Applied Energy 271 (2020) 115196

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

A game theoretic approach for car pricing and its energy efficiency level versus governmental sustainability goals by considering rebound effect: A case study of South Korea

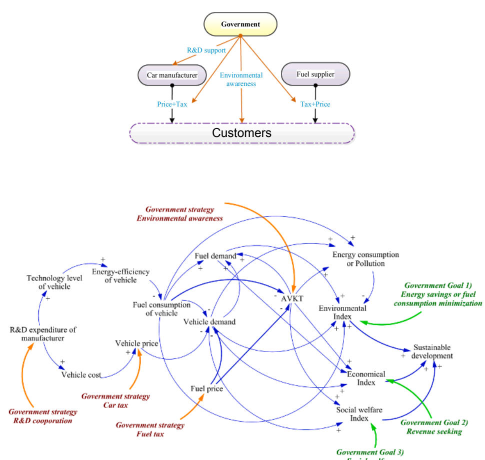
Morteza Rasti-Barzoki[a,b], Ilkyeong Moon[c,*]

[a] Department of Industrial and Systems Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran
[b] Department of Industrial Engineering, Seoul National University, Seoul 08826, Republic of Korea
[c] Department of Industrial Engineering and Institute for Industrial Systems Innovation, Seoul National University, Seoul 08826, Republic of Korea

HIGHLIGHTS

- A practical multi-agent problem in the automobile industry is defined.
- A comprehensive approach including System Dynamics and game theory is provided.
- Energy efficiency, environmental awareness, and social welfare are considered.
- A function for the average of vehicle kilometers traveled in a unit of time is suggested.
- Several managerial insights for both manufacturers and governments are presented.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Sustainability
Energy efficiency
Rebound effect
Pricing
Game theory

ABSTRACT

This paper looks at the effects that environmental policies have on car manufacturers. A standing problem for car manufacturers is determining both a car's price and its level of energy efficiency. The South Korean government has sustainable goals that encompass saving energy, seeking revenue, and advancing social welfare. This study highlights four decision variables in two groups for the government. The government determines the optimal value of each goal, while maintaining a threshold for the two other goals as constraints. The four decision variables are determining the car sales tax, determining the fuel tax, determining the cost of educating the public about environmental awareness, and determining the percentage of government's cooperation in the manufacturer's research and development expenditure. For the purpose of this study, a new function, average of vehicle kilometer traveled in a unit of time (AVKT), is suggested for calculating the average distance driven by a car over a given period of time, based on the cost of fuel, the car's energy efficiency, the driver's environmental awareness quotient, and the rebound effect. This newly defined multi-agent problem is solved by looking at the

* Corresponding author.
E-mail address: ikmoon@snu.ac.kr (I. Moon).

https://doi.org/10.1016/j.apenergy.2020.115196
Received 24 December 2019; Received in revised form 4 April 2020; Accepted 11 May 2020

structure of the Stackelberg game, and equilibrium solutions are offered by implementing the backward induction procedure. By considering demand and profit for fuel, this study offers the most efficient goals and strategies for both car manufacturers and fuel producers alike. Finally, this study offers several results and insights.

1. Introduction

Sustainability is a concern that affects all human behavior, choices, and decisions. During the past twenty years, three important dimensions of sustainability have taken the forefront. These are *economic growth*, *environmental sustainability*, and *social responsibility*, and they have forced both private industries and governments alike to focus on the *planet*, *people*, and *profits*. Therefore, sustainability is a fundamental issue with a decisive role in determining both organizations' and governments' goals and strategies. Concerns about environmental and social issues have led that managers, strategists, and policy makers to change their economic, environmental, and social priorities in order to remain viable and competitive [1]. Lee and Tang [2], have showed that research on sustainability has grown exponentially since 1995. They showed that the research community has explored sustainability issues exhaustively in the area of operations management. Research in this area has made important contributions to energy conservation, natural resources stewardship, carbon-conscious business strategies, environmental regulation, social betterment, and closed-loop supply chain management improvements [2]. In order to better understand the impact that operations management research has had on sustainability, readers of this study are encouraged to review papers that look at this issue in depth [2–9].

The fear of running out of natural resources and the fear of worldwide fuel shortages are two main drivers of sustainability initiatives. Rapid economic development in the twentieth and twenty-first centuries has led to increasing demands on natural resources' such as crude oil, clean water, metals, and forests, and as these natural resources have diminished in the face of growing consumption, major environmental degradation has occurred. In light of this, policy makers are increasingly concerned about energy use, greenhouse gas emissions, and climate change, and environmental sustainability, and have proposed that immediate actions are needed to change the way the earth's resources are consumed [10]. One major factor that must be considered is reducing the environmental effect caused by the energy sector [11].

Sodiq, Baloch [11] showed that improving energy efficiency is critical for making energy systems sustainable, improving regional competitiveness, protecting energy security, and facilitating procedures that advance industry and commerce without emissions or at least with reduced emissions. Especially, in furthering this last goal, transportation is the sector that the International Energy Agency says could benefit the most from advances in sustainability initiatives [12]. The three main characteristics of the transportation sector, as it now stands, are its reliance on gasoline, its standing as the largest emitter of CO_2 [13], and its critical role in moving goods and consumers [14]. Given all this, the automobile industry has received tremendous attention from government policy makers and researchers looking to advance energy efficiency. A major obstacle to progress, however, is the toll that sustainability measures would have on the industry in terms of cost. One of the most important strategic issues for car manufacturers is the pricing of cars, which is intrinsically linked to car's quality issues and car's energy efficiency. This issue, in particular, is what guides car manufacturers and government officials alike as they make decisions on energy efficiency, car pricing, environmental policy, and taxes. It is also an attractive and practical issue for researches.

Taking into account the reasoning above, this study on the issue of car pricing as influenced by energy efficiency and government intervention is the first study of its kind. Given the role of government decisions on sustainability, three main goals are considered in this research. They are minimizing energy consumption (or minimizing pollution while maximizing energy efficiency), maximizing government revenue, and maximizing social welfare. To achieve these goals, two types of strategies, each containing two decision variables, are considered for the government. That breaks down, for the purposes of this study, to six scenarios for the government, resulting insights and possible recommendations. The four decision variables, as noted earlier, are determining the car sales tax and determining the fuel tax (first strategy); and determining the cost of educating the public about environmental awareness and determining the percentage of government's cooperation in the manufacturer's R&D expenditure (second strategy). Considering a case study from South Korea, this research tries to answer following questions:

RQ 1. What is the car manufacturer's pricing strategy and optimal energy efficiency level, as measured against each goal of the government? Also, as a result, what is the optimal car manufacturer's profit?
RQ 2. What are the fuel demands and the fuel producer's profit for each goal and each strategy of the government?
RQ 3. What are the government's projected optimal outcomes for each goal and each strategy?
RQ 4. How do different efficiency scenarios impact prices, energy saving, demand and profits, energy consumption, and overall social welfare?
RQ 5. What are the best scenarios for the government, the manufacturer, the fuel producer, and consumers in terms of price, demand, profit, environmental improvements, and social welfare? Also, under what scenario would car manufacturers and energy producers reap maximum profits?

The remainder of this paper is structured as follows. A brief review of existing studies is provided in Section 2. Section 3 defines the problem. Section 4 provides equilibrium solutions. Section 5 presents a case study with results and insights. The last section includes a summary of the problem, along with conclusions and suggested research for the future.

2. Literature review

In this paper, we focus on two aspects of sustainability-economic and environmental. Pricing, as an economic factor, is very important from both a theoretical and an empirical point of view. Hinterhuber [15] mentioned that, in industrial marketing, pricing is a critical and widely neglected tool. This can be seen from the fact that a 5% price change, on average, leads to about 22% improvement, excluding other operational management measures. However, less than 15% of companies investigate pricing in any systematic way [16]. Cars, in particular, are a commodity where strategic pricing is critical for manufacturers. Although the literature on pricing is rich, however, the issue of pricing cars has not been thoroughly studied. Berry, Levinsohn [17,18] modeled characteristics of cars into frameworks for estimating pricing. Degryse and Verboven [19] studied the pricing of cars in different countries. Goldberg [20] addressed the impact of corporate's standards for average fuel economy on the automobile industry and on car pricing. Other studies used the mixed multi-nominal logit model for analyzing policies aimed at stimulating demand for alternative-fuel vehicles [21,22]. It is clear from existing research, however, that determining a car's price is a multi-agent decision influenced by other players, such as fuel producers and governments. No research, to the authors' knowledge, however, has examined the issue of car pricing, as

Notations that are used in this study are defined as follows:

Indices

m	The car manufacturer
e	The energy producer
g	The government/policy maker

Parameters

α	Market base for the car or maximum possible demand (car)
β	Sensitivity of the car demand to its own price, i.e. self-price elasticity (car/currency, for example car/$)
θ	Sensitivity of the car demand to the cost of using the car for a specific distance, i.e. cross-price elasticity (car/currency, for example car/$)
f_0	The initial or current fuel consumption of the car to move one unit of distance (unit of volume/unit of distance, for example L/Km)
μ	R&D expenditure coefficient in the profit function of the manufacturer (currency*(unit of distance/unit of volume)^2), for example $ (Km/L)^2
ρ	The ratio of maximum use of the car, due to lack of awareness about environmental issues, to minimum use of the car, due to complete awareness about environmental issues (dimensionless)
ν	Car useful life (time unit, for example, one year)
ϕ	Coefficient of AVKT function meaning the average money spent by a consumer for fuel in one unit of time (currency/time unit, for example, $/year)
η	The cost of one unit for increasing the public's environmental awareness (dimensionless)
$\mathfrak{R}$	Rebound effect (dimensionless)
p_e	Fuel, for example, the price of gasoline (currency/unit of volume, for example, $/L)
ζ^{ES}	The upper bound of the government's energy consumption goal (unit of volume/time unit, for example, L/year)
ζ^{RS}	The lower bound of the government's revenue seeking goal (currency, for example, $)
ζ^{SW}	The lower bound of the government's social welfare goal (unit of distance/time unit, for example, Km/year)

Decision variables

p_m	Selling price of the car (currency/car, for example, $/car)
f	Fuel intensity or fuel consumption (the amount of fuel that a car consumes to go one unit of distance) (unit of volume /unit of distance, for example, L/Km)
t_m	The car sales tax (currency/car, for example, $/car)
t_e	The fuel tax (currency/unit of volume, for example, $/L)
s	The magnitude of social environmental awareness (dimensionless)
δ	The percentage of government's cooperation in the manufacturer's R&D expenditure (dimensionless)

Demand and profit functions

U	Average use of a car in unit of time (AVKT) (unit of distance/unit of time, for example, Km/year)
D_m	Demand for the car (car)
D_e	Demand for the fuel in time unit (unit of volume/unit of time, for example, L/year)
π_m	Profit of the manufacturer for total production (currency)
π_e	Profit of the energy producer in useful life of the car (currency)
π_g^{ES}	Government function for *energy consumption minimization or energy savings maximization* goal (unit of volume/unit of time, for example, L/year)
π_g^{RS}	Government function for *revenue seeking* goal (currency/unit of time, for example, $/year)
π_g^{SW}	Government function for *social welfare* goal (unit of distance/unit of time, for example, Km/year)

a decision-making and optimization problem, combined with the effects of other factors, such as the cost of fuel and intervention by the government. This study tries to fill that gap.

For increasing market share and capturing sales in highly competitive markets, car manufacturers must compete not only with pricing but also with quality. From the customer's point of view, one of the chief factors for selecting a car is the car's energy efficiency, or fuel intensity (FI) level. FI reflects, inversely, the technical measurement of energy efficiency, which is defined as the amount of energy used per unit of activity [23]. In this study, we define FI, specifically, as liters of fuel consumed per one kilometer driven (L/km).

Technological advances are employed to great effect in the automobile industry [24]. Research and development (R&D), driven by these advances, aims to increase a car's energy efficiency by reducing FI. Thus, manufactures can improve the energy efficiency of cars by boosting R&D expenditures. Hyundai, for example, has developed, with the use of technology, a new fuel-efficient engine that strongly enhances fuel efficiency and reduces gas emissions [25]. Ajanovic and Haas [23], through cointegration analyses, studied the impact of FI and price have on overall fuel consumption for passenger cars in six European countries. Salvo and Vaz de Almeida [26] studied the relationship between technologies intended to diminish fuel consumption. To the authors' knowledge, however, no research yet exists that has studied the pairing of energy efficiency with pricing as an optimization problem.

It is obvious that the distance traveled by a vehicle is affected by its energy consumption, or energy efficiency level. The distance traveled by a car for a specific distance, or Average of Vehicle Kilometer traveled in a unit of Time (AVKT), is one important performance indicator that can be used extensively for a variety of purposes in transportation planning. These purposes include assessing gasoline consumption, estimating car accidents and vehicle emissions, and assessing the impact driving has on traffic jams and congestion [27]. Also used in this study, Vehicle Miles Traveled (VMT) measures the amount of travel for all vehicles over a period of time in a geographic region, typically a period of one-year. It is calculated as the product of AVKT and the number of vehicles on the road in that region for that given time frame. These measures have been widely used in travel demand analysis [28–30], transport planning [31], energy consumption analysis [32–34], and traffic accident analysis [35–37], as well as battery capacity design for electric vehicles [38]. Governments are under increasing pressure to develop plans that both leads to cleaner air and increase driver safety, with fewer accidents and fatalities. Lowering VMT is one approach to addressing this goal [39].

In this study, we developed a function for calculating of AVKT, based on an end-user's economic situation, environmental awareness quotient, energy consumption, fuel price paid at the pump, and "rebound effect" —the phenomenon that occurs when reducing a car's fuel consumption results in lowering fuel demand but also results in increased usage of the car. The input parameters of this function can be derived from a real case. This function, i.e. AVKT, is used to project the input that both fuel producers and government have on calculations, and to find the equilibrium price and the optimal level of energy efficiency for vehicles.

As mentioned earlier, in most countries vehicles are the major pollution source pushing governments and policy makers to take sustainability measures. Canada is a country where this push for lowering vehicle emissions is particularly evident [40]. The idea of rebates for the buying of fuel-efficient vehicles has been introduced in several provinces [41]. Both fuel efficiency taxes and rebates are offered by Ontario [42,43]. Alberta, British Columbia, Quebec, and Ontario have used a disincentive carbon price on the consumption of fossil fuels [44]. Rivers and Plumptre [45] and Chandler [46], in their research, championed Canada's strictness of greenhouse gas regulations on car manufacturers —regulations that have forced the car industry— to reach tighter vehicle emissions targets per kilometer. A tax credit for using public transportation also has been proposed by Canada's federal government.

