strategy; and a customer and manufacture subsidies are taken into account for the SO-strategy. The South Korean government wants to optimize a tax value for GVs and fuel for the first strategy and to optimize an EV subsidy for the end-user as the buyer of EVs, along with a share of cooperation in expenditure by the manufacturer in R&D programs for the second (or “cost-sharing”) strategy. According to our knowledge, this research, for the first time, investigates this issue. Moreover, several results and managerial insights are provided for decision-makers. The current study aims to respond to these research questions:

RQ 1. *What are the equilibrium prices of GV and EV under different South Korean government goals and strategies? How much should the EV manufacture try to improve the average distance a vehicle can go with a single charge?*

RQ 2. *What are the South Korean government equilibrium taxes and subsidies for the goal? In other words, what amount of government decision variables optimizes the four goals?*

RQ 3. *From the manufacturers' viewpoint, what type of strategies for the South Korean government is most profitable? From this point of view, which goals are the manufacturers most interested in?*

RQ 4. *From the South Korean government's viewpoint, what strategy will help further sustainability goals (i.e., the number of EVs, ER, RS, and CS goals as mentioned in the last paragraph before research questions)?*

RQ 5. *Which scenario is the best- or worst-case for consumers?*

Following, in Section 2, a brief literature review is provided. The problem definition is presented in Section 3. Section 4 includes equilibrium solutions. A case study, as well as results and insights, are provided in Section 5 and a summary of the research is provided in the last section.

2. Literature review

In recent years, a marked increase in the number of research related to EVs has been observed; for example, the optimization of electric car-sharing systems [41–43], the planning and designing of EV charging infrastructure [44–55], optimization of EV battery charging and purchasing [56], and EV battery scheduling [57–60]. In addition, there are many comprehensive reviews of EV-related issues, such as seen in Refs. [16,25,30,61–67]. According to Hu et al. [68], the focus of research in this area include: (1) on the supply side, core technology innovation of EVs; (2) on the demand side, research market aspects of EVs; (3) on the development side, research into factors that affect EV industry, such as oil-price and electricity. In this study, the literature on the factors affecting the demand for EVs, the role of governments in supporting these vehicles, and the application of game theory to issues related to EVs are reviewed.

2.1. Factors affecting demand for Evs

According to Egbue and Long [69], the price of an EV is significantly higher than that of a GV, and this price increases linearly with increasing battery size and range of the EV. This significantly different price between the vehicles creates barriers to the widespread adoption of EVs. More than half of the respondents in this study mentioned that price is the major shortcoming of EV [70,71]. According to the study by Klöckner [72] and Barth et al. [73], the purchase price is one of the most important and critical factors influencing the widespread use of EVs. They state that the eco-friendly nature and lower maintenance costs of EVs as opposed to GVs are the most positive features consumers cite in buying EVs. Gas prices and government incentives are two factors that influence customers' buying of EVs [74]. Zhang et al. [75] studied the EV purchasing behavior of consumers in China and found that a financial incentive, performance characteristics, environmental awareness and mental needs are essential factors in influencing consumers. Performance attributes are the most critical factor in the purchasing decisions of consumers of EVs in China. Hardman et al. [76] came to a deeper understanding of the incentives that motivate customers to buy EVs. According to their study, incentives are needed prior to purchasing (not afterward) in order for customers to apply them. In addition to incentives, awareness-raising and training campaigns are required to promote the purchase of EVs. These training campaigns should increase customer awareness of incentive schemes.

Lin and Wu [77] examined the behavior of customers buying EVs in the major cities of Beijing, Shanghai, Shenzhen, and Guangzhou, China. Their study found that factors such as price, vehicle performance, government subsidies, environmental concerns, and demographic characteristics influenced customers' behavior in buying EVs. Huang and Ge [78] identified product perception, monetary incentive policies, subjective norms, and non-financial incentive policies as factors that affected the buying of EVs in Beijing. These factors were extracted from 502 valid responses to a survey taken by potential consumers of electric vehicles. Tarigan [79] found that the three factors of cost, convenience, and safety were the most influential in affecting customers' decisions to buy EVs in a Norwegian city. These factors were obtained from a telephone survey of more than 1,279 people in Greater Stavanger, Norway. Kim et al. [80] showed that previous driving experience with EVs, the number of vehicles in a household, the education level of buyers, the types of incentives from the South Korean government, and the awareness of customers regarding the benefits of a public park are all factors that influence customers in buying an EV. Kim et al. [81] cited factors such as changes in technology levels, reduced purchasing prices due to government subsidies, and reductions in GHGs with the adoption of alternative fuel vehicles as factors that could change South Korea's EV market share. Based on the above literature, the cost-related factors such as the purchase price, price of alternative fuels, limited range, and so forth are expressed more than other factors for buying EVs. Therefore, government strategy decisions, like subsidy incentives, increase the demand for EVs. Meanwhile, some researchers (for example, [82]) argue that boosting customers' education and awareness levels are better ways to increase EV purchases than government incentives. Other research has shown that campaigns are essential for customer awareness about incentive schemes to increase EV purchases. Other factors, such as psychological needs and subjective norms, are related to individuals' acceptance levels of EVs, yet they are not prominently perceived as affecting the rate of EV purchasing by consumers. In our study, the ADWSC and purchasing price are considered. The ADWSC is considered as an incentive for buying EVs when compared against a limited driving range. The limited range was mentioned as a disadvantage that influences purchasing decisions of EVs among customers.

2.2. The role of governments in promoting Evs

According to the study by Li et al. [83], the Chinese government has provided several strategies to promote the use of EVs, including preferential taxation, technical support, industry management, and subsidies. They also analyzed customer feedback on government policy choices based on questionnaire data. Zhang et al. [84] divided the Chinese government's support for EVs into three categories: fiscal policy, infrastructure upgrading, and R&D. The Japanese government set out a series of Japanese revitalization strategies, such as initial demand development, support for R&D to improve vehicle performance, and infrastructure development to increase 50–70% of sales of new-generation vehicles by 2030 [85]. The U.S. government has supplied incentives for the use of EVs (for example, subsidies and the allocation of financial resources for the charging infrastructure). These incentives are generally divided into three categories: (1) R&D; (2) investment in EV charging infrastructure and service equipment; and (3)

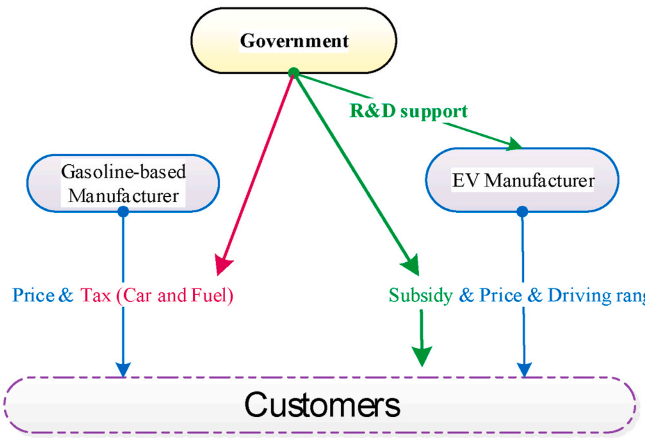

Fig. 4. Structure of the under-hand problem. Note: EV = Electric vehicle.

vehicle tax credit [86,87]. European governments also have adopted policies to increase the use of EVs. Austria exempts fuel and monthly car taxes; Finland offers tax exemption; Italy offers two-year annual circulation tax exemption; Denmark offers tax exemption and free parking; Germany offers five-year exemption from the yearly road tax, and Portugal and Ireland have considered tax exemptions for automobiles as protection policies for EVs [88]. Governments need to sell more EVs by upgrading their charging infrastructure and observing charging standards [89].

The South Korean government has developed some financial and non-financial incentives to improve the EV market. In 2017, about 14 million won (about $12,900) from the central government, and about 3–12 million won (about $2,764 to $11,058) from the local government were allocated for a certain number of EVs. Similarly, the South Korean government has taxed the sale of EVs, and since 2017 has expanded support, commissioning, and installation of charging infrastructure for EVs [90].

The above-mentioned studies indicate that monetary incentives, similar to tax exemptions, have become an important strategy to lower EV prices and encourage technological transformation in many countries. The EV market will be developed through a legislative framework and the promotion of R&D plans. Therefore, many countries such as South Korea, China, and the U.S. have adopted necessary procedures related to R&D support for EVs. If the charging infrastructure is not suitable, however, then fewer customers choose EVs. From this perspective, investing in EV charging infrastructure and service equipment is seen as another government support. These policy incentives are generally divided into three categories: (1) monetary incentives; (2) R&D; and (3) investment in EV charging infrastructure and service equipment. Our study has applied government policies (1) and (2) to support the EV market.

2.3. *Application of game theory in related to Evs problems*

In recent years, the game-theoretic approach as a formal analytical framework with a systematic mathematical tool has been used to examine pricing, government policies, and obtain equilibrium values for other variables in the supply chain of EVs. The framework analyzes several agents or players with interrelated behaviors [6,91,92].

Luo et al. [93] examined an automotive supply chain with one manufacturer and one retailer. In this supply chain, the government pursues a state-of-the-art air pollution reduction plan, a price reduction plan, and a subsidy ceiling for EVs. Unlike retail pricing, which is common in most research, they modeled negotiation of the retail price for each customer. Shao et al. [94] examined the gasoline and EV market in two monopoly and duopoly structures. In this study, the South Korean government uses discount price and subsidies to promote the EV market for social welfare. Their model developed a framework for equilibrium subsidies and optimal discount rates for policymakers. Liu et al. [95] examined the effects of government policies on the development of the EV industry using an evolutionary interplay between automakers and government subsidies. The interplay existed under three scenarios: tax and subsidy fixed, subsidy fixed and tax dynamic, and tax fixed and subsidy dynamic.

Zhu et al. [96] presented a three-tiered Stackelberg model to examine subsidies, charging prices, the number of charging infrastructures, and the market share of EVs between three players, including China's government, charging infrastructure investors, and customers of EVs. One of the limitations of their study was that they considered only one investor for charging infrastructure. Li et al. [97] examined the effect of taxes and government subsidy policies on the adoption of EVs in China, using an evolutionary game on a complex network. Their study found that increasing the manufacturers in the network caused the degree of EV adoption rates to rise at the same level as was seen with a government policy. Gu et al. [98] studied competition between two vehicle supply chains. The first supply chain comprised an EV manufacturer and its relevant retailer, and the second supply chain included a GV manufacturer and its related retailer. A Stackelberg game was presented to investigate the vehicle's supply chain with incomplete information. One of the points of their study is considering the imperfect information conditions for the EV market. Li et al. [99] examined, with a Stackelberg game, the competition between fuel-cell and electric-vehicle manufacturers in light of battery recycling rates and the understanding of performance evaluation. Hu et al. [68] analyzed an evolutionary game of "small world" network models (Newman and Watts [100]) to address the dynamic effects of several Chinese government strategies on the disbursement of EVs. The results show that subsidies given to manufacturers for the production of EVs have a greater effect on EVs than subsidies given to consumers for their purchase of EVs.