In 2017, Seoul's government, in an effort to reduce greenhouse gas emissions and pollution, established a financial reward for motorists who decrease mileage and drive less [47]. Due to this measure, motorists can receive up to 70,000 won ($62) if they decrease their mileage more than 3000 km on an annual basis [48]. According to the authors' knowledge, no other research exists that considers government strategies in car pricing optimization. This study attempts to fill this gap by considering three objectives for the government energy savings, revenue generation, and social welfare. Also addressed in this study are R&D expenditures by car manufacturers, tax strategies by the South Korean government, and environmental awareness initiatives. The next section provides a description of the problem.

3. Problem description

We consider a supply chain that includes one car manufacturer and one fuel supplier/producer under the system of one government (see Fig. 1). The manufacturer wants to determine the price of the car, in addition to the cost of R&D efforts. In this model, it is assumed that the energy efficiency of the car is related to the amount of R&D efforts. Furthermore, the car demand function that we consider in this research includes both price and non-price competitive factors. To make the problem applicable to the real world and to present it in practical terms more analysis for policy makers, we also bring governmental intervention into this problem. Fuel production is another element in this problem, but this study does not address the decision variable for it. The price of one unit of fuel consists of two components -the producer's price and the government's tax, which, in the case of price, we assume is specific and predetermined; and which, in the case of tax, we assume is a decision variable of the government.

In this study, we consider three important goals for the government, including *minimizing energy consumption* (*EC*) (or minimizing pollution or maximizing energy savings (ES)); *maximizing revenue, or revenue seeking* (RS); and *maximizing social welfare* (SW). The government has four decision variables to reach these goals. These include car sales tax, fuel tax, the percentage of government's cooperation in the manufacturer's R&D expenditure, and the cost of boosting social awareness to get the public behind efforts to improve energy consumption habits and thereby decrease their contribution to environmental pollution. These decision variables are grouped into two categories, Strategy 1 and Strategy 2. Strategy 1 consists of *jointly determining the optimal taxes for cars and fuel*, and Strategy 2 consists of *jointly determining optimal environmental awareness among the public and percentage of government's cooperation in the manufacturer's R&D expenditure*. Because this study considers three goals and two strategies for the government, six scenarios will be addressed, and under each scenario the optimal values of the car manufacturer's decision variables will be presented. Further details of each agent's decisions are provided in the formulation Section 3.2, following the notations in notations Section and the assumptions in Section 3.1. Using the system dynamics approach, cause and effect relationships among variables will be presented in the next paragraph (see Fig. 2). In Fig. 2, a positive causal link means the two nodes change in the same direction, (i.e., if the node in which the link starts increases, the other node also increases and if the node in which the link starts decreases, the other node also decreases). A negative causal link means the two nodes change in opposite directions (i.e., if the node in which the link starts increases, the other node decreases, and vice versa).

As Fig. 2 shows, the car manufacturer can increase the quality of the car by increasing R&D efforts. Increasing the quality of car technology increases the car's energy efficiency; therefore, it leads to the reduction of the car's fuel consumption or FI. Decreasing the car's fuel consumption increases the appeal of the car and thereby increases its demand. On the other hand, boosting R&D expenditure will increase the car's price, thereby decreasing its demand. While reducing the car's fuel consumption will result in lower demand for fuel, it also very likely will result in increased usage of the car. In existing studies, this phenomenon is called the "rebound effect" [49,50]. The cost of fuel is also an important factor that strongly influences the car's demand [51]. Increasing the cost of fuel leads to both decreased demand for a car and decreased car use. Increased car use results in both increased pollution and traffic congestion, both of which have detrimental effects on social welfare. In this study, however, social welfare is measured by the government's efforts to maximize the use of cars within a time unit. Many other factors come into play with driving and transportation, but for brevity these explanations are omitted in this study. The objective of this research is to find the optimal solution of decision variables for car manufacturers and government policy makers by analyzing equilibrium solutions and presenting results and insights. The next subsection presents assumptions made in this study. Following that, the formulation of the problem is provided.

3.1. Assumptions

Assumption 1. All parameters and prices are nonnegative and all information about the demand and profit functions are known for all of the agents (game with complete information).

Assumption 2. For car demand, it is assumed that $D^{'}(.) < 0$ and $\int_0^\infty U(.)d(.) < \infty$ where "." is p_m, t_m, f, p_e, and t_e [52]. This means that demand for the car, i.e. D_m, is a decreasing function of p_m, t_m, f, p_e, and t_e and the demand is finite.

Assumption 3. It is assumed that increased R&D expenditure leads to greater energy efficiency of the car, but this relationship is not linear. It is clear that each incremental amount of R&D expenditure causes a progressively lesser effect on the energy efficiency of the car. This means that R&D expenditure of varying f is increasing in Δf. For studying similar approaches about the effect of advertising, quality, and branding on cost function, see [53–55]. Similar to these studies, we use a quadratic function for R&D expenditure.

Assumption 4. For U (AVKT), it is assumed that $U^{'}(.) < 0$ and

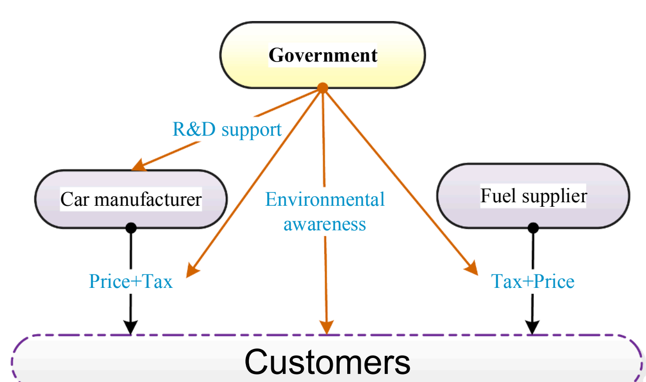


Fig. 1. The structure of the basic problem.

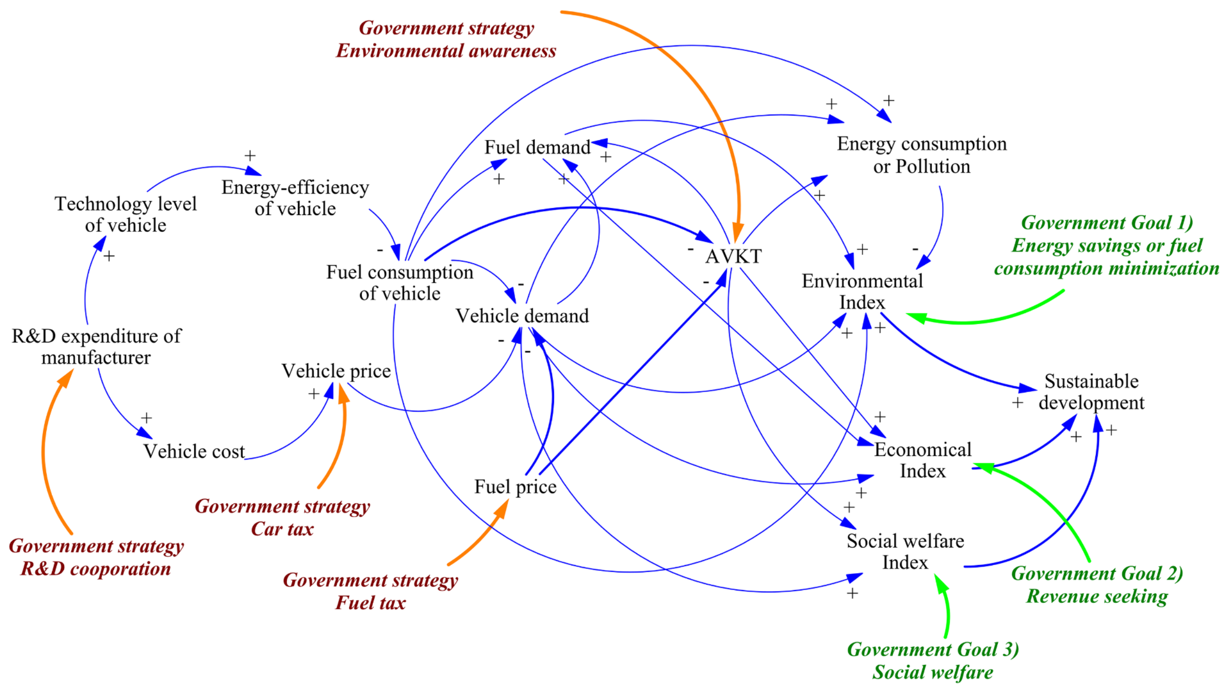


Fig. 2. System dynamics framework of cause-effect relationship of the basic problem.

$\int_0^\infty U(.)d(.) < \infty$ where "." is s, f, p_e, and t_e. AVKT is a decreasing function of s, f, p_e, and t_e. In addition, AVKT is increasing the function of φ and ρ.

Assumption 5. For U (AVKT), it is assumed that the "rebound effect" affects AVKT. The rebound effect is the reduction in expected achievement from increasing energy efficiency, because of systemic or behavioral responses [56,57].

Assumption 6. For energy demand it is assumed that $D'(.) > 0$ and $\int_0^\infty U(.)d(.) < \infty$ where "." is D_m, U and f. Demand of energy is an increasing function of D_m, U and f.

3.2. Formulation

In the next three subsections, respectively, the formulation of the aforementioned problem is presented for the car manufacturer, the energy producer, and the government. For the car manufacturer, a new demand function is presented, and after that the profit function is provided. Also, to formulate the fuel demand and the fuel producer's profit, a new function for calculating the average distance driven by a car within a unit of time, namely AVKT, based on FI, environmental awareness, fuel price at the pump, and the rebound effect is suggested for the first time. For practical use by the government, six models related to the six scenarios are presented.

3.2.1. The manufacturer

Today's world is very competitive for car manufacturers. Many factors influence the purchasing decisions of consumers. As mentioned in the problem definition, this research considers both price and non-price competitive factors for the construction of the demand function. In the area of demand models, Huang, Leng [58] showed that demand models with price dependency are the most commonly used models, because demand is highly dependent on pricing strategies. Also, in previous studies, the linear model is used more than other models because it gives the closed-form optimal solution and explicit results, and also, in an empirical study it is relatively easy to estimate its parameters [57–63]. In this type of pattern, demand is written as a decreasing function of p (price) as $D(p) = a - bp$. The demand variation in response to price variation is called "price elasticity of demand".

The price of a car is one of the most important factors affecting the demand for a car. Also, the price of fuel and FI influence a customer's choice of car. Based on the above explanation, we assumed for this study that demand is a linear function of the car's price and FI; therefore, the demand function investigated in this paper is given in Eq. (1). The first part of this equation is market-based. The second part is based on demand sensitivity to the price of the car. The third part is based on demand sensitivity to FI. This assumption is quite consistent with the fact that car demand is reduced by increasing the cost of the car and increased by boosting the car's energy efficiency (see Assumption 2).

$$D_m = \alpha - \beta(p_m + t_m) - \theta(f(p_e + t_e)) \quad (1)$$

The car manufacturer's net profit is obtained from income minus costs, as shown in Eq. (2). Each car is sold at price p_m and costs c_m. The second part of this equation shows the R&D expenditure that is a function of improving the energy efficiency of the car. f_0 is the current FI that the manufacturer wants to attain, so $f(f \le f_0)$. According to Assumption 3, the R&D expenditure is the function of$(f_0 - f)^2$. μ is the R&D expenditure coefficient that converts $(f_0 - f)^2$ to the cost of the car, and δ is the percentage of government's cooperation in the manufacturer's R&D expenditure.

$$\pi_m = (p_m - c_m)D_m - \mu(1 - \delta)(f_0 - f)^2 \quad (2)$$

3.2.2. The energy producer

In this subsection, we first suggest a function that calculates the AVKT. After that, the demand for fuel and the fuel producer's profit are shown. It is clear that AVKT is a function of an end user's economic situation (ϕ), environmental awareness (s), fuel price at the pump ($p_e + t_e$), FI (f), and the rebound effect ($\Re$). Below we develop a new function for calculating the AVKT as Eq. (3). There are many factors that influence AVKT. These factors can be classified into two categories, including price and non-price factors. According to the problem definition in this study, we considered both price and non-price factors. Price factors include costs that a consumer must pay for using a car. In this research, we considered the fuel cost for using the car for one unit of distance (for example one kilometer) as a price factor. Also, an end user's environmental awareness is considered as a non-price factor. One of the most important issues in the field of energy efficiency and its effects on consumption is the rebound effect. The theoretical background of this function is presented in the Appendix.

$$U = \phi\frac{(s+\rho)}{(1+s)}\frac{(1-(1-\Re)\frac{f_0}{f})}{(p_e+t_e)f} \tag{3}$$

If D_m stands for a car, and AVKT is$U$, and if energy consumption of the car is f per one unit of distance, the demand of energy for one unit of time, according to Assumption 6, can be calculated by Eq. (4), and the net profit of the energy producer is obtained from Eq. (5):

$$D_e = \nu D_m U f \tag{4}$$

$$\pi_e = (p_e - c_e)D_e \tag{5}$$

3.2.3. The government

According to the problem definition, we consider three goals, including minimizing energy consumption (or maximizing energy savings), maximizing revenue seeking, and maximizing social welfare. For the energy savings goal, the government tries to minimize the energy consumption that can be calculated by the product of the number of cars, AVKT, and FI, as follows.

$$\pi_g^{ES} = D_m U f \tag{6}$$

The government function of the revenue-seeking goal is derived from Eq. (7). In this goal, the government wants to increase its profit. The first and second parts of this equation are tax income from car sales and energy consumption, respectively. The third part is the cost of increasing environmental awareness among consumers. The final part is the percentage of government's cooperation in the manufacturer's R&D expenditure.

$$\pi_g^{RS} = D_m t_m + D_e t_e - \eta s - \mu\delta(f_0 - f)^2 \tag{7}$$

The government social welfare function is to maximize usage of cars within a time unit. It should be noted that in other studies the factor of consumer surplus is used for calculating the social welfare gains that are based on the difference between subjective costs and actual costs. Here, however, we consider car use as a measure of social welfare. This function is equal to VMT. In the literature review section, we mentioned several applications of VMT.

$$\pi_g^{SW} = D_m U \tag{8}$$

For each of the above goals, the government has two constraints related to the other goals. Also, as mentioned in the problem description, the government has two strategies for each goal. Given this, we addressed the six resulting scenarios in this study. For the first scenario, for example, the government, with its environmental protection goals (i.e. energy savings), aims to minimize energy consumption, taking into account both pre-specific revenue ζ^{RS} and social welfareζ^{SW}, so that these thresholds are the lower bound for revenue and social welfare, respectively. The model of this scenario, in addition to the other five scenarios, is presented in Table 1. For another example, see the model of Scenario 6 in the table mentioned. In this scenario, the government wants to maximize social welfare, such that energy consumption does not exceed the threshold ζ^{ES} and government revenue does not accrue at less thanζ^{RS}.