Recently Rasti-Barzoki and Moon [6] considered a pricing problem for supply chain members that included a GV manufacturer and a fuel supplier with a government intervention that did not address EVs. According to our review of existing literature and research gaps, this study, for the first time, examines the competition between an EV and a GV supply chain. We consider four governmental goals. These four goals include maximizing the number of EVs, minimizing carbon emissions, maximizing revenue, and maximizing consumer surplus. The minimizing carbon emissions and maximizing revenue goals data are obtained from the work cited in Ref. [6] but with different formulations, due to the consideration of EVs in our problem. The government has adopted two strategies—TO and SO—to achieve its goals. In the TO-strategy for the GV supply chain, the government imposes two types of taxes on cars and fuel, and the SO-strategy it examines customer subsidies and R&D support to the manufacturer. The decision variables for the government are fuel tax rates, car taxes, customer subsidies for EV purchases, and the determination of the percentage of contribution to EV producer's R&D costs. The GV manufacturer is also pricing its vehicle and manufacturing costs according to EV pricing. As stated in the literature review, one of the factors influencing EV demand is the driving range these types of vehicles are capable of. Therefore, for the first time,

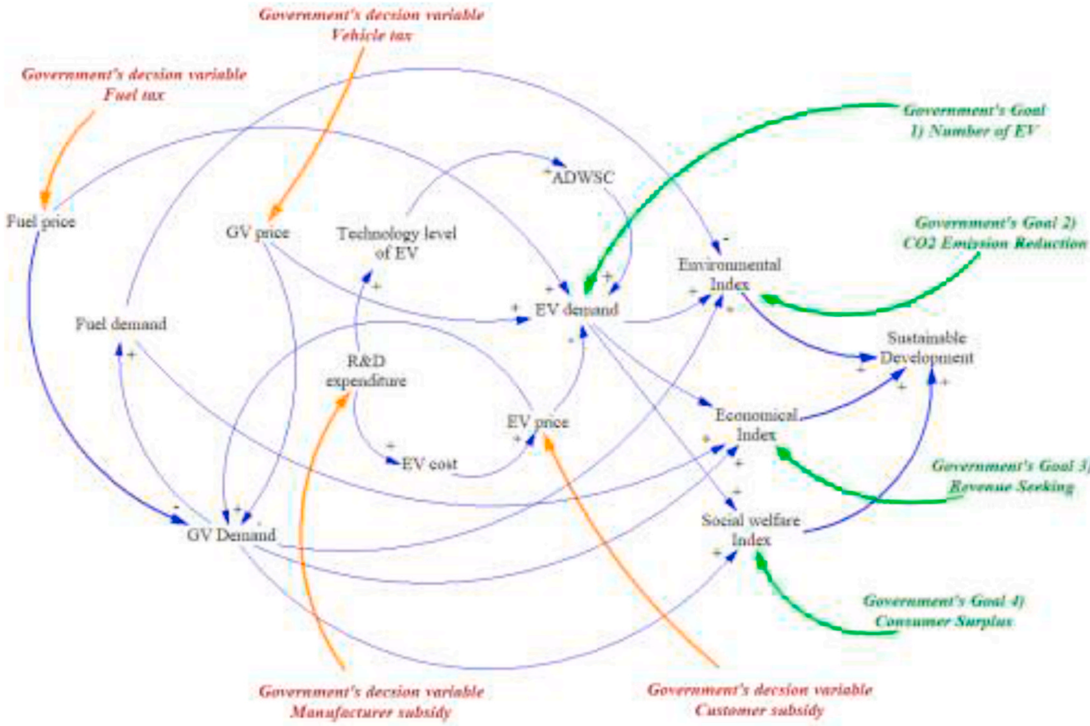

Fig. 5. Cause-and-effect relationship of system dynamics framework for the under-hand problem. Note: EV = Electric vehicle; GV: Gasoline-base vehicle; ADWSC = Average distance a vehicle can go with a single charge.

this factor is considered and investigated the amount of R&D efforts that determine the ADWSC.

3. Problem description and formulation

Consider two vehicle manufacturers, along with the government (See Fig. 4). The first manufacturer produces GVs, and the second manufacturer produces EVs. The first manufacturer's decision variable is the price of the vehicle. For the second manufacturer, two decision variables are considered, including the vehicle price and the determination of the amount of R&D effort that goes into determining the average distance a vehicle can go with a single charge. ADWSC increases the demand for EVs.

In addition to the fact that each manufacturer's decision affects the demand and profitability of the other manufacturer, the decisions of the manufacturers also influence the government's decisions and, vice versa, the decisions of the government influence the decisions of the manufacturers. It is assumed that the government is trying to improve the indicators related to sustainability goals with two types of strategies. The first governmental strategy (TO-strategy) is to find the optimal vehicle tax and gas tax, while the second governmental strategy (SO-strategy) is to find the optimal customer and manufacturer subsidies. For the customer subsidy policy, the government pays an incentive to customers who buy an EV, and in the manufacturer subsidy policy, the government contributes to the R&D expenditure of the second manufacturer to improve the ADWSC of the vehicle. As mentioned before, four objective functions for the government, including the number of EVs, CO_2 emissions reduction (ER), revenue seeking (RS), and customer surplus (CS), are considered. Given the two mentioned types of strategies, along with these four objectives, eight scenarios are designed for the government. In each scenario, one of the above goals is considered as an objective function, and the three other goals are considered as constraints. This means that, similar to Ref. [101], a threshold is assumed for each goal and a goal must be optimized so that the other goals do not deteriorate beyond the assumed threshold. For this problem, a game with complete information with a Stackelberg model is considered [102]. Therefore, it is solved by the backward induction method.

Fig. 5 shows the cause-and-effect diagram of the mentioned problem. According to Fig. 5, the factors affecting EV and GV demand with cause-and-effect relationships of system dynamics based on system thinking are investigated. Moreover, the relationship between EV and GV demand with applied government goals is illustrated in this figure. The concept of systems thinking makes a profound contribution to the scientific analysis of policies [103]. The cause-and-effect relationships associated with EV demand are described as follows: Government subsidies to EV manufacturers for R&D increase EV technology. This increase in technology will likewise increase the vehicle's ADWSC, and the higher the ADWSC is, the more EV demands will increase. The government subsidizes EV customers to encourage them to buy EVs. On the other hand, the more that is invested in R&D, the more the cost of an EV will rise. This price increase will, in turn, reduce EV demand and increase GV demand.

The cause-and-effect relationships associated with GV demand are as follows: The fuel tax determined by the government affects the fuel price, and the fuel price affects the GV demand. Similarly, the amount of other government taxes affects the price of GVs. The increasing price of GVs causes a decrease in GV demand and an increase in EV demand. Increasing GV demand also increases fuel demand.

Both EV and GV demand affect environmental, economic, and social welfare indicators, which are in line with the goals of the government to reduce CO_2 emissions and boost revenue and consumer surplus. The demand for EVs is also directly related to the government's first goal (i.

Table 1
Government's models for eight scenarios.

Goal	Constraints	Strategy	
		TO-strategy	SO-strategy
EV	ER RS CS	1 $\begin{cases} \underset{t,t_f}{\mathrm{Max}}\,\pi_g^{EV} \\ ER \le \zeta^{ER} \\ RS \ge \zeta^{RS} \\ CS \ge \zeta^{CS} \\ t \le \zeta^{t}, t_f \le \zeta^{t_f} \end{cases}$	5 $\begin{cases} \underset{s,\delta}{\mathrm{Max}}\,\pi_g^{EV} \\ ER \le \zeta^{ER} \\ RS \ge \zeta^{RS} \\ CS \ge \zeta^{CS} \\ s \le \zeta^{s}, \delta \le \zeta^{\delta} \end{cases}$
ER	EV RS CS	2 $\begin{cases} \underset{t,t_f}{Min}\,\pi_g^{ER} \\ EV \ge \zeta^{EV} \\ RS \ge \zeta^{RS} \\ CS \ge \zeta^{CS} \\ t \le \zeta^{t}, t_f \le \zeta^{t_f} \end{cases}$	6 $\begin{cases} \underset{s,\delta}{\mathrm{Min}}\,\pi_g^{ER} \\ EV \ge \zeta^{EV} \\ RS \ge \zeta^{RS} \\ CS \ge \zeta^{CS} \\ s \le \zeta^{s}, \delta \le \zeta^{\delta} \end{cases}$
RS	EV ER CS	3 $\begin{cases} \underset{t,t_f}{Max}\,\pi_g^{RS} \\ EV \ge \zeta^{EV} \\ ER \le \zeta^{ER} \\ CS \ge \zeta^{CS} \\ t \le \zeta^{t}, t_f \le \zeta^{t_f} \end{cases}$	7 $\begin{cases} \underset{s,\delta}{\mathrm{Max}}\,\pi_g^{RS} \\ EV \ge \zeta^{EV} \\ ER \le \zeta^{ER} \\ CS \ge \zeta^{CS} \\ s \le \zeta^{s}, \delta \le \zeta^{\delta} \end{cases}$
CS	EV ER RS	4 $\begin{cases} \underset{t,t_f}{Max}\,\pi_g^{CS} \\ EV \ge \zeta^{EV} \\ ER \le \zeta^{ER} \\ RS \ge \zeta^{RS} \\ t \le \zeta^{t}, t_f \le \zeta^{t_f} \end{cases}$	8 $\begin{cases} \underset{s,\delta}{\mathrm{Max}}\,\pi_g^{CS} \\ EV \ge \zeta^{EV} \\ ER \le \zeta^{ER} \\ RS \ge \zeta^{RS} \\ s \le \zeta^{s}, \delta \le \zeta^{\delta} \end{cases}$

e., the number of EVs on the roads). The use by consumers of EVs instead of vehicles with internal combustion engines is an applicable approach for meeting sustainable development goals and relying on renewable energy resources [104].

This paper tries to find the equilibrium solution of manufacturer and government decisions. It analyzes the equilibrium solutions and presents several results and insights for these types of decision-makers. The formulation is provided in the following subsections. The subsections of 3.1 and 3.2 include the demand and profit functions, and goals functions for manufacturers and government, respectively.

3.1. Manufacturers

In this subsection, demand and profit functions of GV and EV manufacturers are provided. The demand functions of the manufacturers are considered as functions for attaining the final price of the vehicle, fuel prices, and ADWSC. Huang et al. [105] mentioned that the price dependency demand models are the most important models to consider. Similar to other research, such as the research cited in Refs. [105–110], the demand functions are considered linear. In consumer theory, substitute goods, as contrasted with complementary goods and independent goods, are goods that can be used in place of each other. In applying this

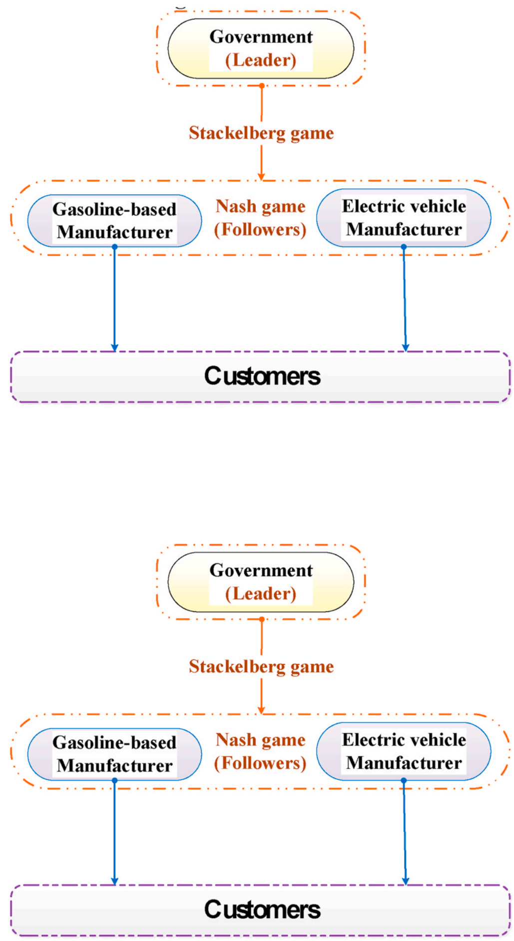

Fig. 6. Schematic Nash and Stackelberg games between players.

to vehicles, if the price of one substitute product increases, then the demand for that substitute vehicle decreases (self-price elasticity of demand), and the demand for another vehicle increases (cross-price elasticity of demand) [111,112]. Elasticities can signal useful and important information about demand as income and prices change [113, 114]. In the current research, GVs and EVs are substitute products, and both self-price and cross-price elasticity of demands are considered. Equations (1) and (2) represent the demand for gasoline and EVs, respectively. These functions consist of five parts. These parts are the market base, self-price elasticity, cross-price elasticity, gasoline price elasticity, and the effect of ADWSC, respectively.

$$D_1 = \omega\alpha - \beta(p_1 + t) + \gamma(p_2 - s) - \beta_f(p_f + t_f) - \lambda\sigma \tag{1}$$

$$D_2 = (1 - \omega)\alpha - \beta(p_2 - s) + \gamma(p_1 + t) + \gamma_f(p_f + t_f) + \lambda\sigma \tag{2}$$

Equations (3) and (4) represent the profit function of manufacturers 1 and 2, respectively. The second part of Equation (4) is the cost function of the R&D effort for improving ADWSC. According to the symbols defined, the δ is the percentage of government participation in the cost of enhancing ADWSC.

$$\pi_1 = (p_1 - c_1)D_1 \tag{3}$$

$$\pi_2 = (p_2 - c_2)D_2 - (1 - \delta)\mu\sigma^2 \tag{4}$$

Fig. 7. Motor vehicle registered [125].