4. Equilibrium solutions

4.1. Equilibrium solutions without the government's intervention

Game theory is an approach for analyzing a competitive environment. The timeline of the problem at hand is as follows. In the first period, the government determines decision variables for each available scenario. In the second period, the car manufacturer determines the amount of R&D efforts and the car price. Standard backward induction is used to solve this game.

The car manufacturer wants to maximize its profits. Given the government's taxes, t_m and t_e, and also s and δ, the manufacturer determines p_m and f to maximize its profits. Hence, regarding Eq. (2), the model of this game is as follows:

$$\max_{p_m, f}\pi_m = (p_m - c_m)D_m - \mu(1-\delta)(f_0 - f)^2 \tag{9}$$

Lemma 1. $\boldsymbol{\pi_m}$is a joint concave function on $\boldsymbol{p_m}$ and $\boldsymbol{f}$.

The proof of this lemma, as well as the rest of the proofs, are provided in the Appendix.

Theorem 1.. *The equilibrium price, energy consumption, demand, and profit of the manufacturer are as follows:*

$$p_m^* = \frac{2(1-\delta)(\alpha + c_m\beta - t_m\beta - f_0(p_e+t_e)\theta)\mu - c_m(p_e+t_e)^2\theta^2}{4\beta(1-\delta)\mu - (p_e+t_e)^2\theta^2} \tag{10}$$

$$f^* = \frac{4f_0\beta(1-\delta)\mu - (p_e+t_e)(\alpha - (c_m+t_m)\beta)\theta}{4\beta(1-\delta)\mu - (p_e+t_e)^2\theta^2} \tag{11}$$

$$D_m^* = \frac{2\beta(1-\delta)(\alpha - (c_m+t_m)\beta - f_0(p_e+t_e)\theta)\mu}{4\beta(1-\delta)\mu - (p_e+t_e)^2\theta^2} \tag{12}$$

$$\pi_m^* = \frac{(1-\delta)(\alpha - (c_m+t_m)\beta - f_0(p_e+t_e)\theta)^2\mu}{4\beta(1-\delta)\mu - (p_e+t_e)^2\theta^2} \tag{13}$$

Theorem 2.. *The equilibrium AVKT, energy demand and profit of the energy producer are as follows:*

$$U = \phi\frac{\begin{array}{c}((p_e+t_e)^2\theta^2 + 4\beta(-1+\delta)\mu)((p_e+t_e)\theta(\alpha-(c_m+t_m)\beta\\ +f_0(p_e+t_e)(-1+R)\theta) + 4f_0R\beta(-1+\delta)\mu)(s+\rho)\end{array}}{\begin{array}{c}(1+s)(p_e+t_e)((p_e+t_e)^2\theta^2 + 4\beta(-1+\delta)\mu)\\ ((p_e+t_e)(\alpha-(c_m+t_m)\beta)\theta + 4f_0\beta(-1+\delta)\mu)\end{array}} \tag{14}$$

$$D_e = \frac{\begin{array}{c}2\beta(1-\delta)(-\alpha+(c_m+t_m)\beta + f_0(p_e+t_e)\theta)\mu((p_e+t_e)\theta\\ *(\alpha-(c_m+t_m)\beta + f_0(p_e+t_e)(-1+R)\theta) + 4f_0\\ R\beta(-1+\delta)\mu)\nu(s+\rho)\phi\end{array}}{\begin{array}{c}(1+s)(p_e+t_e)((p_e+t_e)^2\theta^2 + 4\beta(-1+\delta)\mu)\\ ((p_e+t_e)(\alpha-(c_m+t_m)\beta)\theta + 4f_0\beta(-1+\delta)\mu))\end{array}} \tag{15}$$

$$\pi_e = \frac{\begin{array}{c}2(p_e-c_e)\beta(-1+\delta)(\alpha-(c_m+t_m)\beta - f_0(p_e+t_e)\theta)\\ *\mu((p_e+t_e)\theta(\alpha-(c_m+t_m)\beta + f_0(p_e+t_e)(-1+R)\theta)\\ +4f_0R\beta(-1+\delta)\mu)\nu(s+\rho)\phi\end{array}}{\begin{array}{c}(1+s)(p_e+t_e)((p_e+t_e)^2\theta^2 + 4\beta(-1+\delta)\mu)\\ ((p_e+t_e)(\alpha-(c_m+t_m)\beta)\theta + 4f_0\beta(-1+\delta)\mu)\end{array}} \tag{16}$$

Table 1
The six scenarios for the government.

Goal	Constraints	Strategy Car and fuel taxes	Environmental awareness and percentage of government's cooperation in the manufacturer's R&D expenditure
ES	*RS* *SW*	$\begin{cases}\mathrm{Min}_{t_m,t_e}\pi_g^{ES}(p_m^*, f^*)\\ RS \ge \zeta^{RS}\\ SW \ge \zeta^{SW}\end{cases}$	$\begin{cases}\mathrm{Min}_{s,\delta}\pi_g^{ES}(p_m^*, f^*)\\ RS \ge \zeta^{RS}\\ SW \ge \zeta^{SW}\end{cases}$
RS	*ES* *SW*	$\begin{cases}\mathrm{Max}_{t_m,t_e}\pi_g^{RS}(p_m^*, f^*)\\ ES \le \zeta^{ES}\\ SW \ge \zeta^{SW}\end{cases}$	$\begin{cases}\mathrm{Max}_{s,\delta}\pi_g^{RS}(p_m^*, f^*)\\ ES \le \zeta^{ES}\\ SW \ge \zeta^{SW}\end{cases}$
SW	*ES* *RS*	$\begin{cases}\mathrm{Max}_{t_m,t_e}\pi_g^{RS}(p_m^*, f^*)\\ ES \le \zeta^{ES}\\ SW \ge \zeta^{SW}\end{cases}$	$\begin{cases}\mathrm{Max}_{s,\delta}\pi_g^{RS}(p_m^*, f^*)\\ ES \le \zeta^{ES}\\ SW \ge \zeta^{SW}\end{cases}$

With the above relations now established, the next subsection presents models of the government.

4.2. Equilibrium solutions with the government intervention

As mentioned at the outset of this paper, for the purpose of this study, the government is labeled as a Stackelberg leader, and the car manufacturer is labeled as a follower. The government has two strategies determining taxes for cars and fuel, and determining the percentage of government's cooperation in the manufacturer's R&D expenditure. The government also assumes the costs associated with increasing the public's environmental awareness and commitment to sustainability.

After substituting Eqs. (11), (12), and (14) into Eq. (6), and Eqs. (11), (12), and (15) into Eq. (7), and Eqs. (12) and (14) into Eq. (8), the three objective functions of the government (i.e., π_g^{ES}, π_g^{RS}, and π_g^{SW}), are obtained, respectively, as follows:

$$\pi_g^{ES}=\frac{\begin{array}{c}2\beta(1-\delta)(-\alpha+(c_m+t_m)\beta+f_0(p_e+t_e)\theta)\mu((p_e+t_e)\\ *\theta(\alpha-(c_m+t_m)\beta+f_0(p_e+t_e)(-1+R)\theta)+4f_0\\ R\beta(-1+\delta)\mu)\nu(s+\rho)\phi\end{array}}{\begin{array}{c}(1+s)(p_e+t_e)((p_e+t_e)^2\theta^2+4\beta(-1+\delta)\mu)\\ ((p_e+t_e)(\alpha-(c_m+t_m)\beta)\theta+4f_0\beta(-1+\delta)\mu)\end{array}} \tag{17}$$

$$\pi_g^{RS}=-s\eta-E_1-E_2-\frac{\begin{array}{c}(2t_e\beta(-1+\delta)(-\alpha+(c_m+t_m)\beta\\ +f_0(p_e+t_e)\theta)\\ \mu((p_e+t_e)\theta(\alpha-(c_m+t_m)\beta+f_0(p_e+t_e)(-1+R)\theta)\\ +4f_0R\beta(-1+\delta)\mu)\nu(s+\rho)\phi)\end{array}}{\begin{array}{c}(1+s)(p_e+t_e)((p_e+t_e)^2\theta^2+4\beta(-1+\delta)\mu)\\ ((p_e+t_e)(\alpha-(c_m+t_m)\beta)\theta+4f_0\beta(-1+\delta)\mu)\end{array}} \tag{18}$$

$$\pi_g^{SW}=\frac{\begin{array}{c}2\beta(1-\delta)(-\alpha+(c_m+t_m)\beta+f_0(p_e+t_e)\theta)\mu((p_e+t_e)\\ *\theta(\alpha-(c_m+t_m)\beta+f_0(p_e+t_e)(-1+R)\theta)+4f_0\\ R\beta(-1+\delta)\mu)(s+\rho)\phi\end{array}}{(1+s)(p_e+t_e)((p_e+t_e)(\alpha-(c_m+t_m)\beta)\theta+4f_0\beta(-1+\delta)\mu)^2} \tag{19}$$

where

$$E_1=\frac{(p_e+t_e)^2\delta\theta^2(-\alpha+(c_m+t_m)\beta+f_0(p_e+t_e)\theta)^2\mu}{((p_e+t_e)^2\theta^2+4\beta(-1+\delta)\mu)^2}$$

$$E_2=\frac{2t_m\beta(-1+\delta)(-\alpha+(c_m+t_m)\beta+f_0(p_e+t_e)\theta)\mu}{(p_e+t_e)^2\theta^2+4\beta(-1+\delta)\mu}$$

5. Case study

To better understand the problem and the procedure used to solve it, and also to present practical results and managerial insights, this section presents a case study based on evidence from South Korea. This section includes four subsections. In the first Section 5.1, some information about the Korean automobile industry is presented. In the second subsection, feasible regions and the effect of some parameters on demands, profits, and governmental goals for current data are presented (5.2). In Section 5.3, the equilibrium solution is presented. In the last Section 5.4 results and insights from this case study are presented.

5.1. Some information about the Korean automobile industry

The automobile industry of South Korea comprises a large ratio of Korea's economy [64]. This industry, which ranked 6th in the world in 2018 in terms of production volume, is a key industry that has played a crucial role in creating jobs and boosting the economy through increasing exports [65]. According to data from the Korea Automobile Manufacturers Association (KAMA), seven domestic carmakers, including Hyundai Motor, Kia Motors, SsangYong Motor, GM Korea, Renault Samsung, Tata Daewoo, and Zyle Daewoo, sold 3.64 million vehicles between January and November 2018.

The passenger cars' registration in Korea increased significantly in the 1990s, and stood at approximately 10 million in 2002, compared to 2.1 million in 1990. The number of vehicles also continued to increase in 2018, and stood at more than 22.8 million in South Korea as of late June 2019 [66]. South Korea's registered motor vehicle data also was reported at 23,500,774 units overall, and in Seoul alone the count was 3,121,140 units in July 2019 [67,68]. According to these data, there exists in the Korean population one automobile per 2.46 citizens [69].

Give these statistics, it makes sense that South Korea is the ninth-largest emitter of CO_2. Between 1992 and 2017, the GDP of Korea more than tripled, and its CO_2 emissions more than doubled. In 2017, although South Koreans make up only 0.7% of the world's population, the country is responsible for 1.7% of global carbon output, with 616.1 million tons of CO_2 emissions from fossil fuel [70]. In South Korea, vehicles are one of the biggest emissions sources and produced about 21% of domestic air pollutants and approximately 13% of domestic greenhouse gas emissions [71]. Korea has pledged to decrease its greenhouse gas emissions by 37% by 2030 [72]. Achieving this goal, however, requires appropriate R&D programs to increase energy efficiency of cars and to use fewer pollutant-causing energy sources.

According to the Korea National Oil Corporation (KNOC and Opinet), the current pump price for one liter of gasoline in Seoul is about 1592 won ($1.32). The gasoline tax was lowered from 821 won per liter to 763 won per liter [73,74]. According to a survey performed by Lee and Cho [51], the average distance driven per year by South Korean citizens is about 14,829.3 km for all kinds of cars. In the remainder of this study, we refer to other findings for VMT in Korea as well [27,75]. In this case study, we consider the Santafe Brand of car. According to a sample that we found on a used car site [76], the AVKT for Santafe is about 9,728 km/year. The price of this 2020 car is between $24,900 and $35,750, depending on the features it supports [77]. Also, much research exists about price elasticity of demand for this car in different areas of South Korea (see [78–87]).

Hyundai Motor and Kia Motors provided 4.1 trillion won as an investment in R&D (or 2.8 percent of their combined sales) in 2017 [88]. The two companies together made a record high R&D investment of $3.90 billion in 2018. Hyundai Motor Company and Kia Motors Corporation are expected to invest more than $8.81 billion in facilities and R&D in 2019 [89].

According to the above information and other data from South

Table 2
The values of the parameters for the case study.

Parameter	α	β	θ	f_0	μ	ρ	ν	ϕ	η
Unit	car	car/$	car/$	L/Km	$ (Km/L)^2	–	year	$/year	$
Value	1.9e+5	2.9	4.7e+5	0.094	2e+11	3	10	725	2e+7
Parameter	c_m	p_m	c_e	p_e	$\mathfrak{R}$	ζ^{ES}	ζ^{RS}	ζ^{SW}	
Unit	$/car	$/car	$/L	$/L	–	L/year	$	Km/year	
Value	2.2e+4	2.646e4	0.67	0.71	77.6%	4.85e+8	3e+8	6.27e+8	

Korea, the data for the problem under consideration is provided in Table 2. Some of the data are estimations of the real data, and details such as car prices, car sales tax, and price elasticity were provided in other studies [77,90]. The next subsection includes the equilibrium and results for this case study.

5.2. Feasible regions and sensitivity analysis of the current data

Fig. 3 shows the feasible region for concavity of the manufacturer model for βandθ and also μandδ, in addition to the current data for these parameters. Outside the specified region, all the critical points must be examined for finding the manufacturer's solution to the problem.