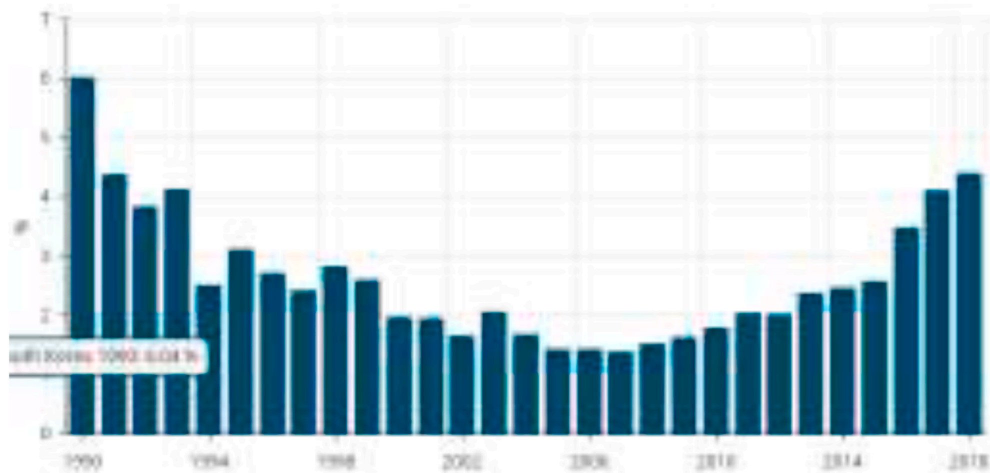

Fig. 8. Share of renewables in electricity production [124].

Table 2
Numbers of BEVs and PHEVs for South Korea and the world [38].

	Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Korea	a) BEV						60	340	850	1450	2760	5670	10770	24070	53710
	b) PHEV											270	440	1840	5890
	c) a+b						60	340	850	1450	2760	5940	11210	25910	59600
World	d) BEV	1890	2230	2690	5150	7480	14590	53530	112920	225500	415740	736900	1198370	1945780	3290800
	e) PHEV						380	9420	69900	161690	296510	517540	806290	1201500	1831650
	f) a+b	1890	2230	2690	5150	7480	14970	62950	182820	387190	712250	1254440	2004660	3147280	5122450
Ratio	g) a/d						0.41	0.64	0.75	0.64	0.66	0.77	0.90	1.24	1.63
	h) b/e						0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.15	0.32
	i) c/f						0.40	0.54	0.46	0.37	0.39	0.47	0.56	0.82	1.16

Table 3
A direct comparison between GV and EV.

	GV	EV
Gasoline and electricity prices	1.32 (\$/L) or about 0.12 (\$/km)	0.16 (\$/kWh) or about 0.03 (\$/km)
The costs of fossil fuel and electricity for a 100 km ride	\$10.38	\$4.49
CO_2 generation	207 (g/km)	163 (g/km)

In this subsection, demand and profit functions of GV and EV manufacturers are provided based on the problem definition. Since one of the important agents or decision-maker in the mentioned problem is the government, the next subsection includes the government goal functions formulation.

Table 4
Values of parameters for case study.

α	6e6	c_1	2.2e4	p_1	2.86e4	ζ^{EV}	223851
ω	0.75	c_2	3e4	p_2	3.9e4	ζ^{ER}	2.15 e6
β	54	μ	1e6	σ	0	ζ^{RS}	7.01e9
β_f	6.3e5	k_1	1.656	t	2100	ζ^{CS}	3e10
γ	5.1	k_2	0.1125	t_f	0.52		
γ_f	1.89e5	e	7200	s	5000		
p_f	0.71	δ	0.1				
λ	3.4e2						

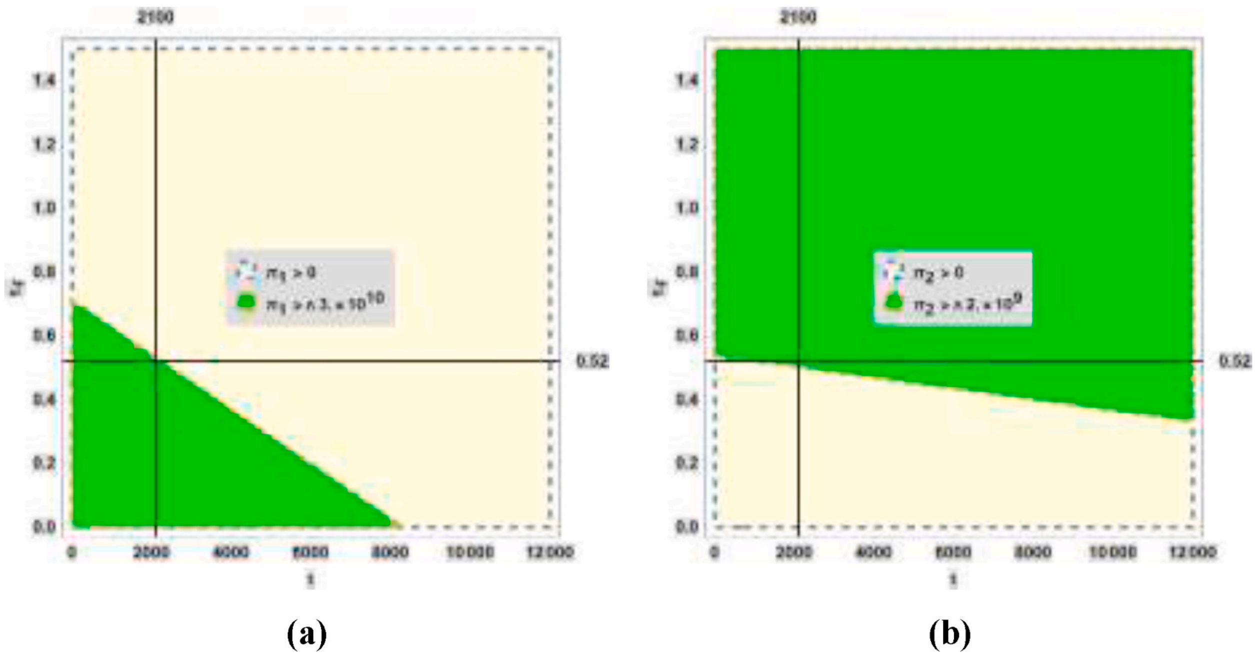

Fig. 9. Feasible zone for Manufacturers 1 (a) and 2 (b) under *TO-strategy* of government.

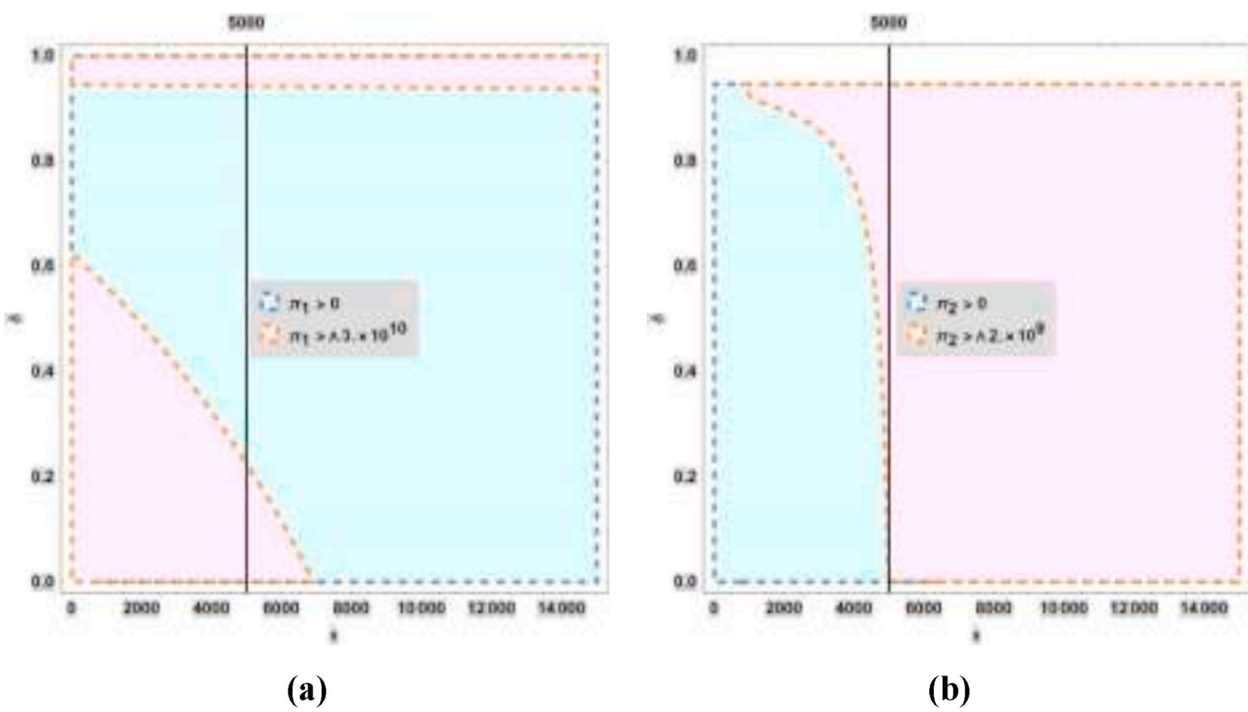

Fig. 10. Feasible zone for Manufacturers 1 (a) and 2 (b) under *SO-strategy* of government.

3.2. Government

As mentioned before, four objective functions are considered for the government, which are provided in Equations (5)–(8), respectively. The first objective function, Equation (5), is to increase the number of EVs on the roads, which is one of the goals of the energy program [38,115]. The second objective function is to minimize vehicle pollution, which is also one of the goals of the energy program (see Equation (6)). Government revenue is calculated in Equation (7) in which the first and second parts are tax revenues related to GVs and fuel consumption, and the third and fourth parts are consumer and manufacturer subsidies.

The final objective function, Equation (8), is the consumer surplus, which is calculated based on differences between market price and customer willingness to pay for two vehicles [116–118].

$$\pi_g^{ES} = D_2 \tag{5}$$

$$\pi_g^{ER} = k_1 D_1 + k_2 D_2 \tag{6}$$

$$\pi_g^{RS} = D_1 t + e D_1 t_f - D_2 s - \delta \mu \sigma^2 \tag{7}$$

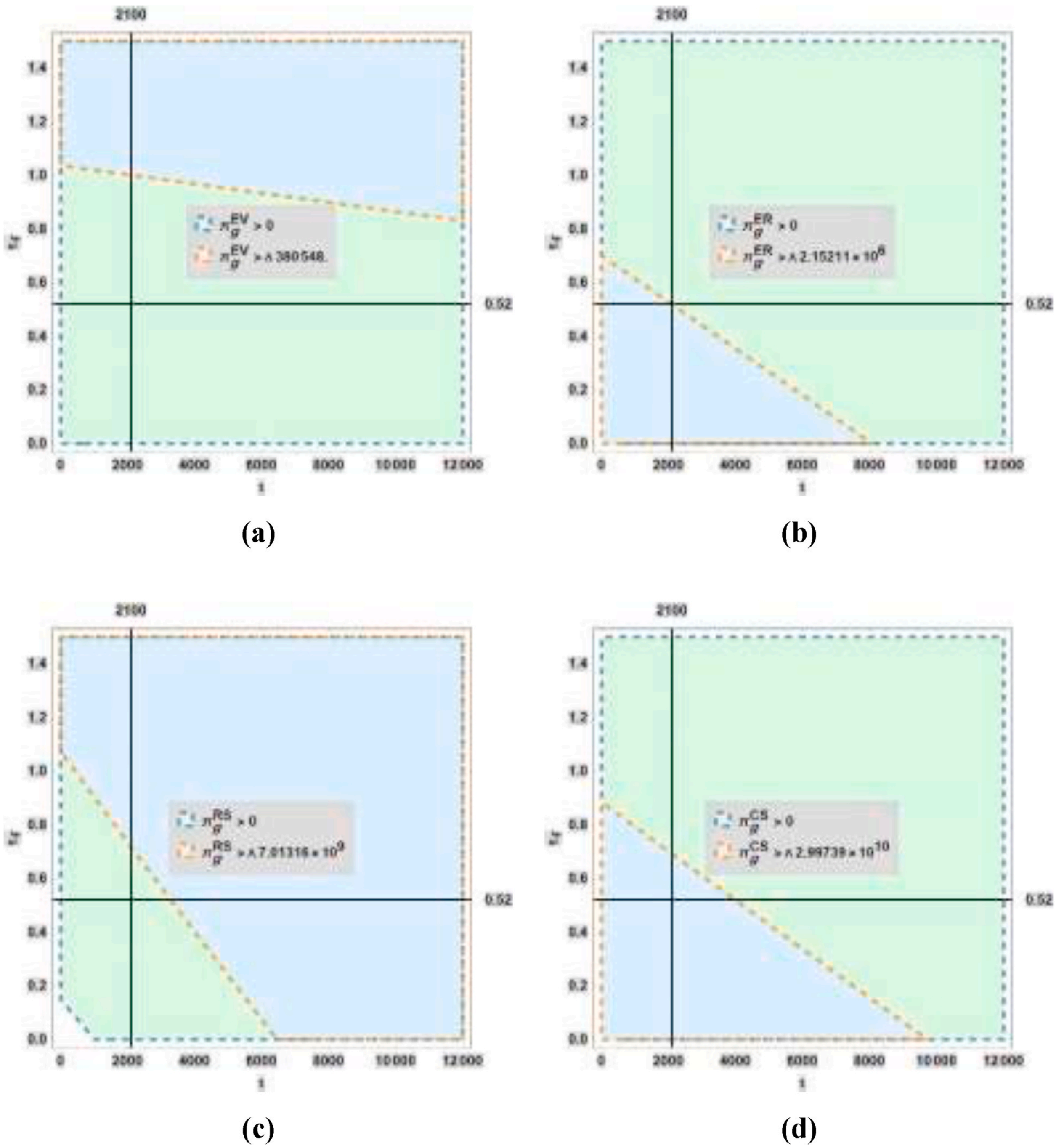

Fig. 11. Feasible zone for government's goals (a) EV, (b) ER, (c) RS, and (d) CS under *TO-strategy*.

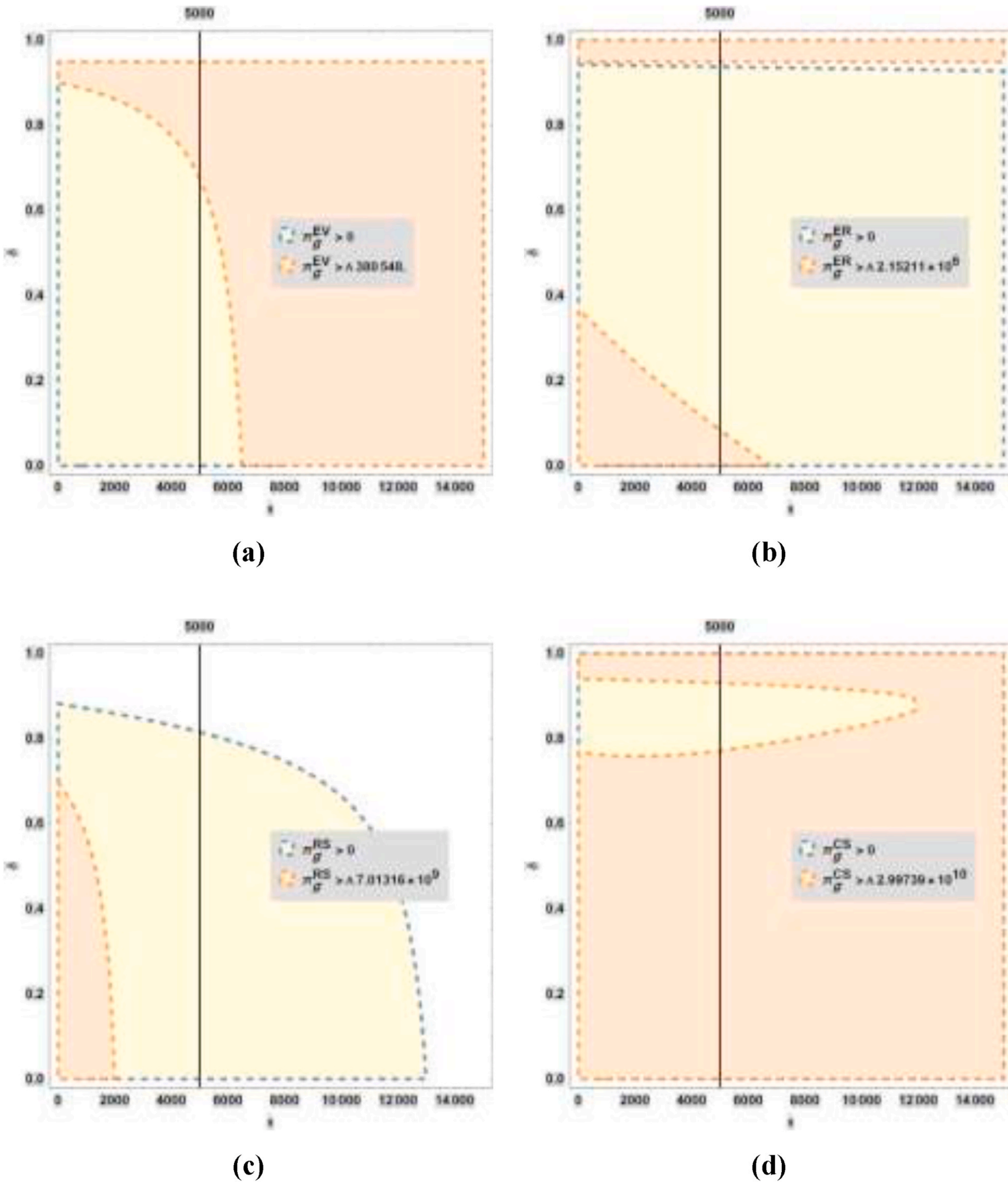

Fig. 12. Feasible zone for government's goals (a) EV, (b) ER, (c) RS, and (d) CS under *SO-strategy*.

$$\pi_g^{CS} = \int_{p_1+t}^{\frac{\alpha\omega+p_2\gamma-s\gamma-\lambda\sigma-p_f\beta_f-t_f\beta_f}{\beta}} D_1 \mathrm{d}p_1 + \int_{p_2-s}^{\frac{\alpha(1-\omega)+p_1\gamma+t\gamma+p_f\gamma_f+t_f\gamma_f+\lambda\sigma}{\beta}} D_2 \mathrm{d}p_2 \tag{8}$$

Table 1 shows the eight mentioned scenarios. In Scenario 1, the government wants to maximize the number of EVs, such that emission does not exceed the threshold ζ^{ER}, government revenue must be at leastζ^{RS}, and CS must be more than or equal to ζ^{CS}. The final row for

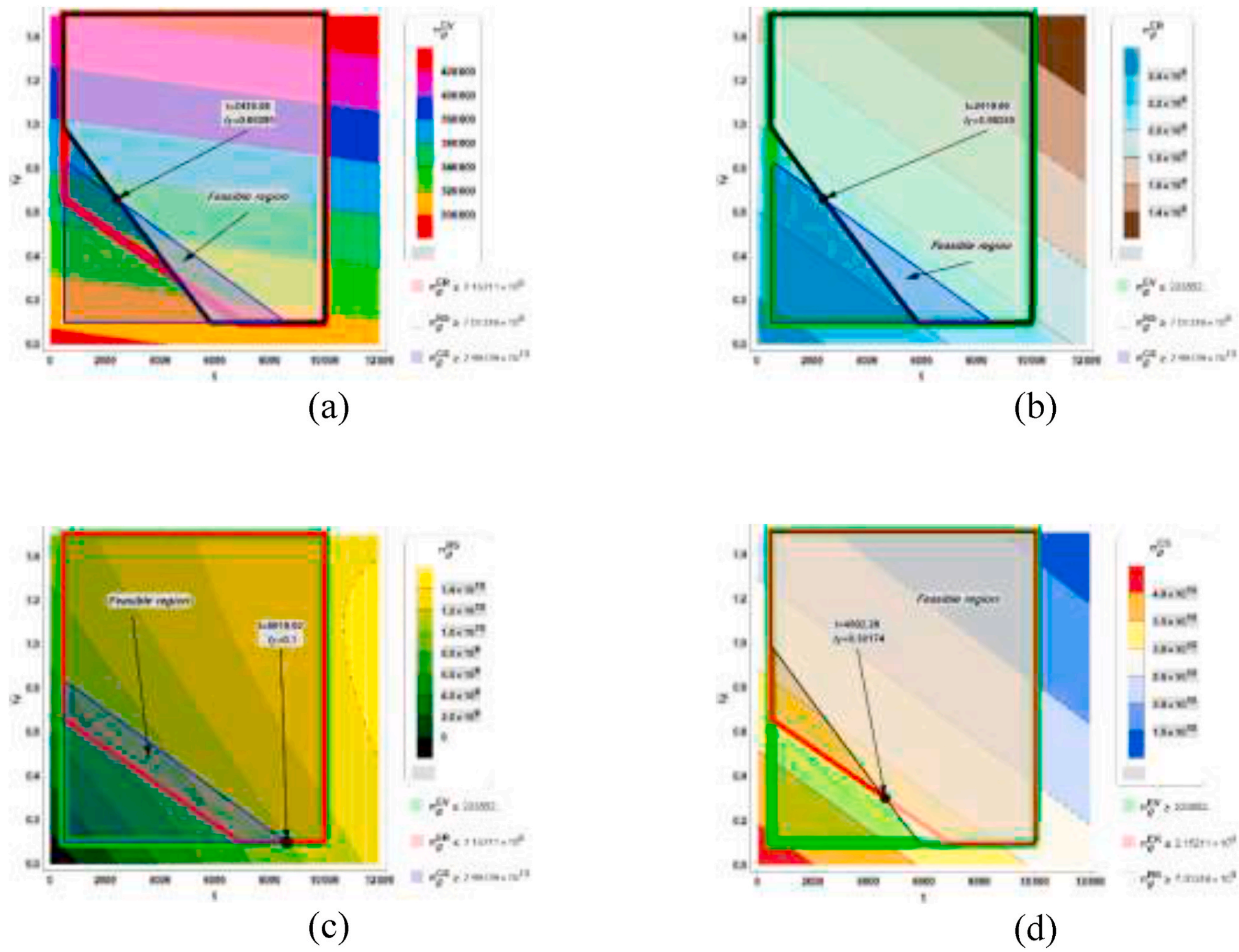

Fig. 13. Optimal solution of government's Scenarios 1-4.

Scenario 1 shows the bound for decision variables. The other scenario has a similar procedure for each goal and each strategy.

The subsections of 3.1 and 3.2 include the necessary functions and models for manufacturers and the government for analyzing the problem. Based on these functions and models and also based on the methodology and solution procedure that are presented in the supplementary material, the equilibrium solutions are provided in the next section.

4. Equilibrium solutions

In this study, backward induction is used to solve the problem by considering the government as the leader and by considering a Nash game between two manufacturers as followers (see Fig. 6).

The manufacturers optimize their profit function, so they simultaneously solved a Nash game to find the best response to each other's decisions. Manufacturer 1 determines p_1 and Manufacturer 2 determines p_2 and σ to maximize their profits based on the given taxes t and t_f and also on s and δ. Hence, the game model for this problem is as follows:

$$\begin{cases} \max\limits_{\substack{decision\\variables}} \ (\min) Each scenario \\ \text{where } (p_1, p_2, \sigma) \text{ are obtained by simultaneously solving the following nash game}: \\ \begin{cases} \max\limits_{p_1} \pi_1 \\ \max\limits_{p_2,\sigma} \pi_2 \end{cases} \end{cases} \tag{9}$$

Lemma 1. *π_1 on p_1 is a concave function.*

The appendix includes the proofs of all Lemmas and Theorems.