Fig. 4, where green occurs, shows the areas where the profit of the manufacturer is positive, with changes of a) manufacturer decision variables (i.e., $p_m$and$f$); b) taxes (i.e., $t_m$andt_e); and awareness parameters (i.e., μandδ). Although the positive profit ensures that the manufacturer makes a profit, it does not ensure the manufacturer's presence for the long-term in a competitive market. Therefore, we show a blue area, in which the manufacturer expects a minimum profit, for example 3E + 8, in order to stay in business.

The effect of a car manufacturer's decision variables on a car's demand on and the manufacturer's profit are shown in Fig. 5. This figure as well as other figures in this paper are drawn by Mathematica software. The maximum or minimum surfaces of Figs. 5–7 are shown with the hot colors. If the price, or energy consumption, of the car increases, the demand of the car decreases (Fig. 5 (a)). If the car price increases, the manufacturer's profit increases; but if the car's price continues to increase, the manufacturer's profit starts to decrease, because demand decreases. Also, if the manufacturer increases its R&D efforts, this leads to an energy consumption decrease, and the demand for the resulting car increases; therefore, the manufacturer's profit increases. However, because improving energy consumption means increasing R&D costs, after an optimum point, the car manufacturer's profits start to decrease (Fig. 5 (b)).

5.3. Equilibrium solution

Fig. 8 shows the feasible region and the optimal solution for each scenario separately. For the six scenarios, the feasible region created by the two constraints is shown by the area covered by green, blue, and purple lines for energy savings, revenue seeking, and social welfare constraints, respectively. The government's goal for each scenario is also illustrated by the contour plot. Given the constraints created, the specified point optimizes the government's objective function for each scenario. We use these figures to express the results and insights in Section 5.4. The equilibrium solutions for all of the agents are presented in Table 3. It is clear that the government's goals and strategies have a significant effect on the price, energy efficiency, demand of the car, manufacturer and fuel profits, pollution, government income, social welfare, and consumer behavior (such as a driver's average use of a car in a year, i.e., AVKT). In the following, we show these effects with more details discovered as a result of this case study.

5.4. Results and insights

In this subsection, we present several results and insights from exploring the above case study.

Fig. 9 (a) and (b) show the equilibrium taxes for the car and fuel, respectively; and Fig. 9 (c) and (d) show the equilibrium amount of environmental awareness and the percentage of government's cooperation in the manufacturer's R&D expenditure, respectively. Remember, when reviewing these figures, that the scope of environmental awareness and the percentage of government's cooperation in the manufacturer's R&D expenditure for the first three scenarios are specific and driven by input parameters. Additionally, the two types of taxes for the second three scenarios are also specific and driven by input parameters.

By comparing Fig. 9 (a) and (b), it is concluded that the lowest equilibrium car sales tax and the highest equilibrium fuel tax belong to the first scenario when the government pursues a fuel consumption minimization goal with a tax strategy. The equilibrium taxes assessed on cars and fuel for the second scenario (i.e., when the government pursues a revenue-seeking goal with a tax strategy), are opposite to the first scenario. In the second scenario, the highest equilibrium car sales tax and the lowest equilibrium fuel tax were obtained. Therefore, according to Fig. 9 (a) and (b), we conclude that:

Corollary 1. *Under the tax strategy, the government must, simultaneously, decrease the car sales tax and increase the fuel tax if its goals are for energy savings (or energy consumption and pollution reduction) or social welfare maximization. The government must also simultaneously increase the car sales tax and decrease the fuel tax if it has a revenue-seeking goal.*

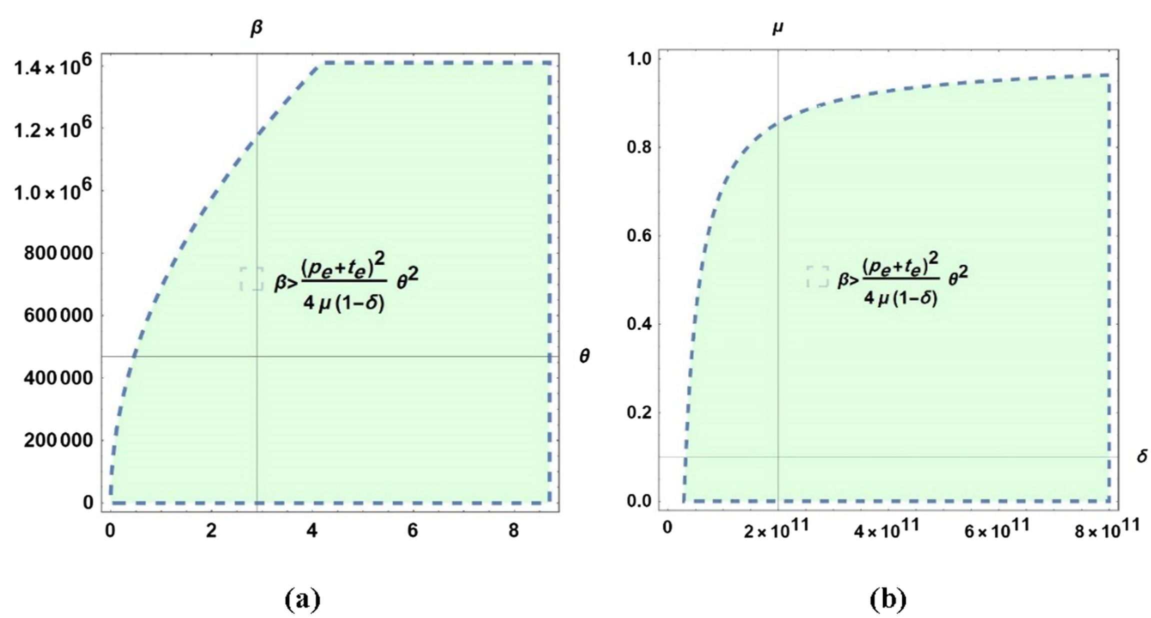


Fig. 3. The feasible region for concavity of the car manufacturer's problem with changes of a) β and θ and b) μ and δ.

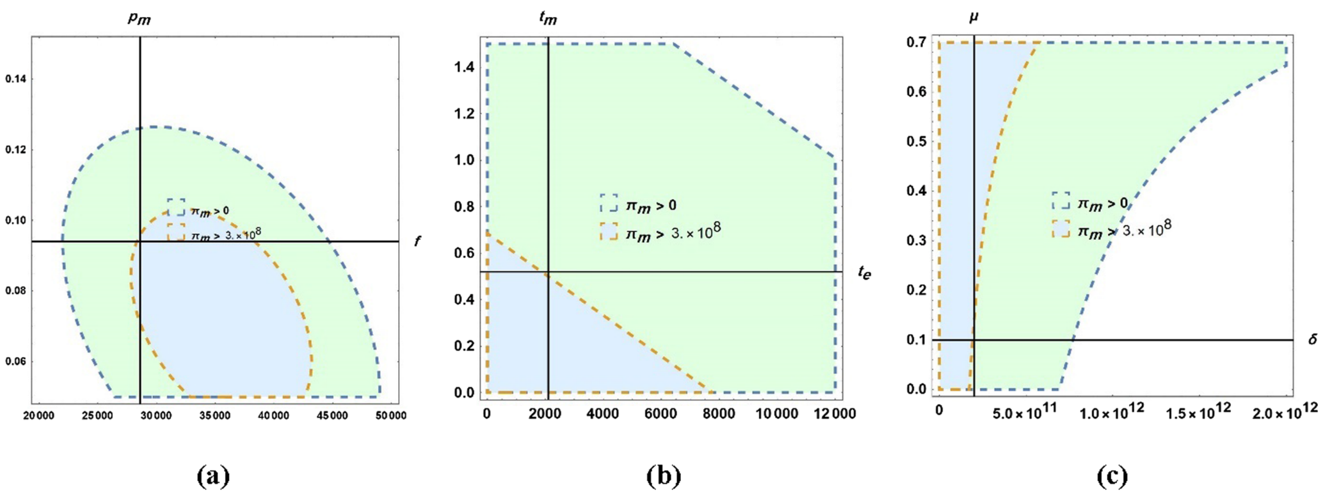


Fig. 4. The feasible region for a car manufacturer's profit, with changes a) p_m and f, b) t_m and t_e, and c) μ and δ.

According to Fig. 9 (c), environmental awareness at the equilibrium point under the fourth scenario is higher than in the other scenarios. In other words, when the government pursues the goal of energy savings with environmental awareness and R&D support, the equilibrium of environmental awareness is at its highest value, in respect to the other scenarios. Also, according to Fig. 9 (d), the social welfare goal leads to the maximum cooperation on R&D expenditures by car manufacturers. Therefore, according to the above explanation and the other obtained equilibrium solutions:

Corollary 2. *Under the environmental awareness and R&D support strategy, the government must increase environmental awareness and the percentage of government's cooperation in the manufacturer's R&D expenditure if its goal is to increase energy savings and social welfare. The government must also decrease the percentage of government's cooperation in the manufacturer's R&D expenditure, while not impacting environmental awareness, if it has a revenue-seeking goal.*

Fig. 10 (a) and (b) show the equilibrium solution for the car manufacturer's decision variables, (i.e., car price and FI). The equilibrium car price, plus tax, also is provided in Fig. 10 (a). According to Fig. 10 (a), the highest price a customer should pay for a car belongs to Scenario 2, where the government is seeking to maximize revenue by using a tax strategy. The lowest price paid by the customer is also, for Scenario 1, where the government wants to minimize energy consumption by adopting a tax strategy. According to Fig. 10 (b), Scenario 6 leads to a more energy-efficient car. Therefore, we conclude that:

Corollary 3. *In the equilibrium solutions, the government's energy savings goal with a tax strategy (i.e., Scenario 1), is from the customer's perspective, more suitable for buying a car because it leads to a lower car price. The government's revenue-seeking goal with a tax strategy (i.e., Scenario 2), leads to a more expensive car, as does the government's social welfare maximization goal with environmental awareness and R&D support (i.e. Scenario 6).*

Corollary 4. *When the government pursues a social welfare goal with environmental awareness and R&D support (i.e. Scenario 6), equilibrium fuel intensity is at a minimum value, compared to the other scenarios. However, there is no significant difference between equilibrium energy efficiency in the scenarios under consideration.*

AVKT values for each scenario are shown in Fig. 11. AVKT increases under all the scenarios regarding the current situation (for comparison with the current situation, see Table 2). Scenario 6, however, in which the government's goal is to maximize social welfare with environmental awareness and R&D support, led to maximum AVKT; and Scenario 1 (i.e., with the government's goal being to minimize energy consumption with a tax strategy), led to minimum AVKT, with respect to the other scenarios.

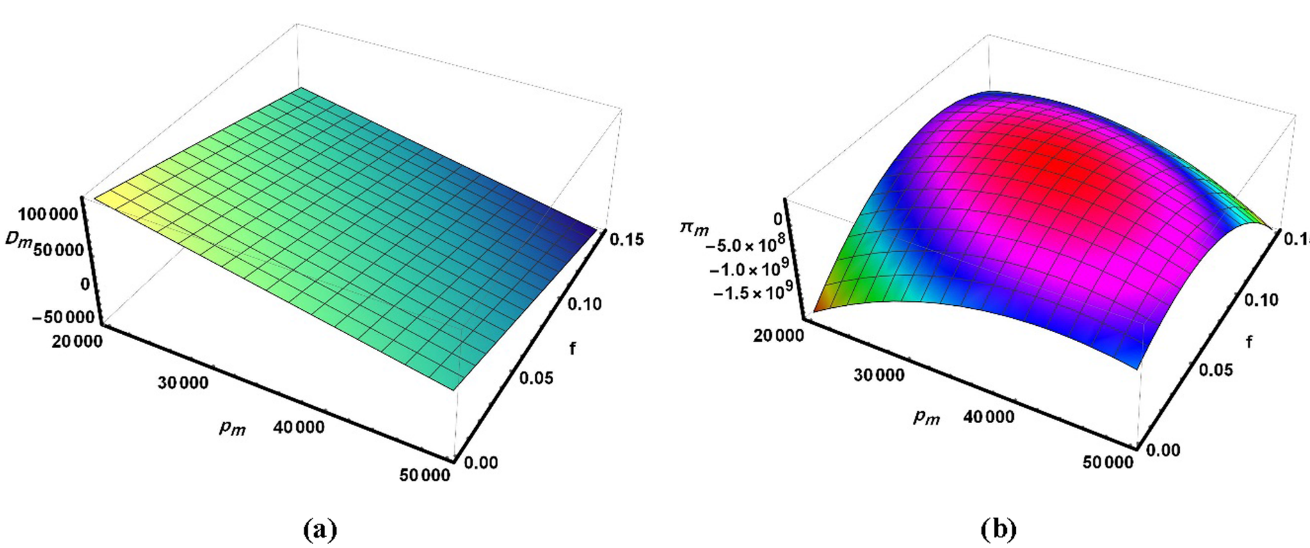
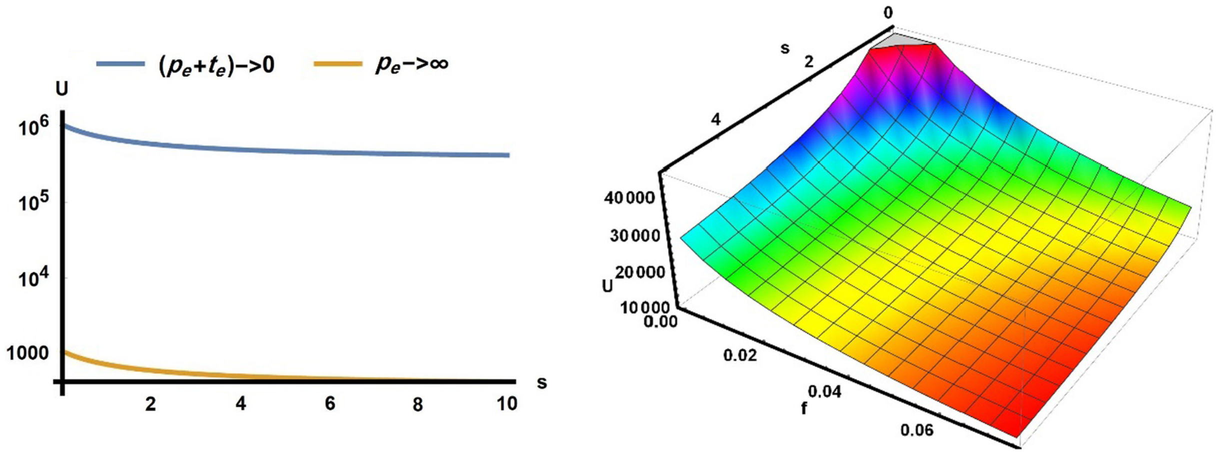


Fig. 5. The effect of a car manufacturer's decision variables on a) car demand and b) manufacturer's profit.