Lemma 2. *π_2 is a joint concave function on p_2 and σ_m.*

Theorem 1. *The equilibrium gasoline-based vehicle price and EV price and ADWSC are as follows:*

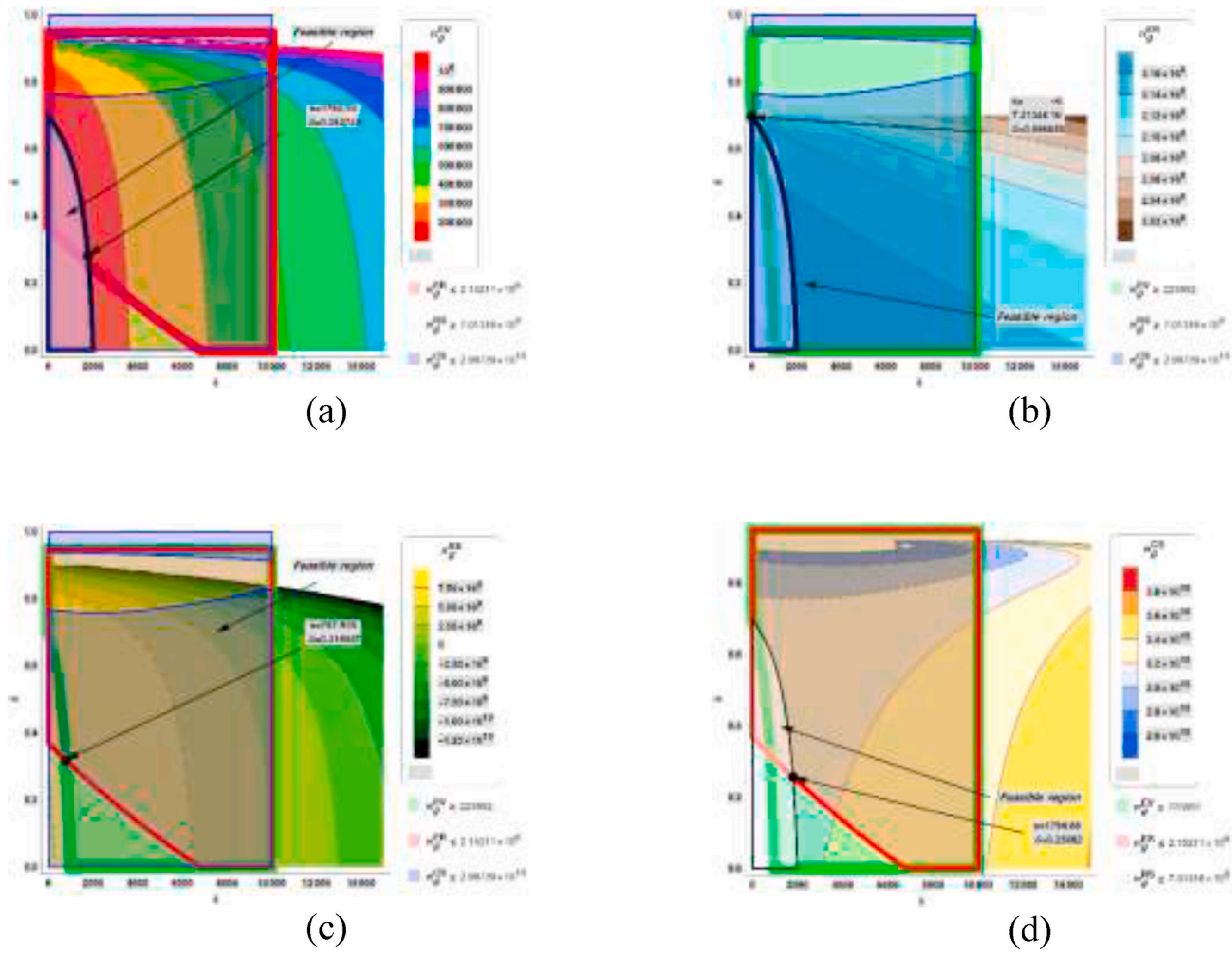

Fig. 14. Optimal solution of government's Scenarios 5-8.

$$p_1=\frac{1}{(2\beta-\gamma)(\lambda^2+2(2\beta+\gamma)(-1+\delta)\mu)}\left\{(c_1\beta-(c_2-s+t)(\beta-\gamma)+(p_f+t_f)\gamma_f)\lambda^2\right.$$
$$+2\left(2c_1\beta^2+(c_2-s)\beta\gamma+t\left(-2\beta^2+\gamma^2\right)+(p_f+t_f)\gamma\gamma_f\right)(-1+\delta)\mu+\alpha(\lambda^2$$
$$\left.+2(-1+\delta)\mu(\gamma+2\beta\omega-\gamma\omega))-(p_f+t_f)\left(\lambda^2+4\beta(-1+\delta)\mu\right)\beta_f\right\} \tag{10}$$

$$p_2=\frac{1}{(2\beta-\gamma)(2(2\beta+\gamma)(1-\delta)\mu-\lambda^2)}\left\{c_2(-2\beta+\gamma)\lambda^2-2(1-\delta)\mu\left(-2\beta\left(\alpha+(c_2+s)\beta+t\gamma+(p_f+t_f)\gamma_f-\alpha\omega\right)+\gamma\left(-c_1\beta+t\beta+s\gamma-\alpha\omega+(p_f+t_f)\beta_f\right)\right)\right\} \tag{11}$$

$$\sigma=\frac{1}{(2\beta-\gamma)(\lambda^2+2(2\beta+\gamma)(-1+\delta)\mu)}\left\{\lambda\left(2c_2\beta^2-2s\beta^2-c_1\beta\gamma-t\beta\gamma-c_2\gamma^2+s\gamma^2-2(p_f+t_f)\beta\gamma_f+2\alpha\beta(-1+\omega)-\alpha\gamma\omega+(p_f+t_f)\gamma\beta_f\right)\right\} \tag{12}$$

Theorem 2. *The equilibrium demands and profits of the Manufacturer* 1 *are obtained in Equations* (13) *to* (16) (*in Supplementary material*).

Theorem 3. *The government goals are obtained according to Equations* (17)-(20) (*in Supplementary material*), *respectively*.

5. Case study

This section with four subsections provides a case study from South Korea. In the first subsection (5.1), the related data for the South Korean automobile industry is provided. The second subsection (5.2) consists of feasible zones and the effect of the most important parameters on manufacturer and government functions. In the third subsection (5.3), the equilibrium solutions are provided, and the last subsection (5.4) includes insights and results for the South Korea case study.

5.1. South Korea's automobile industry information

5.1.1. The overall view of the current situation

South Korea's automobile industry is the fifth largest manufacturer of passenger vehicles in the world, accounting for about 13% of

Table 5
Eight scenarios' equilibrium solutions.

Scenario No	Decision variables						Functions								Related Figure
	Government				Manufacturer		Demand		Manufacturer's profit		Government				
	t	t_t	s	δ	p_1	p_2	D_1	D_2	π_1	π_2	π_g^{EV}	π_g^{ER}	π_g^{RS}	π_g^{CS}	
	2,263	0.68	[a]	[a]	44,640	36,520	1.2E+06	3.5E+05	2.8E+10	2.2E+09	[b]	2.1E+06	7.0E+09	3.0E+10	Fig. 13-a
	2,263	0.68	[a]	[a]	44,640	36,520	1.2E+06	3.5E+05	2.8E+10	2.2E+09	3.5E+05	[b]	7.0E+09	3.0E+10	Fig. 13-b
	8,669	0.10	[a]	[a]	44,837	35,792	1.2E+06	3.1E+05	2.8E+10	1.7E+09	3.1E+05	2.1E+06	[b]	3.0E+10	Fig. 13-c
	4,456	0.32	[a]	[a]	45,657	36,020	1.3E+06	3.3E+05	3.0E+10	1.9E+09	3.3E+05	2.2E+06	7.0E+09	[b]	Fig. 13-d
	[a]	[a]	1,762	0.3	45,739	34,662	1.3E+06	2.5E+05	3.0E+10	1.1E+09	[b]	2.2E+06	7.0E+09	3.2E+10	Fig. 14-a
	[a]	[a]	0	0.7	45,417	34,149	1.3E+06	2.2E+05	3.0E+10	7.7E+08	2.2E+05	[b]	7.0E+09	3.1E+10	Fig. 14-b
	[a]	[a]	768	0.3	45,785	34,145	1.3E+06	2.2E+05	3.1E+10	8.6E+08	2.2E+05	2.2E+06	[b]	3.1E+10	Fig. 14-c
	[a]	[a]	1,795	0.3	45,749	34,667	1.3E+06	2.5E+05	3.0E+10	1.1E+09	2.5E+05	2.2E+06	7.0E+09	[b]	Fig. 14-d

[a] Pre-determined (see Table 4).
[b] Pre-determined lower bound or upper bound of the government goals (see Table 4).

manufacturing output, 12% of value-added taxes, and 12% of total employment in South Korea in 2019 [119] and accounting for $600 billion in exports in 2018 [120]. On the other hand, this country ranks as the ninth-largest CO_2 emitter in the world. The GDP of South Korea more than tripled and its emissions of CO_2 more than doubled between 1992 and 2017 [121]. In this country, vehicles act as one of the most significant producers of emissions, contributing to approximately 21% of indoor air pollutants and 13% of domestic emissions of GHG [122]. South Korea is among the top five importers of LNG, crude oil, coal, and refined products in the world.

The number of registered vehicles in South Korea—23,594,014 units in October 2019—increased 3% from the previous year, with one automobile per 2.26 citizens in a population of 52 million. The number of newly registered vehicles from January to December last year fell to 1,843,000 units [123]. Fig. 7 shows the number of vehicles registered between 1988 and 2018. The share of renewables in electricity production is 4.42% [124]. Fig. 8 shows the share of renewables in electricity production between 1990 and 2018.

Table 2 shows the number of BEVs and PHEVs for South Korea and the world between 2005 and 2018. The number of EVs sold in 2018 was 34,000 units [126]. The number of EVs on the road has doubled every year [127]. In South Korea, the number of low-carbon vehicles with the capability of national subsidy support increased from 32,000 to 57,000 units from 2018 to 2019 [126]. The number of South Korea's exported EVs was $225 million units in August 2019, with a growth rate of 106.7% [128].

As an investment in R&D, Kia Motors and Hyundai Motor provided $0.0037 trillion (4.1 trillion KRW) in 2017 [120], with a total R&D investment of $3.90 billion in 2018.

The current price of 1 L of gasoline is about $1.32 in Seoul (South Korea National Oil Corporation) after an applied tax per liter of $0.69 (763 KRW) [129,130]. The average distance driven for one year is about 14,829.3 km for all types of vehicles Lee and Cho [131]. Our survey on one type of car from the manufacturing site [132] shows that the average distance driven is about 9,728 km per year. Based on the Yonhap report [133], the costs of fossil fuel for a 100 km ride are, on average, $10.38 (11,480 KRW). To travel 100 km, an EV consumes electricity in the value of $4.49 (4,970 KRW), and the price per kWh charged to the public at charging points is $0.16 (173.80 KRW). Burning one liter of gasoline generates about 2.3 kg of CO_2 or about 207 g/km [134,135], while an EV generates about 163 g/km CO_2 [136–146]. In South Korea, consumers use a car for about six years after purchase, on average, and after approximately eight years a car is scrapped [147]. Table 3 summarizes this information.

In the current subsection, the overall view of the current situation of EV adoption is provided. In the next subsection, the vision and supportive plans of EV are presented.

5.1.2. *Vision and supportive plans*

According to a plan of the Ministry of Trade, Industry, and Energy, South Korea wants to reach the goal of having 33% of total vehicles on the road to be electric and hydrogen vehicles by 2030 [148,149]. Adjusting energy tax rates is one of the most influential measures in South Korea's energy master plan to achieve this goal [150]. The details of government support and policies are presented in three categories, as follows:

1 Subsidy policies

Tax rebates per EV are capped at a maximum of $4,200 [151]. BEV subsidies are capped at a maximum $16,400, and PHEVs are capped at a maximum of $4,300. By 2022, Korea wants to have 430,000 BEVs and 67,000 FCEVs [152]. The objective for 2019 was to register 46,000 vehicles [127]. Subsidy information for EVs is provided in Ref. [153].