(a) (b)

Fig. 6. The effect of a) environmental awareness and b) energy consumption and environmental awareness on AVKT.

Corollary 5. *If the government selects an energy savings goal with a tax strategy (Scenario 1), the average distance driven by each driver will be at the minimum amount; and if the government selects a social welfare goal with environmental awareness and R&D support (Scenario 6), the average distance driven by each driver will be at the maximum amount.*

The demand for a car and a car manufacturer's profit are presented in Fig. 12 (a) and (b). We see that Scenario 6 (i.e., when the government's goal is social welfare with environmental awareness and R&D support), creates the highest demand for a car; but Scenario 3, in which the government's goal is social welfare with a tax strategy, creates the highest profit for the car manufacturer. In addition, we see that the minimum demand for a car and a car manufacturer's profit belongs to Scenario 2, in which the government's goal is to generate revenue and use a tax strategy to reach this goal. Therefore, we conclude that:

Corollary 6. *If the government wants to maximize the demand for a specific car, it must select Scenarios 1, 3 or 6 (i.e., energy savings and social welfare goals with a tax strategy, or a social welfare goal with environmental awareness and an R&D support strategy).*

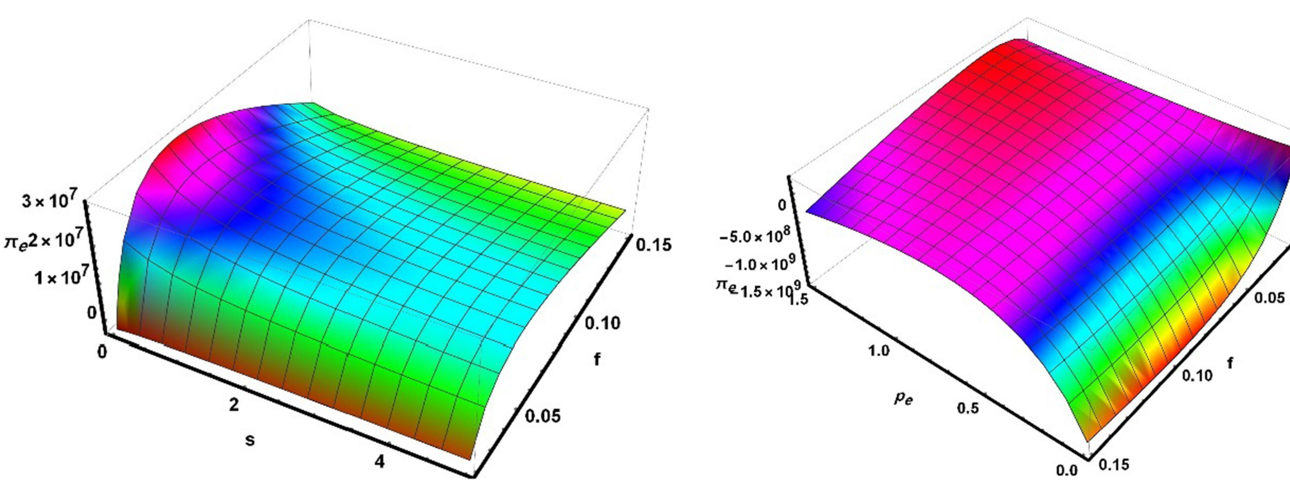
Corollary 7. *If the government wants to maximize the manufacturer's profit, it must select Scenarios 3 or 6 (i.e., a social welfare goal with a tax strategy or a social welfare goal with environmental awareness and an R&D support strategy).*

Fig. 13 shows the energy producer's equilibrium functions, including fuel demand and producer profit. By comparing these figures, we conclude:

Corollary 8. *The lowest energy consumption (minimum pollution) equilibrium is related to Scenario 1, and after that to Scenario 4 (i.e., when the government pursues a goal of energy consumption with a tax strategy or a goal of environmental awareness with an R&D support strategy). Also shown is the fact that a tax strategy has a greater impact on energy consumption than an environmental awareness and R&D support strategy. Also, according to Fig. 13 (b), the lowest profits for energy producers are related to these two scenarios. Therefore, fuel producers prefer Scenarios 2, 3, 5, and 6.*

The equilibrium solutions of the government models are provided in Fig. 14. It is clear that the best values for energy savings, revenue generation, and social welfare are obtained through Scenarios 1 and 4, 2 and 5, and 3 and 6, respectively. By comparing the equilibrium solution of Scenario 1 with the equilibrium solution of Scenario 4, and 2 with 5, and 3 with 6, it can be concluded that:

Corollary 9. *If the government pursues the objectives of energy savings and*



(a) (b)

Fig. 7. The effect of a) environmental awareness and fuel consumption and b) fuel consumption and fuel price on a fuel producer's profit.

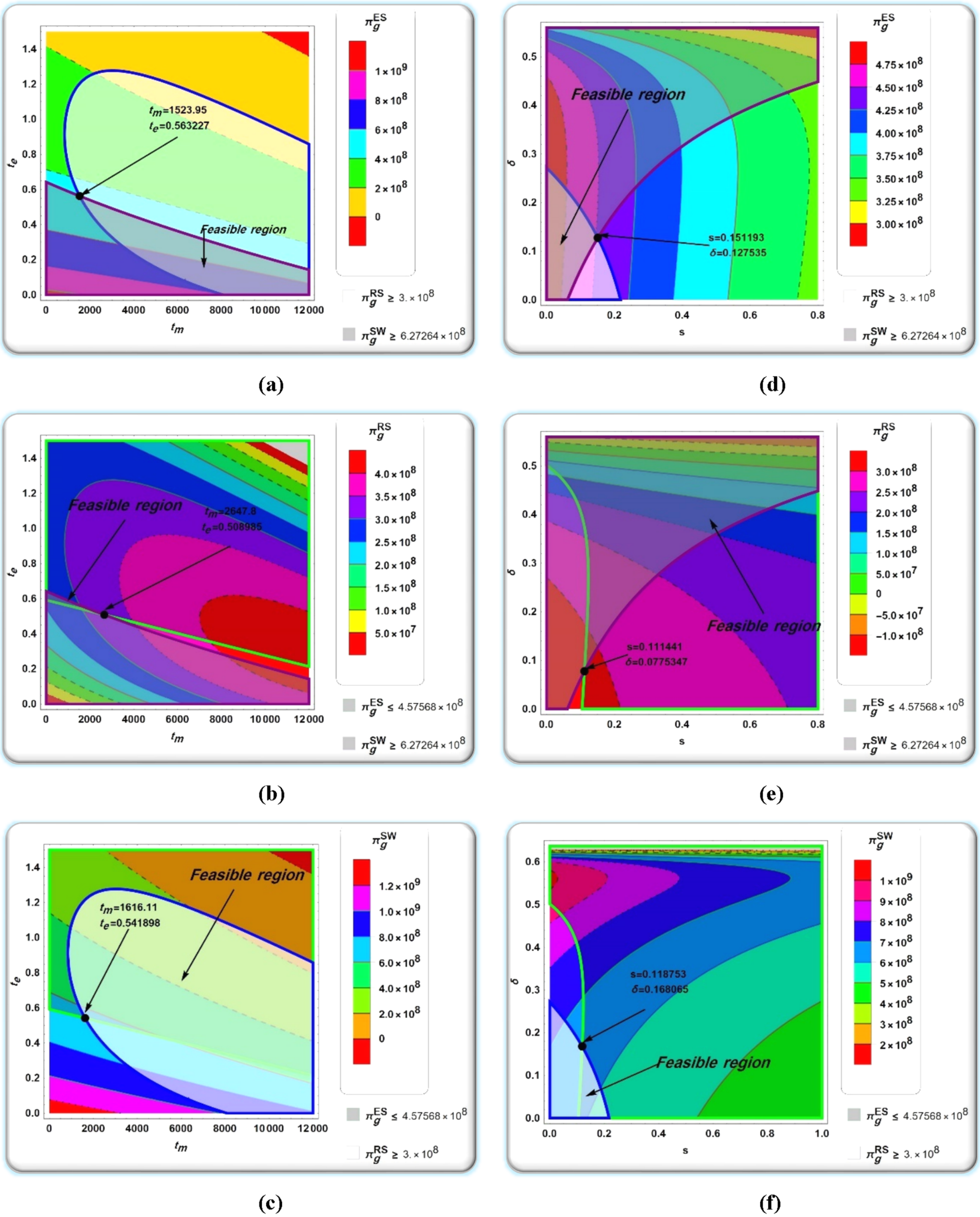


Fig. 8. The government's optimal solution for each scenario.

revenue generation, a tax strategy will have a greater impact than an environmental awareness and R&D support strategy. But if the government pursues a goal of social welfare, environmental awareness and an R&D support strategy are more effective than a tax strategy.

Insight 1

The lowest equilibrium price paid by the customer is obtained from Scenario 1, where the government seeks to minimize energy consumption by adopting a tax strategy. In addition, the minimum amount of demand for a given car, as generated from the other scenarios, is

Table 3
The equilibrium solutions for the six scenarios.

Scenario	*Decision variables*						*Functions*								*Related Figure*
	Government				*Manufacturer*		*Manufacturer*		*Energy producer*			*Government*			
No	t_m	t_e	s	δ	p_m	f	D_m	π_m	U	D_e	π_e	π_g^{ES}	π_g^{RS}	π_g^{SW}	Fig. 8.
	1,524	0.56	*	*	35,637	0.071	4.0E+04	4.5E+08	15,861	4.5E+08	1.8E+07	4.5E+08	**	**	(a)
	2,648	0.51	*	*	35,229	0.073	3.8E+04	4.3E+08	16,350	4.6E+08	1.8E+07	**	3.2E+08	**	(c)
	1,616	0.54	*	*	35,683	0.072	4.0E+04	4.5E+08	16,091	4.6E+08	1.8E+07	**	**	6.4E+08	(e)
	*	*	0.15	0.13	35,582	0.072	3.9E+04	4.5E+08	15,925	4.5E+08	1.8E+07	4.5E+08	**	**	(b)
	*	*	0.11	0.08	35,438	0.073	3.9E+04	4.4E+08	16,096	4.6E+08	1.8E+07	**	3.1E+08	**	(d)
	*	*	0.12	0.17	35,714	0.070	4.0E+04	4.5E+08	16,395	4.6E+08	1.8E+07	**	**	6.5E+08	(f)

* Pre-determined (see Table 2).
** Pre-determined for the government goals' lower or upper bound (see Table 2).

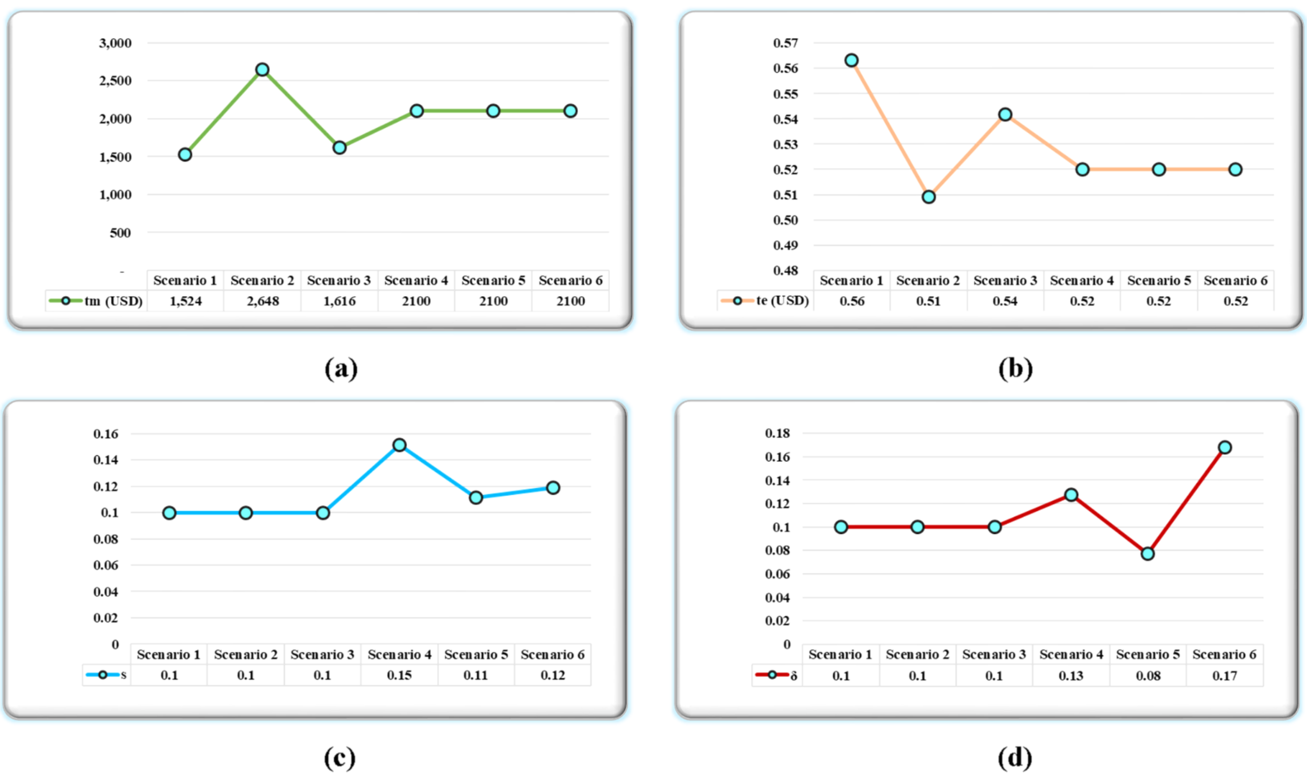


Fig. 9. The government's equilibrium strategies, including. a) car sales tax, b) fuel tax, c) environmental awareness, and d) R&D cooperation for each scenario.