2 Charging infrastructure

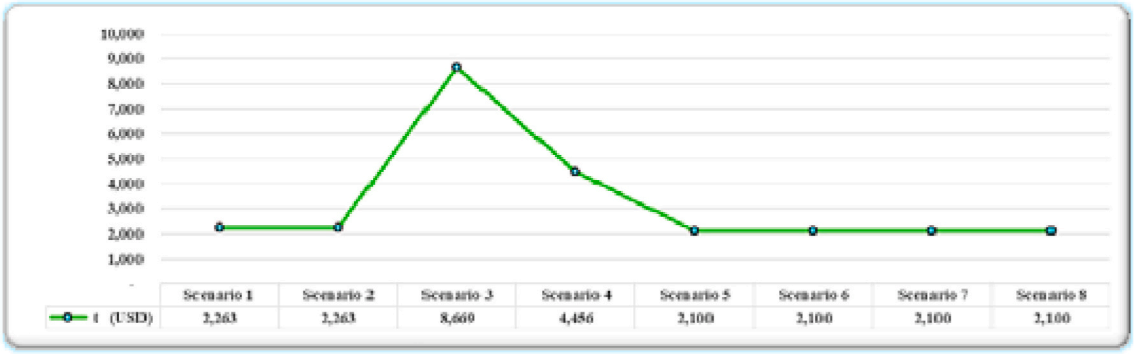

Fig. 15. GV tax equilibrium price.

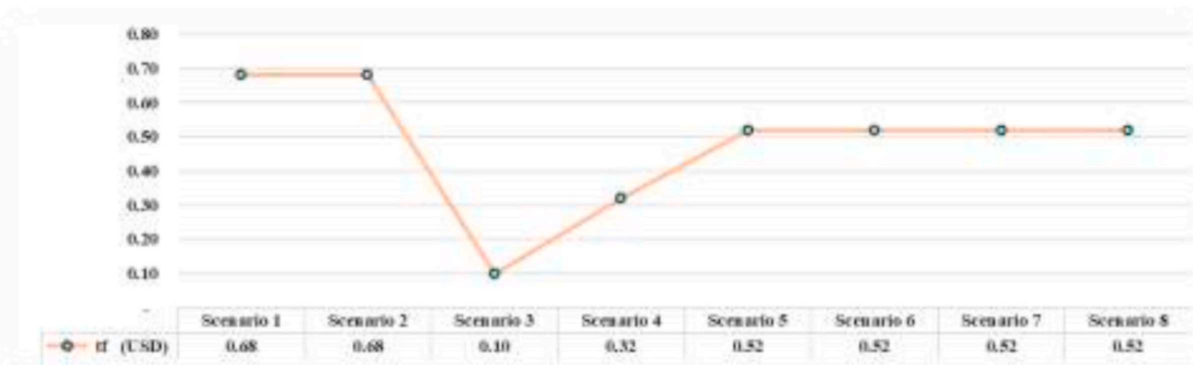

Fig. 16. Gasoline tax equilibrium price.

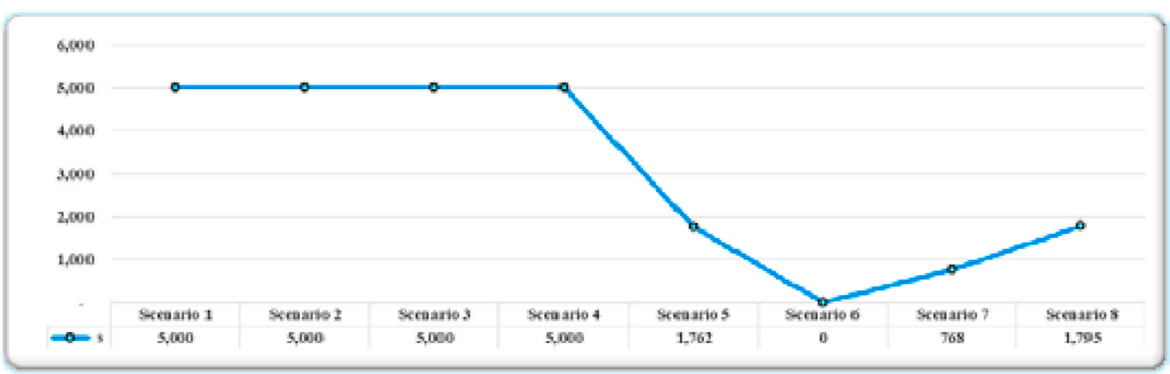

Fig. 17. Customer equilibrium subsidy.

For 2022, 10,000 fast EV chargers were planned for use by the public by South Korea's government [127,152]. South Korean drivers of EVs benefited from the government's deployment of chargers in 2019, made available to the public through subsidies. These chargers included fast chargers, which EV drivers could use in place of slow chargers ($3,000 in subsidies); portable chargers ($350 in subsidies), and private chargers ($1,200 in subsidies) [152]. The target for public available EV chargers for 2025 is 15,000, compared with the current number of 5,427 now used throughout the country [133].

3 Industrial policies

Korea, similar to Japan, wants to improve the overseas sales of low-emission vehicles by 2022, with a tenfold increase in production of zero-emissions vehicles—more than 10%—from the current production rate of about 1.5% [96]. To encourage this, manufacturers of such vehicles will be supported to increase their ZEV exports. In this same time frame, the government will try to increase BEV exports sevenfold, from 36,000 to 250,000 units [127]. The government will grow support for R&D to develop important and key technologies, such as lithium-sulfur, solid--state, and lithium-metal batteries to help access these aggressive targets [96]. Recently, the South Korean government announced new EV subsidies for 2020 [154].

Table 4 summarizes the necessary data for the current research, according to evidence from South Korea, the above information, and other data from Refs. [155,156]. For this case study, the equilibrium solutions and results are presented in the next subsection.

In the current subsection, some information for the South Korean automobile industry and the related data are provided. The next subsection consists of feasible zones and the effect of the most important parameters on manufacturer and government functions based on the solution procedure provided in the supplementary material.

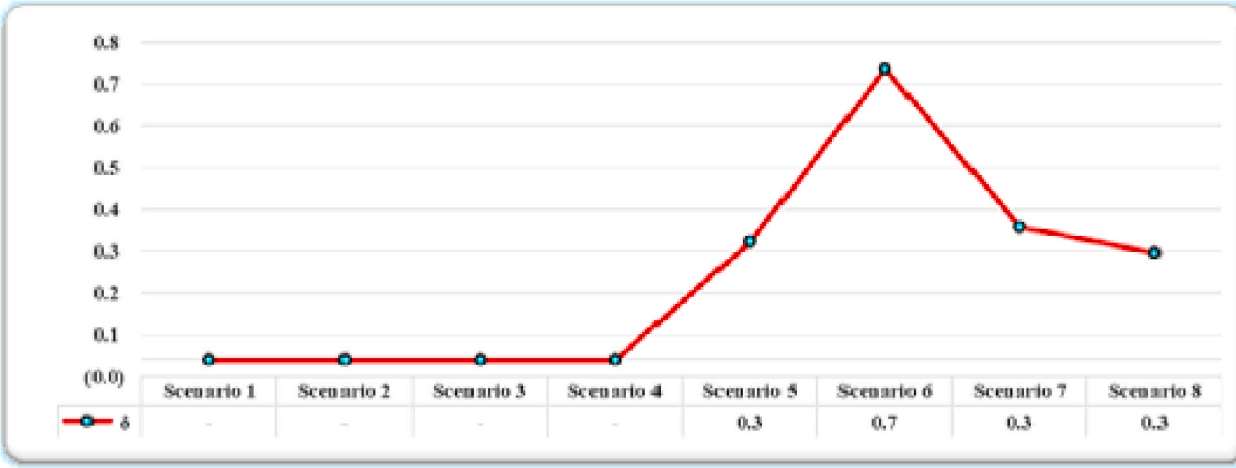

Fig. 18. *Manufacturer equilibrium subsidy (share of cooperation in expenditure by the manufacturer in R&D programs).*

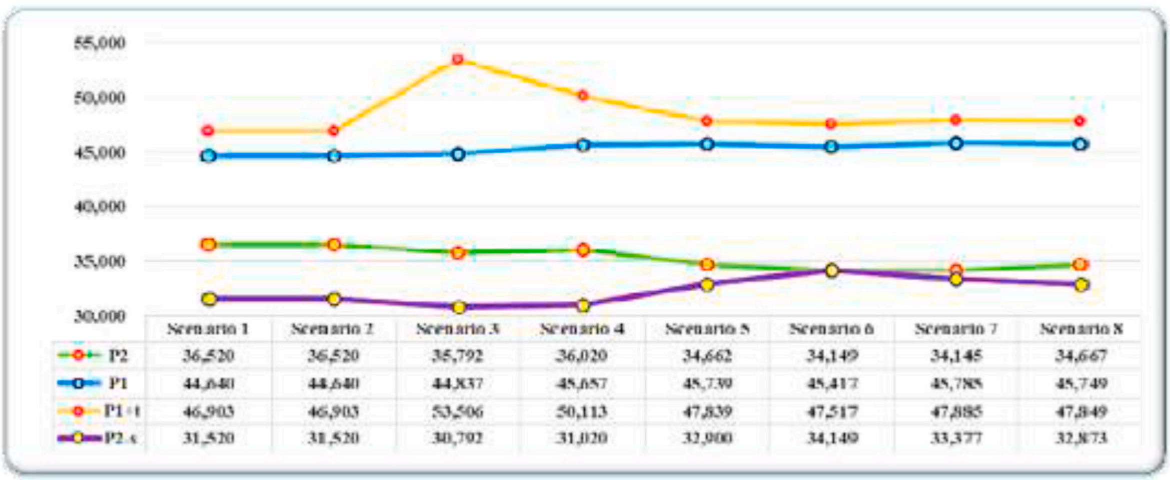

Fig. 19. Manufacturers' and end-user's equilibrium prices.

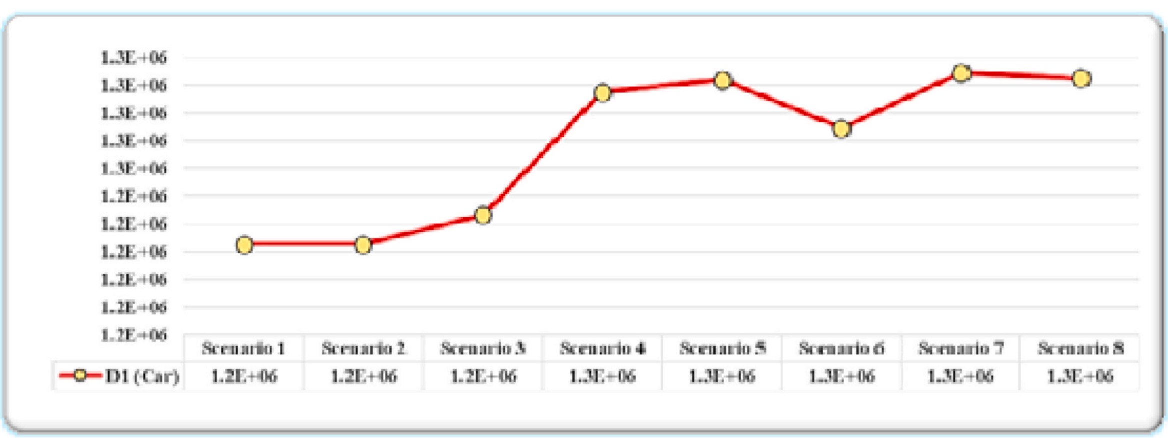

Fig. 20. GV equilibrium demand for eight scenarios.

5.2. Feasible zones and Sensitivity analysis of the current data

Fig. 9 (a) and (b) shows the areas where the objective of the GV and EV manufacturers are positive and higher than an assumed threshold value under the ***TO-strategy***, respectively. Moreover, Fig. 10 (a) and (b) shows a similar area for two manufacturers under the ***SO-strategy***. Figs. 11 and 12 also show a feasible zone for the four government goals (i.e., EV, ER, RS, and CS) for the *TO- and SO-strategies*, respectively. These figures are intended to help the government find a range of decision variables, such as taxes and subsidies, where the profits of EV manufacturers (Figs. 9 and

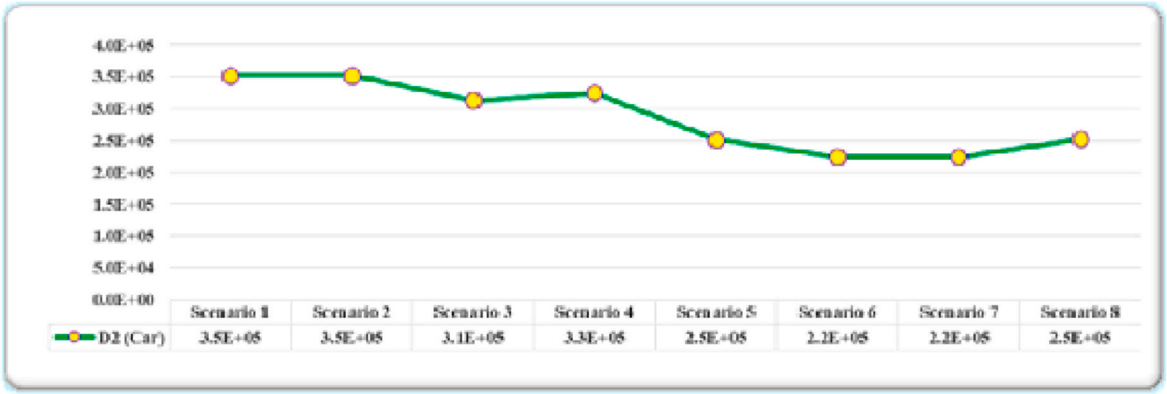

Fig. 21. EV equilibrium demand for eight scenarios.

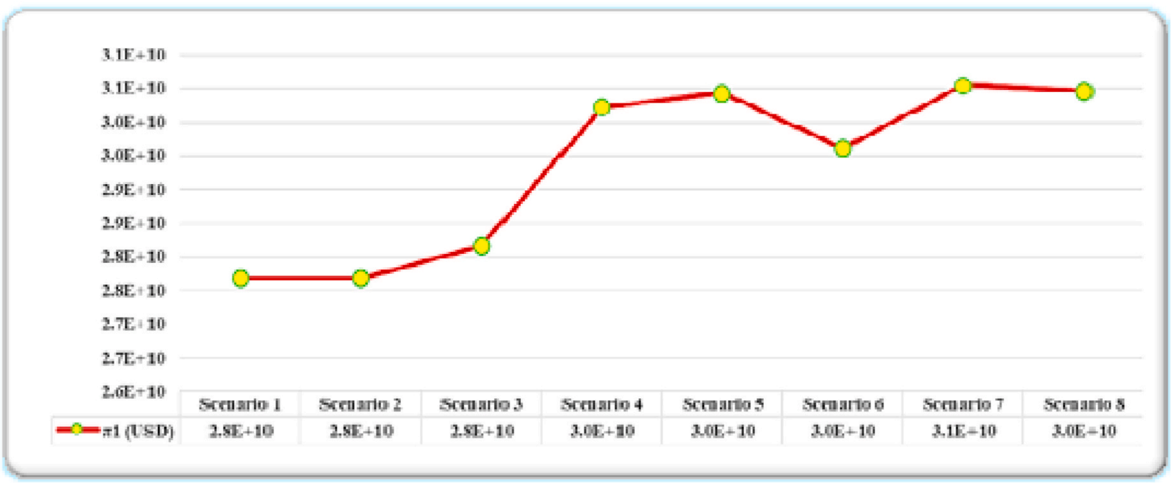

Fig. 22. GV equilibrium profit for eight scenarios.

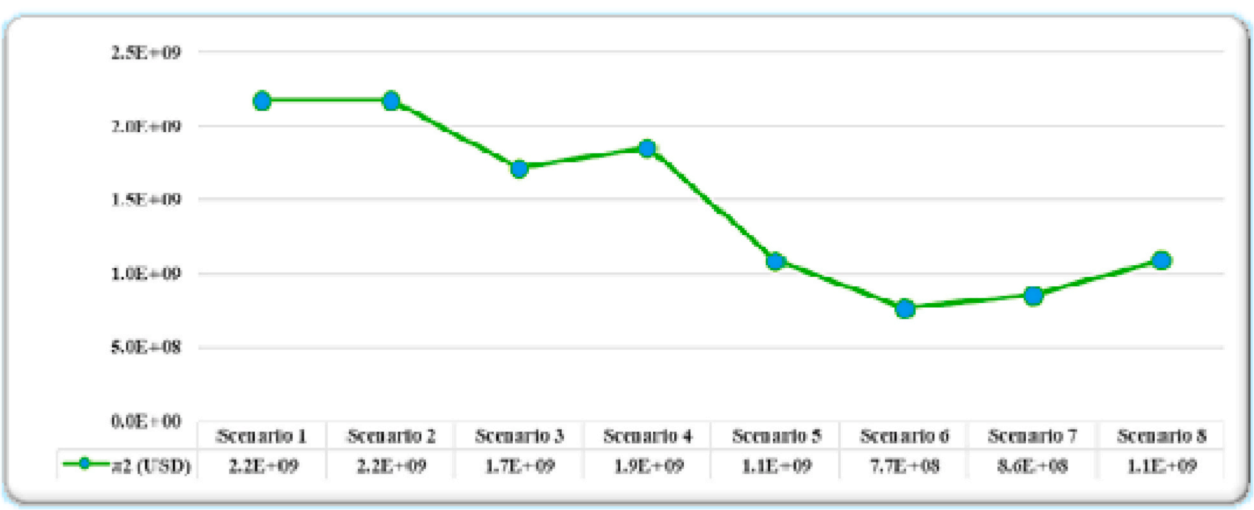

Fig. 23. EV equilibrium profit for eight scenarios.

10) or each goal of the manufacturers (Figs. 11 and 12) are not less than (for the goals with the maximization approach, such as EV, RS, and CS) or above (for the ER goal) the assumed threshold value. In other words, using these figures, the government can find the range of its decision variables in which the manufacturers have some profit so that the manufacturers do not leave the market. More applications of these figures will be provided in Section 5.4.

In the next subsection, the equilibrium solution of the current case study based on the equilibrium relations in Section 4 and the considered data in Subsection 5.1 are presented.

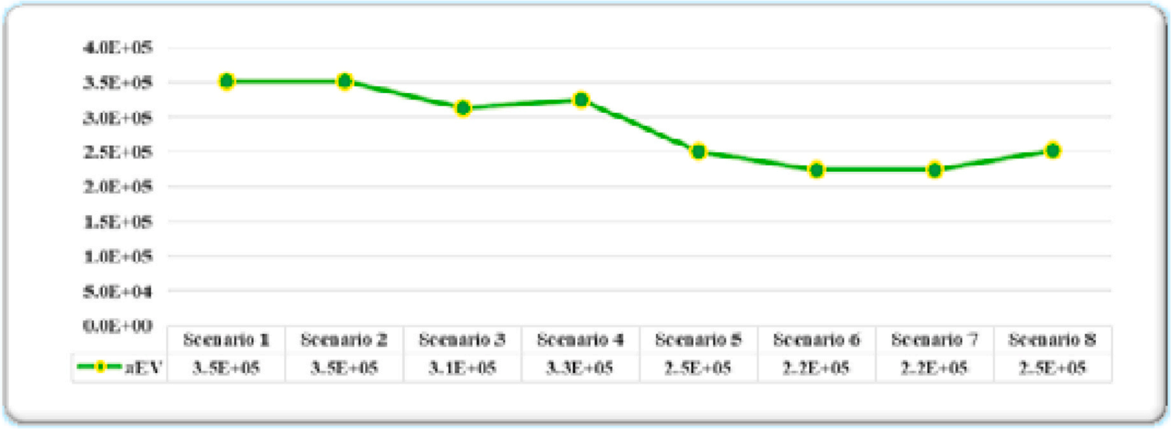

Fig. 24. Government's EV equilibrium for eight scenarios

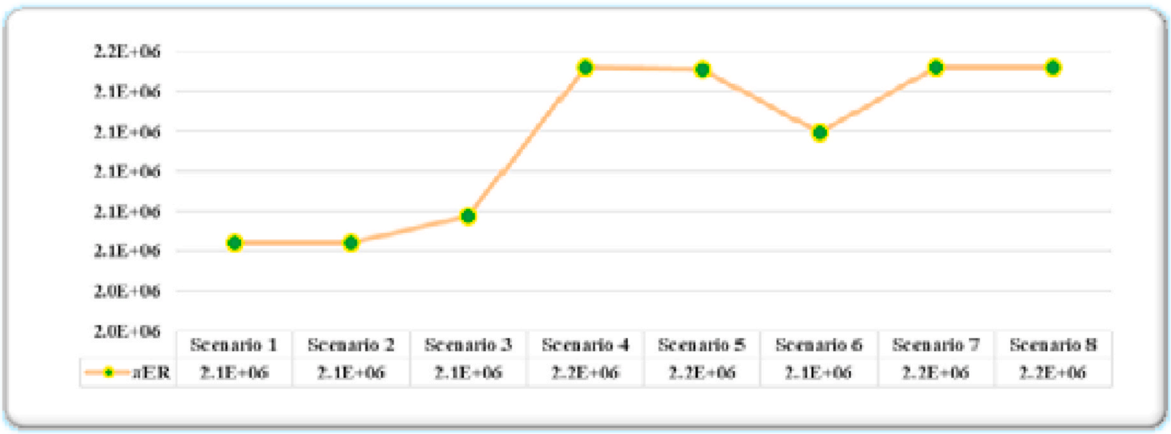

Fig. 25. Government's ER equilibrium for eight scenarios

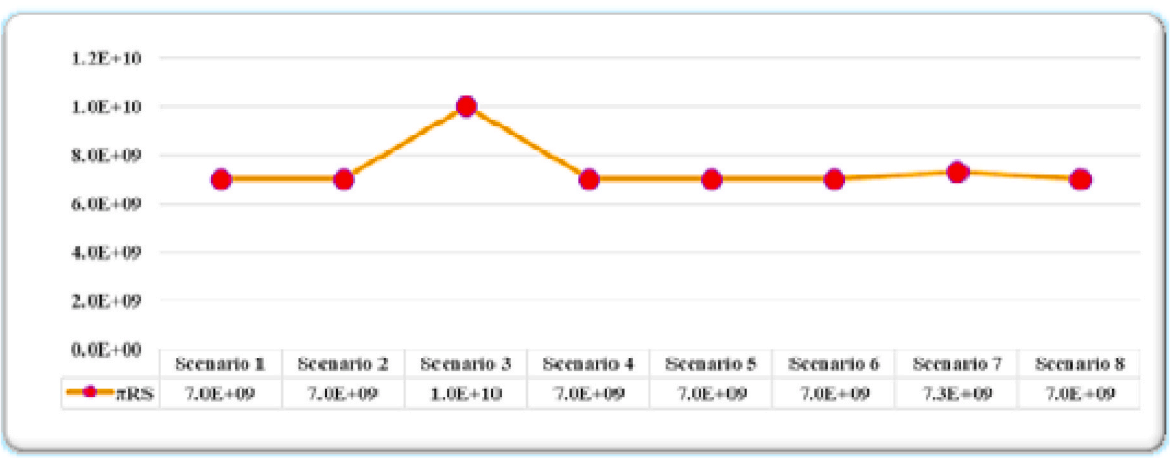

Fig. 26. Government's RS equilibrium for eight scenarios

5.3. Equilibrium solution

Figs. 13 and 14 illustrate the optimal solutions in each scenario and show the optimal solution for the TO- and SO-strategies, respectively. The details of equilibrium solutions for the manufacturer and the government are presented in Table 5. Based on the obtained results that are presented in this table, Fig. 15 through 24 are drawn to better provide the results. The next subsection includes an analysis and the results of the equilibrium solutions. In that subsection, several managerial insights are provided for manufacturers and the government. According to the presented results, manufacturers and government policymakers can get optimal (equilibrium) solutions and strategies for each scenario.