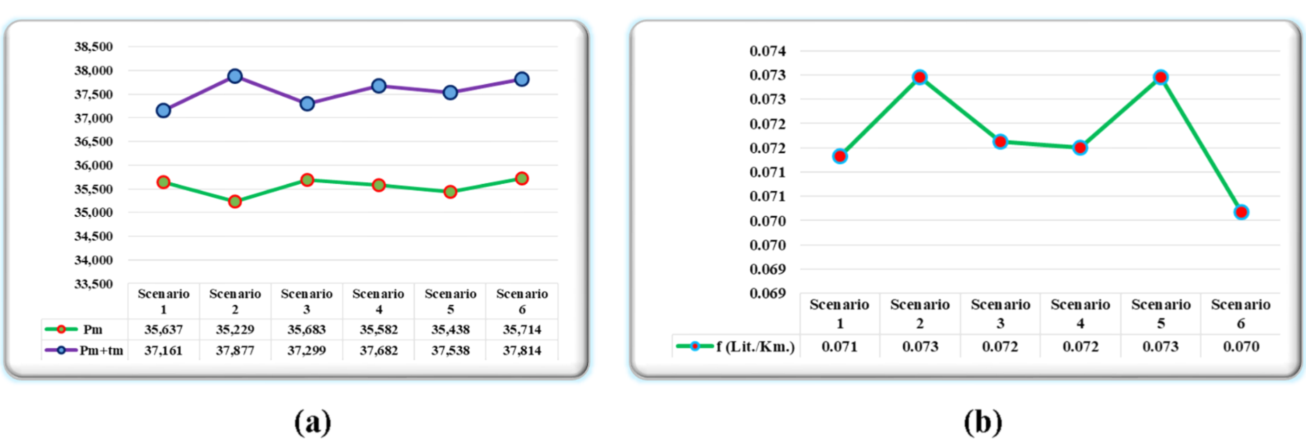


Fig. 10. The car price and car price plus tax (a) equilibrium and FI (b) equilibrium.

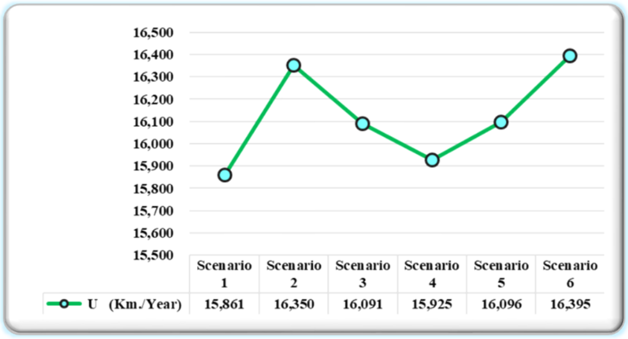


Fig. 11. The AVKT equilibrium.

shown in Fig. 12. A question this study asked was why the minimum lowest price does not belong to other scenarios (for example, the social welfare goal scenarios), and why the minimum demand for a given car does not work for Scenario 1 (i.e., energy consumption minimization). Fig. 8 (a) helps to find the answer to this two-pronged question. In answering the question, we kept in mind the fact that the models of government interventions include constraints. For Scenario 1, for example, income and social welfare constraints can be seen in Fig. 8. The equilibrium solution was found in the region that was created by these two constraints. But this prompts the question of how energy consumption is minimized in this scenario. The answer to this question is shown in Fig. 9 (b). The highest energy tax equilibrium was obtained in this scenario. Also, according to Fig. 11, AVKT is at a minimum in this scenario.

Insight 2

When the government seeks to generate revenue with a tax strategy (i.e., Scenario 2), we can, perhaps, expect that the government will reduce the price of the car and increase the price of fuel, because this leads to more cars bought and more fuel consumed. According to Fig. 9 (a) and (b), however, and Corollary 1, the obtained results are quite contrary to this expectation. The contour plot in Fig. 8 (b) shows, in addressing this finding, an upward direction of government revenue. The optimal solution of this goal is shown in the red ellipse, and increasing this goal will occur when the car sales tax increases and the fuel tax decreases. However, due to pollution and welfare constraints, the optimal solution was obtained before further increases in the given car's price and further reductions in fuel prices. Despite all this, however, we wondered why the aforementioned finding is the case for the purpose of raising revenue. The reason for increasing the car sales tax is related to market elasticity for the car, and the reason for decreasing the fuel tax, in order to increase government revenue, is due to increasing the AVKT if the fuel tax decreases (Fig. 11). In other words, increasing the use of cars, along with lowering the fuel tax, will lead to more revenue for the government than increasing the fuel tax and reducing the use of cars.

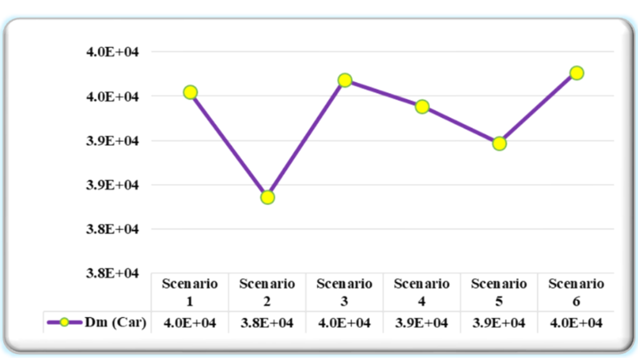
Insight 3

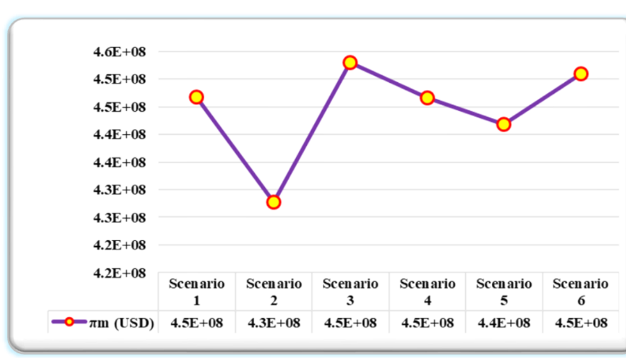
If we look carefully at the results obtained from Scenario 3, we see that the greatest profit made by car manufacturers is obtained by this scenario (see Fig. 13 and Corollary 7). By comparing Scenario 3 with Scenario 6, however, we find that the manufacturer's car price and the demand for that given car are both less in Scenario 3 than they are in Scenario 6 (Fig. 10 (a) and Fig. 12 (a)). In addition, according to Fig. 9 (d), we see that the percentage of government's cooperation in the manufacturer's R&D expenditure in Scenario 6 is greater than the percentage arrived at in Scenario 3. This, then, prompts the question of why the profit obtained by car manufacturers in Scenario 3 is greater than the profit obtained in Scenario 6. The answer to this question can be deduced from Fig. 10 (b). In Scenario 3, the car manufacturer must spend less for R&D than it spends in Scenario 6.

6. Summary and conclusions

The importance of the problem, followed by a brief statement: Sustainability is a rich area for academic research, and studies have the potential to affect people, manufacturers, and government strategies. Increasing greenhouse gases, due to the combustion of fossil fuels, and the impacts these gases have on the environment, have increased concerns about life on planet Earth in the coming decades. Unfortunately, the world's demand for fossil fuels and the world's pollution level have increased significantly over time. In this study, we addressed a problem in which a car manufacturer wants to determine, simultaneously, the price of a particular car and the amount of research and development efforts needed to improve the energy efficiency of that car, according to government intervention strategies. We considered three important goals for these government intervention strategies, including *maximizing energy savings* (or minimizing energy consumption), *maximizing revenue*, and *maximizing social welfare*. These strategies involved two approaches, including *car and fuel taxes* and *environmental awareness and research and development support*. This created, for the purpose of this study, six scenarios/models for the government. After solving the problem with backward induction, we analyzed a case study. As mentioned at the outset of this paper, we think that this research can enhance the use of operations research in sustainability. The main contributions, results and insights, and limitations and future research are provided in the following three paragraphs.

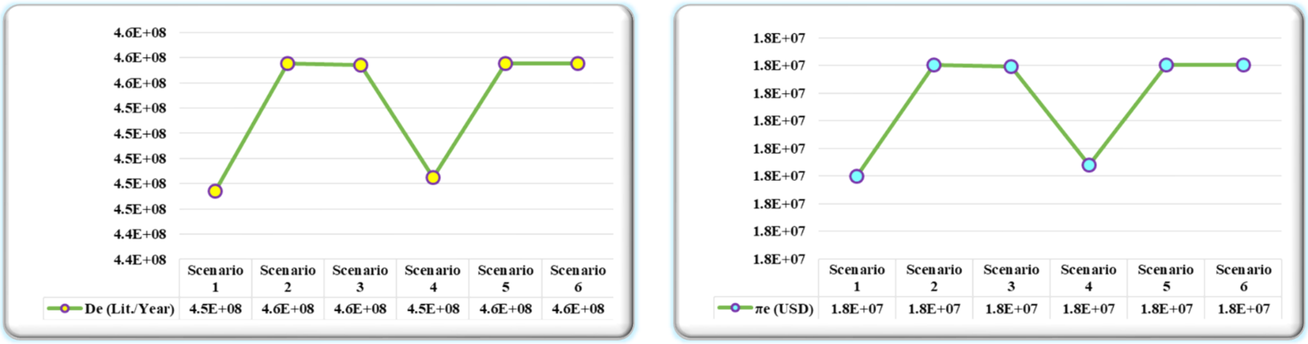
Theoretical contributions: To our knowledge, there is not much literature on determining a car's price according to its energy efficiency level and government initiatives such as energy savings, revenue generation, and social welfare. This research offers several contributions to existing studies. First, our study extends previous research in the area of car pricing by developing a new function for car demand by fuel





(a) (b)

Fig. 12. The car demand (a) equilibrium and the manufacturer's profit (b) equilibrium.



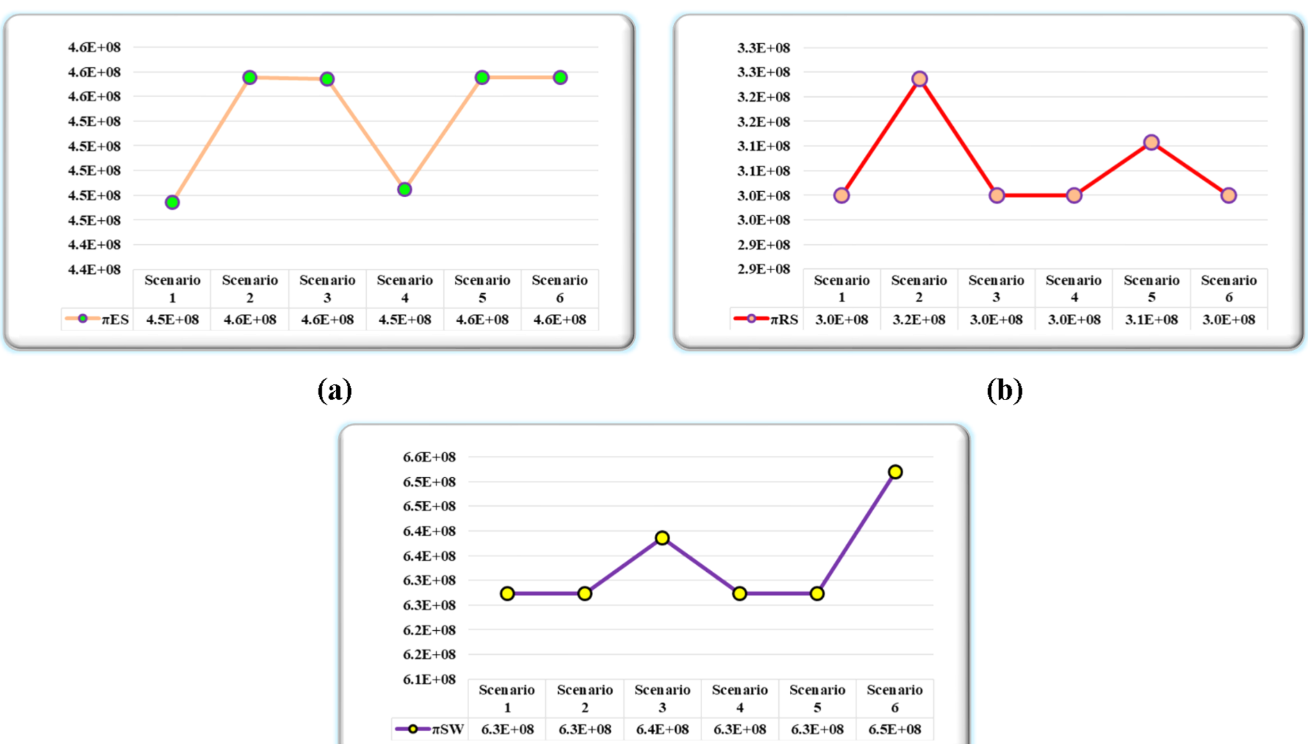
(a) **(b)**

Fig. 13. The energy demand (a) and the energy producer's profit (b) equilibrium.

intensity. Second, a new function, namely AVKT (average of vehicle kilometer traveled in a unit of time), for calculating the average distance driven by a car in a specific time is introduced. Five factors, including an end user's economic situation, environmental awareness, energy consumption, fuel price at the pump, and "rebound effect," are considered in this combined function. Third, this research, for the first time, studied the effect of different government goals and strategies on car and energy demands, while also examining car manufacturer and fuel producer profits. Fourth, using the system dynamics approach, we presented the cause and effect of relationships between the problem's variables and game theory. Finally, we provided a case study and offered several results and insights to this problem.

Some results and insights: Our experimental results, based on a case study, have important implications for Korean car manufacturers looking to find the equilibrium price and the energy efficiency level of cars, as applied to different interventions by the government. In addition, this study presents the equilibrium solution for each scenario of government intervention, and suggests several results and insights for each scenario.

Furthermore, our findings show that *from the manufacturer's point of view*, the best goal, out of other government goals that maximize a car manufacturer's equilibrium profit, is the social welfare maximization with tax strategy goal. Our findings also show that the worst goal, from the manufacturer's point of view, is revenue generation with a tax strategy. *From the fuel producer's point of view*, the best goals, out of other government goals that maximize a fuel producer's equilibrium profit, are revenue generation and social welfare maximization goals, both with a tax strategy and with an environmental awareness and research and development support strategy. Energy savings with a tax strategy and energy savings with an environmental awareness and research and development support strategy are the worst scenarios for a fuel producer. *From a car buyer's, point of view*, the energy savings goal with a tax strategy and the revenue generation goal with a tax strategy are, respectively, the best and worst scenarios, because of the resulting



(c)

Fig. 14. The government's goals equilibrium for a) energy savings b) revenue generation, and c) social welfare.

minimum and maximum equilibrium car prices. *From a car owner's point of view*, the revenue generation goal with a tax strategy is the best scenario in terms of fuel price; and the social welfare goal with the environmental awareness and research and development support strategy scenario is the best in terms of average of vehicle kilometer traveled in a unit of time. Additionally, the energy savings goal with a tax strategy and revenue seeking with tax strategy are the worst scenarios in terms of fuel price and average of vehicle kilometer traveled in a unit of time, respectively. *From the government's point of view*, with a goal of energy savings and revenue generation, the tax strategy is the best scenario; and, with a goal of social welfare, the environmental awareness and research and development support strategy is the best scenario.

Limitations and future research: We identify in this study several limitations that may be useful to know about for future research. First, in this problem, no decision variable was considered for the fuel producer, which this research could have included by considering one or more decision variables for the fuel producer. Specifically, the fuel price considered could be determined as a decision variable. This would mean that the fuel producer, as an agent in the problem, could also maximize profits. Second, in this study we considered three factors that influence the average of vehicle kilometers traveled in a unit of time. We know that many other factors, such as household income, can affect the average of vehicle kilometers traveled in a unit of time, so considering other factors could extend this research. Third, this research could be extended by applying the Jevons paradox, a possibility that has interesting implications. Fourth, this research also could be expanded by considering the effect of other factors, such as car design or price of a car, have on AVKT. Finally, we focused on three goals and two strategies for government intervention in this study, and thus neglected other potentially important goals, such as social responsibility. We conclude by saying that these unexplored routes are suggested for future work

CRediT authorship contribution statement

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

Acknowledgments

The authors are grateful for the valuable comments from the associate editor and anonymous reviewers. This research was supported by the Brain Pool Program of National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT and Future Planning [Grant No. NRF-2019H1D3A2A01059749].

Appendix

Theoretical background of AVKT function

There are many factors that influence AVKT. These factors can be classified into two categories, including price and non-price factors. According to the problem definition in this study, we considered both price and non-price factors. Price factors include costs that a consumer must pay for using a car. In this research, we considered the fuel cost for using the car for one unit of distance (for example one kilometer) as a price factor. Therefore, we know that$U \propto f_1(f, p_e, t_e)$. Also, an end user's environmental awareness is considered as a non-price factor. Hence, $U \propto f_2(s)$. It is clear that the effect of these two factors on AVKT is not independent; the multiplicative form of these two functions (i.e. $f_1(f, p_e, t_e)$ and $f_2(s)$), should be used for calculating the AVKT, not the collective form. Thus, $U \propto f_1(f, p_e, t_e)f_2(s)$. Finally, we convert it to an equation as $U = \phi f_1(f, p_e, t_e)f_2(s)$. We discuss this setup at more length in the following paragraphs.

According to the notation, if f is the FI, or fuel consumption of the car per unit of distance, and the cost of one unit of fuel for an end user is equal to $p_e + t_e$, then the cost for using the car for one unit of distance is $f(p_e + t_e)$. It is assumed in this study that AVKT decreases as the payment for one unit of distance increases. According to Assumption 2, we assume this decline decreases with reciprocal behavior, to make the formula applicable to the real world. Hence, $f_1(f, p_e, t_e) = \frac{1}{(p_e + t_e)f}$ and $U \propto \frac{1}{(p_e + t_e)f}$. The behavior of this function is consistent with the fact that if the fuel price approaches zero, then the average car use rate tends to be infinite; conversely, if the fuel price approaches infinity, then the average car use rate tends to be zero. More factually, if the fuel price approaches zero, the average car use rate tends to be high—though not infinite, because of other costs associated with using a car, such as car maintenance, traffic congestion, and opportunity. Because of this, we added a small number, (ϵ), beside the $(p_e + t_e)f$, so that we have $U \propto \frac{1}{(p_e + t_e)f + \epsilon}$. This means that when $(p_e + t_e)f$ is zero, AVKT is finite, but high. We show this with the equation$\omega = (p_e + t_e)f$.

On the other hand, as mentioned before, a non-price factor that affects AVKT is environmental awareness, i.e. s.For constructing the $f_2(s)$statement, we need some facts from the real world as follows. First, as the public's awareness about the environment increases, AVKT decreases, so$\partial_s AVKT < 0$. Second, as mentioned before, the effect of s on AVKT depends on ω why and how. Consider the four extreme cases that are shown in Table 4 and Fig. 15 below. Case 1) If an end user's awareness and commitment to environmental issues is zero and, if ω is zero, then AVKT will be a big number, which we show with M_1 in Table 4 and "1″ in Fig. 15. Case 2) If the environmental awareness of the end user is zero and ω is infinite, then AVKT will be zero ("2"). Case 3) If the end user's environmental awareness is infinite and ω is zero, then the AVKT is an amount that we show with M_2 in Table 4 and "3" in Fig. 15. Case 4) If the end user's environmental awareness and also price are infinite, then AVKT becomes zero. The best function that we found to match to these facts is $f_2(s) = \left(\frac{s+\rho}{s+1}\right)$. Therefore, $U = \phi\left(\frac{s+\rho}{s+1}\right)\left(\frac{1}{(p_e + t_e)f + \epsilon}\right)$. We provided the results of this function for the above four cases in Table 5 below. These results help us understand why this math applies to the above facts. They also help us understand what ρ means. We explain the meaning of ρ in the following paragraph.

If we divide the result of AVKT in Case 1, i.e. $\phi\rho\frac{1}{\epsilon}$, by the result of AVKT in Case 3, i.e. $\phi\frac{1}{\epsilon}$, then we obtain ρ ($\frac{U(s \to 0 and \omega \to 0)}{U(s \to \infty and \omega \to 0)} = \rho$). So, ρ is the ratio of AVKT when environmental awareness is zero, factoring in when the end user's environmental awareness is complete under the given that the fuel cost of using a car is zero. In other words, when the fuel cost of using the car is zero ($\omega = 0$), and the end user's environmental awareness is zero, then

Table 4
The behaviour of AVKT with respect to $\boldsymbol{s}$ and $\boldsymbol{\omega}$.

U	$\omega \to 0$	$\omega \to \infty$
$s \to 0$	M_1(Point **"1″**)	0 (Point **"2″**)
$s \to \infty$	M_2(Point **"3″**)	0 (Point **"4″**)

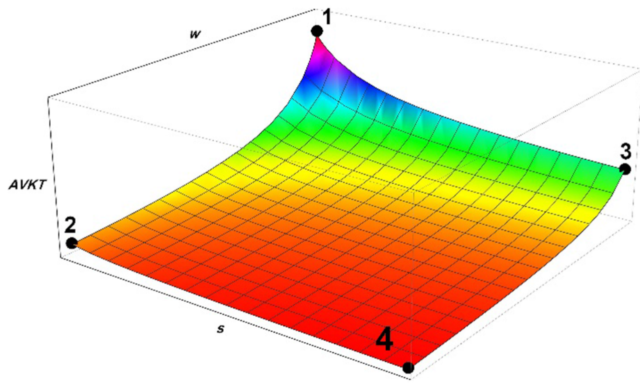


Fig. 15. AVKT behavior with respect to environmental awareness and fuel cost.

AVKT is equal to $\phi\rho\frac{1}{\epsilon}$. In this situation, i.e. ($\omega = 0$), if the end user's environmental awareness is complete, AVKT is reduced by ρ. Fig. 6 shows the behavior of this function for the case study.

What can be said about epsilon, and how much is it, and how is it achieved? One of the most important issues in the field of energy efficiency and its effects on consumption is the rebound effect. According to economic theories, improving energy efficiency influences people's consumption habits [91]. Higher energy efficiency in cars decreases the amount of fuel required to travel one unit of distance, but the decrease in fuel cost incentivizes more driving, and thus leads to the energy rebound effect [92]. For more details about the rebound effect, we refer to [93–95]. According to this effect, we find an amount for ϵ and also add the $\Re$ in the established AVKT. Hence, if a car's energy efficiency is improved from $\frac{1}{f_0}$ to $\frac{1}{f}$, the ratio of energy efficiency improvement is $(1/f - 1/f_0)/(1/f_0) = \frac{f_0 - f}{f}$. To simplify and avoid complexity, we consider the rebound effect for energy consumption of an end user. The consumption of an end user is $U * f$ in a unit of time. So, the ratio of $\frac{Uf|_{f_0} - Uf|_f}{Uf|_{f_0}}$ can be obtained by:

$$\frac{Uf|_{f_0} - Uf|_f}{Uf|_{f_0}} = \frac{\frac{f_0(s+\rho)\phi}{(1+s)(f_0(p_e+t_e)+\epsilon)} - \frac{f(s+\rho)\phi}{(1+s)(f(p_e+t_e)+\epsilon)}}{\frac{f_0(s+\rho)\phi}{(1+s)(f_0(p_e+t_e)+\epsilon)}} = \frac{(-f+f_0)\epsilon}{f_0(f(p_e+t_e)+\epsilon)}$$

Therefore, the rebound effect is equal to:

$$\Re = \frac{ff_0(p_e+t_e) - f\epsilon + f_0\epsilon}{f_0(f(p_e+t_e)+\epsilon)}$$

So, we can obtain ϵ as:

$$\epsilon = \frac{ff_0(p_e+t_e)(1-\Re)}{f - f_0 + f_0\Re} = \frac{(p_e+t_e)}{\frac{1}{(1-\Re)f_0} - \frac{1}{f}}$$

By substituting the obtained ϵ in $U = \phi\left(\frac{s+\rho}{s+1}\right)\left(\frac{1}{(p_e+t_e)f+\epsilon}\right)$ and simplification, the AVKT function can be obtained as:

$$U = \phi\frac{(s+\rho)}{(1+s)}\frac{(1-(1-\Re)\frac{f_0}{f})}{(p_e+t_e)f}$$

The proof of Lemma 1**.**

After substituting Equation (1) in Equation (2), the Hessian matrix of π_m is obtained as $\begin{bmatrix} -2\beta & -(p_e+t_e)\theta \\ -(p_e+t_e)\theta & 2(-1+\delta)\mu \end{bmatrix}$, which is negative definite, considering the assumption that $\beta > \frac{(p_e+t_e)^2}{4\mu(1-\delta)}\theta^2$. □

The proof of Theorem 1**.**

According to Lemma 1, π_m is a concave function and its maximum is obtained from the first order condition. Solving the system of equations ($\partial_{p_m}\pi_m = 0$, $\partial_f\pi_m = 0$), p_m^* and f^* are obtained according to Eqs. (10) and (11), respectively. By substituting these values in Eqs. (1) and (2), Eqs. (12) and (13) are obtained and the proof is completed. □

The proof of Theorem 2**.**

By replacing Eq. (11) in Eq. (3), the AVKT obtained is Eq. (14). Also, by replacing Eqs. (11), (12) and (14) in Eq. (4) and Eq. (15) in Eq. (5), the equilibrium demand and the profit made by the energy producer in the optimal solution are obtained, respectively. □

Table 5
The results of AVKT with respect to $\boldsymbol{s}$ and $\boldsymbol{\omega}$.

U	$\omega \to 0$	$\omega \to \infty$
$s \to 0$	$U = \phi\rho\frac{1}{\epsilon}$(Point **"1"**)	$U = 0$(Point **"2"**)
$s \to \infty$	$U = \phi\frac{1}{\epsilon}$ (Point **"3"**)	$U = 0$(Point **"4"**)