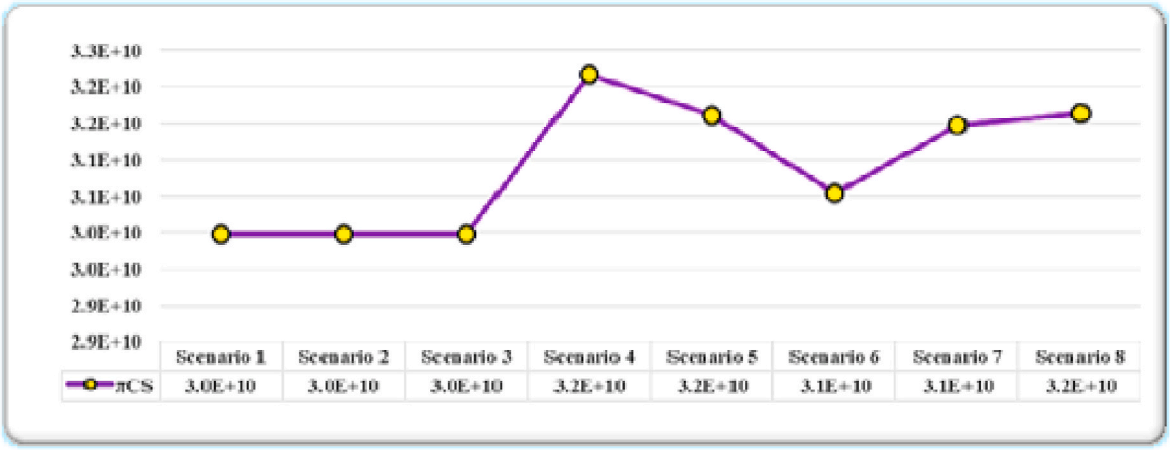

Fig. 27. Government's CS equilibrium for eight scenarios

6. Results and insights

As shown in Fig. 15 through 19, several results, and corollaries are achieved. Also, as illustrated in Fig. 13 through 14, several findings are presented as follows.

Proposition 1. *Fig. 15 shows that the greatest GV tax is obtained from Scenario* 3 (*i.e., a revenue-seeking goal with a tax optimization strategy*), *and after that from Scenario* 4 (*i.e., a consumer surplus goal with the same strategy*). *Therefore, the government must increase the GV tax for revenue seeking and must maximize consumer surplus goals over the* ***TO-strategy****. Fig. 16 shows different results for the fuel tax; the optimal value of the fuel tax for Scenarios* 3 *and* 4 *is less than the optimal value for other scenarios. The fuel tax in Scenarios* 1 (*i.e., the number of EVs goal with tax optimization strategy*), *and in Scenario* 2 (*i.e.,* CO_2 *emissions reduction with tax optimization strategy*), *is more than it is in other scenarios. Therefore, we obtain the following corollaries*:

Corollary 1. *Under the* ***TO-strategy****, if the government has RS or CS goals, by considering the threshold for other goals, the government must increase the GV tax and decreases the fuel tax. If the government has EV or ER goals, the government must increase both taxes.*

Corollary 2. *The maximum fuel tax will be obtained from performing the* ***TO-strategy*** *in line with EV and ER goals, and the minimum fuel tax will be obtained from performing the* ***TO-strategy*** *in line with the RS goal. The end-user of the GV prefers that the government pursue the RS goal with the* ***TO-strategy****.*

Proposition 2. *Figs. 17 and 18 show the optimum subsidy values for each scenario. Generally, Scenarios* 5–8 (*i.e., EV, ER, RS, and CS goals with tax optimization strategy*) *have less customer subsidy and more manufacturer subsidy than do Scenarios* 1–4 (*i.e., EV, ER, RS, and CS goals with subsidy optimization strategy*). *According to these figures*:

Corollary 3. *Under the* ***SO-strategy****, the government must increase its manufacturer subsidy and decrease its customer subsidy.*

Corollary 4. *The maximum equilibrium manufacturer subsidy and minimum equilibrium customer subsidy will be obtained from performing the* ***SO-strategy*** *in line with the ER goal.*

Proposition 3. *According to Fig. 19, except for Scenarios* 3 *and* 4, *i.e. revenue seeking and customer surplus goals with tax optimization strategy, there is not much difference between final GV prices. Also, the difference between the final prices of EVs is less than* 15*percent. Scenarios* 1 *and* 2, *and Scenarios* 3 *and* 4 *have a minimum GV price and EV price, respectively. Therefore, the customer of a GV prefers Scenarios* 1 *and* 2, *and the customer of an EV prefers Scenario* 3, *and after that Scenario* 4.

Corollary 5. *GV customers prefer that the government pursue EV and ER goals and perform the* ***TO-strategy*** *rather than pursue other scenarios.*

Corollary 6. *EV customers prefer that the government perform the* ***TO-strategy*** *rather than the* ***SO-strategy****. In particular, the best policy by the government for EV customers is RS with the* ***TO-strategy****.*

Proposition 4. *According to Fig. 20, the* ***SO-strategy*** *leads to a greater demand for GVs than does the* ***TO-strategy****. In particular, Scenario* 7, *i.e. revenue seeking goal with subsidy optimization strategy, leads to the largest demand for GVs, and Scenarios* 1 *and* 2 *lead to the minimum demand for GVs. In addition, according to Fig. 21, the maximum demand for EVs is achieved by performing Scenarios* 1 *and* 2; *and by following Scenarios* 6 *and* 7, *the minimum demand for EVs is observed. According to Figs. 22 and 23, the maximum equilibrium profit of Manufacturers* 1 *and* 2 *is obtained from following Scenarios* 7, 1, *and* 2, *respectively.*

Corollary 7. *The equilibrium demand for GVs was maximized when the government had the RS goal and the customer and manufacturer followed the* ***SO-strategy****. Equilibrium demand for GVs for Scenarios* 1 *and* 2 (*EV and ER goals with the* ***TO-strategy***) *is the lowest value. This result is vice versa for EVs. In addition, the demand for EVs when the government had the ER goal with the* ***SO-strategy*** *is lowest, similar to the RS goal and the* ***SO-strategy****.*

Corollary 8. *The government must pursue the RS goal with the* ***SO-strategy*** *if the government aims to maximize the equilibrium profit of Manufacturer* 1. *If the gover*nment wants to maximize the equilibrium profit of Manufacturer 2, the government must pursue EV or ER goals with the **TO-strategy**.

Proposition 5. *Fig. 24 through 27 show the equilibrium value of goals for each scenario separately. According to these figures, Scenarios* 1 *and* 2 *are the best scenarios for EV and ER goals* (*Figs. 24 and 25*), *Scenario* 3 *is best for the RS goal* (*Fig. 26*), *and Scenario* 4 *is best for the CS goal* (*Fig. 27*). *According to Fig. 24, the* ***TO-strategy*** *has a better result for the EV goal. If the government wants to maximize the equilibrium value of EVs by considering the* ***SO-strategy****, then Scenarios* 5 *and* 8 *are better than the two other scenarios* (*i.e.,* 6 *and* 7). *As can be seen from Fig. 25, the first three scenarios* (*i.e., maximizing EV and RS goals and minimizing the ER goal, with the* ***TO-strategy***) *lead to less pollution compared to the other scenarios. There is not much difference between the scenarios except in Scenario* 3 *when the government has the RS goal* (*Fig. 26*). *It can be seen from Fig. 27 that Scenario* 3 *has the best outcome for the CS goal, and after that, all the* ***SO-strategy*** *scenarios* (*i.e., Scenarios* 5–8) *are better than the* ***TO-strategy*** *scenarios* (*i.e., Scenarios* 1–3). *In general, CS increases when the government follows the* ***SO-strategy****, except for in Scenario* 4.

Corollary 9. The **TO-strategy** leads to better values for each goal, under the existing threshold for other goals, with respect to the **SO-**

strategy.

7. Discussion and results

According to Corollary 9, to reach the maximum increase in EVs, to reach the minimum ER, to reach the maximum increase in RS, and to reach the maximum increase in CS, the ***TO-strategy*** is better than the ***SO-strategy***. Therefore, the ***TO-strategy*** for all goals provided better results. Therefore, if the government seeks to maximize the number of EVs on the road, or minimize pollution, or maximize revenue or maximize consumer surplus, it should consider a tax optimization strategy rather than a subsidy optimization strategy. If the government pursues an ***SO-strategy***, then Scenarios 5 and 8 provide the best approach to maximize the number of EVs on the road. Scenario 6 brings about the greatest pollution reductions, and Scenarios 5, 7, and 8 generate the best consumer surplus values. There is no significant difference between Scenarios 5, 6, 7, and 8 for the revenue-seeking goal. Of all the goals and strategies, the GV manufacturer prefers that the government pursue the RS goal with the ***SO-strategy***. Also, the EV manufacturer prefers the EV and ER goals with the ***TO-strategy*** for vehicle and fuel consumption. From the GV customer's viewpoint, the EV manufacturer would do the best to pursue EV and ER goals with the ***TO-strategy*** for vehicle and fuel consumption while EV customers, as well as end-users of GVs, prefer RS goals with the ***TO-strategy***.

From observing Figs. 15 and 16, two questions arise: (1) why is applying fuel tax the lowest-ranking among all scenarios if the government's goal is to maximize revenue (i.e., in Scenario 3)? (2) why does the vehicle tax increase when the government seeks to maximize consumer surplus (Fig. 15)? These two questions have a similar answer. The answer is related to the constraints considered. For example, see Fig. 13 (c) to answer the first question. As the counterplot shows, raising the two types of taxes (i.e., vehicle and fuel taxes) increases government revenue, but the constraint of consumer surplus (blue range) prevents both taxes from increasing simultaneously. The optimal solution is obtained by increasing the GV tax along with reducing the fuel tax so that the RS is maximized, and the consumer surplus does not decrease from the assumed value. The answer to the second question also can be seen by looking at Fig. 13 (a), taking into account the income and ER constraints.

8. Conclusions

This paper, for the first time, considers the EV pricing problem with competition from GVs using optimization tools. This paper first finds the optimal solutions to the problem of EV and GV pricing by determining the amount of R&D efforts that go into each type of vehicle, and by taking into account four objective functions, two strategies, and four decision variables for the government. Four goals, which include the number of EVs on the road, CO_2 emissions reduction, revenue seeking, and customer surplus for the government, were considered and contribute to the literature for this problem. This research addresses these government goals and pairs them with different tax and subsidy strategies on EV and GV pricing, customer demands, and manufacturers' profits. A cause-and-effect relationship for the problem's elements was proposed, and this was integrated with a game theory approach. Our research provides a guide for manufacturers and the government to find equilibrium solutions and thereby design an effective vehicle pricing model, pursue R&D efforts, and set appropriate tax and subsidy strategies that depend on the value placed on a renewable energy plan. The different goals and strategies that governments have affect the supply chain members' profits. It has been shown which scenarios are more appropriate for each of the agents, including GV and EV manufacturers and customers. With the help of the present study, governments can select and execute better scenarios with regard to their goals. In addition, optimum pricing and R&D efforts by manufacturers for each goal and each strategy are provided. Finally, we provide a case study, as well as several insights and results.

The following challenges and limitations in the current research can be extended for future research: (a) there are other vehicles in addition to GVs and EVs that can be studied by adding their demand function; (b) according to other research, such as [80,81,146], other factors—including prior experience driving EVs, changes in technology levels, number of household vehicles, educational level, and perception of government incentives and public parking benefits— are also affecting the demand for EVs that are not considered in this study, and adding those factors to the demand for EVs can be one aspect of extending this research; (c) adding other decision variables for the government, such as improving the infrastructure required for EVs, could be another aspect of developing this research. For example, planning for a number of charging stations [38,61] and considering the annual charging demand are two possibilities suggested in the current research. The annual demand for charging is a very important topic and is a noticeable call-out in the current research. Taking Germany as an example, the annual charging demand for EVs will be 24.8 TW-hours in 2050. That is five times more than it was in 2015 [166,167]; (d) our research can also be extended by adding other types of government goals, for instance, job creation and enhancing energy security; (e) one of the most critical and challenging issues in the energy field is the rebound effect [168]. This effect is not considered in our current research. Therefore, considering this issue in concert with similar studies [106,169–173] is another way for us to extend this research.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2021.111139.

Credit statement

Morteza Rasti-Barzoki: Conceptualization, Methodology, Software, Data curation, Writing - original draft, Visualization, Investigation. Ilkyeong Moon: Supervision, Validation, Writing - review & editing.

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