References

[1] Epstein MJ. Making sustainability work: Best practices in managing and measuring corporate social, environmental and economic impacts: Routledge; 2018.
[2] Lee HL, Tang CS. Socially and environmentally responsible value chain innovations: new operations management research opportunities. Manage Sci 2017;64:983–96.
[3] Kleindorfer PR, Singhal K, Van Wassenhove LN. Sustainable operations management. Product Operat Manage 2005;14:482–92.
[4] Linton JD, Klassen R, Jayaraman V. Sustainable supply chains: An introduction. J Oper Manage 2007;25:1075–82. https://doi.org/10.1016/j.jom.2007.01.012.
[5] Baños R, Manzano-Agugliaro F, Montoya FG, Gil C, Alcayde A, Gómez J. Optimization methods applied to renewable and sustainable energy: a review. Renew Sustain Energy Rev 2011;15:1753–66. https://doi.org/10.1016/j.rser.2010.12.008.
[6] Schneider S, Spieth P. Business model innovation: towards an integrated future research agenda. Int J Innovat Manage 2013;17:1340001.
[7] Plambeck EL. OM Forum—Operations management challenges for some "cleantech" firms. Manufact Serv Operat Manage 2013;15:527–36.
[8] Wang Q, Jiang X-t, Yang X, Ge S. Comparative analysis of drivers of energy consumption in China, the USA and India – a perspective from stratified heterogeneity. Sci Total Environ 2020;698:134117https://doi.org/10.1016/j.scitotenv.2019.134117.
[9] Wang Q, Ge S. Uncovering the effects of external demand on China's coal consumption: a global input–output analysis. J Clean Prod. 2020;245:118877https://doi.org/10.1016/j.jclepro.2019.118877.
[10] Gupta S, Palsule-Desai OD. Sustainable supply chain management: review and research opportunities. IIMB Manage Rev 2011;23:234–45. https://doi.org/10.1016/j.iimb.2011.09.002.
[11] Sodiq A, Baloch AAB, Khan SA, Sezer N, Mahmoud S, Jama M, et al. Towards modern sustainable cities: review of sustainability principles and trends. J Clean Prod 2019;227:972–1001. https://doi.org/10.1016/j.jclepro.2019.04.106.
[12] IEA. 2012. https://www.iea.org/publications/freepublications/publication/IEA_Annual_Report_publicversion.pdf.
[13] EIA. 2016. https://www.eia.government/environment/emissions/carbon/pdf/2016_co2analysis.pdf.
[14] Munyon VV, Bowen WM, Holcombe J. Vehicle fuel economy and vehicle miles traveled: an empirical investigation of Jevon's Paradox. Energy Res Soc Sci 2018;38:19–27. https://doi.org/10.1016/j.erss.2018.01.007.
[15] Hinterhuber A. Towards value-based pricing—an integrative framework for decision making. Ind Mark Manage 2004;33:765–78.
[16] Clancy KJ, Shulman RS. Marketing with blinders on. Across Board 1993;30:33.
[17] Berry S, Levinsohn J, Pakes A. Automobile prices in market equilibrium. Econometrica: J Econ Soc 1995;63:841–90. https://doi.org/10.2307/2171802.
[18] Berry S, Levinsohn J, Pakes A. Differentiated products demand systems from a combination of micro and macro data: the new car market. J Polit Econ 2004;112:68–105. https://doi.org/10.1086/379939.
[19] Degryse H, Verboven F. Car price differentials in the European Union: An economic analysis. 2000.
[20] Goldberg PK. The effects of the corporate average fuel efficiency standards in the US. The J Ind Econ 1998;46:1–33.
[21] Brownstone D, Bunch DS, Golob TF, Ren W. A transactions choice model for forecasting demand for alternative-fuel vehicles. Res Transport Econ 1996;4:87–129.
[22] McFadden D, Train K. Mixed MNL models for discrete response. J Appl Economet 2000;15:447–70.
[23] Ajanovic A, Haas R. The role of efficiency improvements vs. price effects for modeling passenger car transport demand and energy demand-Lessons from European countries. Energy Pol 2012;41:36–46. https://doi.org/10.1016/j.enpol.2011.03.086.
[24] Jun S, Park S. Examining technological competition between BMW and Hyundai in the Korean car market. Technol Anal Strat Manage 2016;28:156–75. https://doi.org/10.1080/09537325.2015.1073252.
[25] Agency YN. Hyundai develops new fuel-efficient engine technology. 2019. https://en.yna.co.kr/view/AEN20190703004851320.
[26] Salvo Od, Vaz de Almeida FG. Influence of technologies on energy efficiency results of official Brazilian tests of vehicle energy consumption. Applied Energy. 2019; 241:98–112. 10.1016/j.apenergy.2019.02.042.
[27] Kim S, Park D, Heo TY, Kim H, Hong D. Estimating vehicle miles traveled (VMT) in urban areas using regression kriging. J Adv Transport 2016;50:769–85. https://doi.org/10.1002/atr.1374.
[28] Rentziou A, Gkritza K, Souleyrette R. VMT, energy consumption, and GHG emissions forecasting for passenger transportation. Transport Res A: Pol Pract 2012;46:487–500. https://doi.org/10.1016/j.tra.2011.11.009.
[29] Paul A. Land-use-accessibility model: a theoretical approach to capturing land-use influence on vehicular flows through configurational measures of spatial networks. Int J Urb Sci 2012;16:225–41.
[30] Barr LC. Testing for the significance of induced highway travel demand in metropolitan areas. Transp Res Rec 2000;1706:1–8.
[31] Zhang L, He X, Lu Y, Krause C, Ferrari N. Are we successful in reducing vehicle miles traveled in air quality nonattainment areas? Transport Res A: Pol Pract 2014;66:280–91.
[32] Kim D, Lee J. Application of neural network model to vehicle emissions. Int J Urb Sci 2010;14:264–75.
[33] Park D, Kim NS, Park H, Kim K. Estimating trade-off among logistics cost, CO2 and time: a case study of container transportation systems in Korea. Int J Urban Sci 2012;16:85–98.
[34] Ko J, Park D, Lim H, Hwang IC. Who produces the most CO2 emissions for trips in the Seoul metropolis area? Transport Res D: Transp Environ 2011;16:358–64.
[35] Kumarage AS, Weerawardana J. System cost-based multi-criteria analysis for urban transport solutions. Int J Urban Sci 2013;17:212–25.
[36] Kim D-G, Lee Y. Modelling crash frequencies at signalized intersections with a truncated count data model. Int J Urban Sci 2013;17:85–94.
[37] Ma L, Yan X, Weng J. Modeling traffic crash rates of road segments through a lognormal hurdle framework with flexible scale parameter. J Adv Transport. 2015;49:928–40. https://doi.org/10.1002/atr.1322.
[38] Li Z, Jiang S, Dong J, Wang S, Ming Z, Li L. Battery capacity design for electric vehicles considering the diversity of daily vehicles miles traveled. Transport Res C: Emerg Technol 2016;72:272–82. https://doi.org/10.1016/j.trc.2016.10.001.
[39] Renne JL, Tolford T. A planning tool for evaluating vehicles miles travelled and traffic safety forecasts of growth management scenarios: a case study of Baton Rouge and New Orleans. Transport Res D: Transp Environ 2018;59:237–45. https://doi.org/10.1016/j.trd.2018.01.001.
[40] Antweiler W, Gulati S. Market-based policies for green motoring in Canada. Can Public Pol 2013;39:S81–94. https://doi.org/10.3138/CPP.39.Supplement2.S81.
[41] Chandra A, Gulati S, Kandlikar M. Green drivers or free riders? An analysis of tax rebates for hybrid vehicles. J Environ Econ Manage 2010;60:78–93. https://doi.org/10.1016/j.jeem.2010.04.003.
[42] Rivers N, Schaufele B. Gasoline price and new vehicle fuel efficiency: evidence from Canada. Energy Econ 2017;68:454–65. https://doi.org/10.1016/j.eneco.2017.10.026.
[43] Sallee JM, Slemrod J. Car notches: Strategic automaker responses to fuel economy policy. J Publ Econ 2012;96:981–99. https://doi.org/10.1016/j.jpubeco.2012.06.005.
[44] Rivers N, Schaufele B. Salience of carbon taxes in the gasoline market. J Environ Econ Manage 2015;74:23–36. https://doi.org/10.1016/j.jeem.2015.07.002.
[45] Rivers N, Plumptre B. The effectiveness of public transit subsidies on ridership and the environment: evidence from Canada. Available at SSRN 2724768. 2016. 10.2139/ssrn.2724768.
[46] Chandler V. The effectiveness and distributional effects of the tax credit for public transit. Can Publ Pol 2014;40:259–69. https://doi.org/10.3138/cpp.2013-073.
[47] Herald TK. Seoul to reward motorists for reducing mileage. 2017. http://www.koreaherald.com/view.php?ud=20170406000659.
[48] Agency YN. Seoul to reward motorists for reducing mileage. 2017. https://en.yna.co.kr/view/AEN20170406006400315.
[49] Berkhout PH, Muskens JC, Velthuijsen JW. Defining the rebound effect. Energy policy. 2000; 28:425-32. 10.1016/S0301-4215(00)00022-7.
[50] Sorrell S. The rebound effect: definition and estimation. Chapters 2009.
[51] Lee J, Cho Y. Demand forecasting of diesel passenger car considering consumer preference and government regulation in South Korea. Transport. Res. A: Pol. Pract 2009;43:420–9.
[52] Stahl Ii DO. Oligopolistic pricing and advertising. J Econ Theory 1994;64:162–77.
[53] Karray S, Martín-Herrán G. A dynamic model for advertising and pricing competition between national and store brands. Eur J Oper Res 2009;193:451–67. https://doi.org/10.1016/j.ejor.2007.11.043.
[54] Lambertini L. Coordinating research and development efforts for quality improvement along a supply chain. Eur J Oper Res 2018;270:599–605. https://doi.org/10.1016/j.ejor.2018.03.037.
[55] Lu F, Tang W, Liu G, Zhang J. Cooperative advertising: a way escaping from the prisoner's dilemma in a supply chain with sticky price. Omega 2019;86:87–106. https://doi.org/10.1016/j.omega.2018.07.003.
[56] Adua L. Reviewing the complexity of energy behavior: Technologies, analytical traditions, and household energy consumption data in the United States. Energy Res Soc Sci 2020;59:101289https://doi.org/10.1016/j.erss.2019.101289.
[57] Safarzadeh S, Rasti-Barzoki M. A game theoretic approach for assessing residential energy-efficiency program considering rebound, consumer behavior, and government policies. Appl Energy 2019;233–234:44–61. https://doi.org/10.1016/j.apenergy.2018.10.032.
[58] Huang J, Leng M, Parlar M. Demand functions in decision modeling: A comprehensive survey and research directions. Decis Sci 2013;44:557–609. https://doi.org/10.1111/deci.12021.
[59] Guo S, Choi T-M, Shen B. Green product development under competition: a study of the fashion apparel industry. Eur J Oper Res 2020;280:523–38. https://doi.org/10.1016/j.ejor.2019.07.050.
[60] Kharaji Manouchehrabadi M, Yaghoubi S, Tajik J. Optimal scenarios for solar cell supply chain considering degradation in powerhouses. Renew Energy 2020;145:1104–25. https://doi.org/10.1016/j.renene.2019.06.096.
[61] Ren J, Chen X, Hu J. The effect of production- versus consumption-based emission tax under demand uncertainty. Int J Prod Econ 2020;219:82–98. https://doi.org/10.1016/j.ijpe.2019.05.009.
[62] Jabarzare N, Rasti-Barzoki M. A game theoretic approach for pricing and determining quality level through coordination contracts in a dual-channel supply chain including manufacturer and packaging company. Int J Prod Econ 2019. https://doi.org/10.1016/j.ijpe.2019.09.001.
[63] Li X, Chen P, Wang X. Impacts of renewables and socioeconomic factors on electric vehicle demands – Panel data studies across 14 countries. Energy Pol 2017;109:473–8. https://doi.org/10.1016/j.enpol.2017.07.021.
[64] Oh I, Lee J-D, Hwang S, Heshmati A. Analysis of product efficiency in the Korean automobile market from a consumer's perspective. Empirical Econ 2010;38:119–37.
[65] KAMA PC. 2019. http://www.kama.or.kr/InfoController.
[66] News YS. Korea's registered vehicle numbers top 22.8 mln units: data. 2018. https://en.yna.co.kr/view/AEN20180715002400320.
[67] Ceicdata. South Korea Registered Motor Vehicles. 2019. https://www.ceicdata.

com/en/korea/number-of-registered-motor-vehicles/registered-motor-vehicles.
[68] Data.seoul. 2019. http://data.seoul.go.kr.
[69] Times TK. Number of cars in Korea nears 21 million. 2016. http://www.koreatimes.co.kr/www/news/biz/2016/01/123_195662.html.
[70] Today U. These countries produce the most CO2 emissions. 2019. https://www.usatoday.com/story/money/2019/07/14/china-us-countries-that-produce-the-most-co-2-emissions/39548763/.
[71] Transportpolicy. SOUTH KOREA: LIGHT-DUTY: FUEL ECONOMY AND GHG. 2019. https://www.transportpolicy.net/standard/south-korea-light-duty-fuel-economy-and-ghg/.
[72] Koreaherald. Korea to reduce greenhouse gases 37% by 2030. 2016. http://www.koreaherald.com/view.php?ud=20161206000461.
[73] Corporation KNO. 2019. http://www.knoc.co.kr/ENG/main.jsp.
[74] Opinet. 2019. http://www.opinet.co.kr/user/main/mainView.do.
[75] Association BICatAPTI. Peak Car and Public Transport. 2016. http://bic.asn.au/information-for-moving-people/peak-car.
[76] Autowini. 2019. https://www.autowini.com/main.
[77] Hyundai. Hyundai. 2019. https://www.hyundaiusa.com/santa-fe/index.aspx.
[78] Chang B, Kang SJ, Jung TY. Price Elasticity of Industrial Sector Energy Demand: Empirical Evidence from OECD Countries. AFORE. 2017:85.
[79] Chang B, Kang SJ, Jung TY. Price and output elasticities of energy demand for industrial sectors in OECD countries. Sustainability. 2019;11:1786.
[80] Dargay JM. The irreversible demand effects of high oil prices: motor fuels in France, Germany and the UK: Oxford Institute for Energy Studies; 1991.
[81] Pindyck RS. The structure of world energy demand: MIT press Cambridge, MA; 1979.
[82] Galvin R, Sunikka-Blank M. Including fuel price elasticity of demand in net present value and payback time calculations of thermal retrofits: Case study of German dwellings. Energy Buildings. 2012;50:219–28.
[83] Bohi DR. Analyzing demand behavior: a study of energy elasticities: RFF Press; 2013.
[84] Johansson O, Schipper L. Measuring the long-run fuel demand of cars: separate estimations of vehicle stock, mean fuel intensity, and mean annual driving distance. J Transp Econ Pol 1997;31:277–92.
[85] Brons M, Nijkamp P, Pels E, Rietveld P. A meta-analysis of the price elasticity of gasoline demand. A SUR approach. Energy Econ 2008;30:2105–22.
[86] Bernstein MA, Griffin J. Regional differences in the price-elasticity of demand for energy. National Renewable Energy Lab.(NREL), Golden, CO (United States); 2006. https://www.rand.org/pubs/technical_reports/TR292.html.
[87] Lim K-M, Yoo S-H. Short-run and long-run elasticities of gasoline demand: the case of Korea. Energy Sources Part B 2016;11:391–5.
[88] Koreatimes. Korea's car industry to face strong headwind in 2019. 2019. https://www.koreatimes.co.kr/www/tech/2019/07/419_261026.html.
[89] BusinessKorea. Hyundai Motor, Kia Motors to Invest More than 10 Tril. Won in Facilities, R&D in 2019. 2019. http://www.businesskorea.co.kr/news/articleView.html?idxno=30569.
[90] Realty A. Life in Korea - Driving. 2019. http://www.acerealty.kr/korea/driving/car_registration.php.
[91] Jin T, Kim J. A new approach for assessing the macroeconomic growth energy rebound effect. Appl Energy 2019;239:192–200. https://doi.org/10.1016/j.apenergy.2019.01.220.
[92] Taiebat M, Stolper S, Xu M. Forecasting the impact of connected and automated vehicles on energy use: a microeconomic study of induced travel and energy rebound. Appl Energy 2019;247:297–308. https://doi.org/10.1016/j.apenergy.2019.03.174.
[93] Yoo S, Koh KW, Yoshida Y, Wakamori N. Revisiting Jevons's paradox of energy rebound: Policy implications and empirical evidence in consumer-oriented financial incentives from the Japanese automobile market, 2006–2016. Energy Pol 2019;133:110923https://doi.org/10.1016/j.enpol.2019.110923.
[94] Dimitropoulos A, Oueslati W, Sintek C. The rebound effect in road transport: a meta-analysis of empirical studies. Energy Econ 2018;75:163–79. https://doi.org/10.1016/j.eneco.2018.07.021.
[95] Moshiri S, Aliyev K. Rebound effect of efficiency improvement in passenger cars on gasoline consumption in Canada. Ecol Econ 2017;131:330–41. https://doi.org/10.1016/j.ecolecon.2016.09.018.