공학박사학위논문

전과정 분석을 통한 새로운 경량 자동차 온실가스 규제에 대한 평가: 한국의 사례 연구

Evaluation of New Greenhouse Emission Standards for Light-Duty Vehicles through a Well-to-Wheel Analysis: A Case Study in South Korea

2020 년 2 월

서울대학교 대학원

기계항공공학부

유 은 지

전과정 분석을 통한 새로운 경량 자동차 온실가스 규제에 대한 평가: 한국의 사례 연구

Evaluation of New Greenhouse Emission Standards for Light-Duty Vehicles through a Well-to-Wheel Analysis: A Case Study in South Korea

지도교수 송 한 호

이 논문을 공학박사 학위논문으로 제출함

2019 년 10 월

서울대학교 대학원

기계항공공학부

유 은 지

유은지의 공학박사 학위논문을 인준함

2019 년 12 월

위 원 장 : 민 경 덕

부위원장 : 송 한 호

위 원 : 송 성 진

위 원 : 김 재 경

위 원 : 박 준 홍

Abstract

Evaluation of New Greenhouse Gas Emission Standards for Light-Duty Vehicles through a Well-to-Wheel Analysis: A Case Study in South Korea

Eunji Yoo
Department of Mechanical and Aerospace Engineering
The Graduate School
Seoul National University

Various regulations are in place around the world to reduce greenhouse gas emissions that cause global warming problems. In the road transportation sector, greenhouse gas emissions are to be reduced through fuel economy standard or greenhouse gas standard. The characteristic of this regulation is that the emission of greenhouse gas emissions from the exhaust port is zero for vehicles in electric driving mode, and additional incentives are provided. However, the electric vehicle does not emit GHG while driving the vehicle, but greenhouse gas is generated in the process of obtaining electricity required for driving the vehicle. Besides, various discussions have been made on estimating GHG emissions in the electric driving mode as 0, ignoring the upstream greenhouse gases. Especially in recent years such discussions have become more specific.

In particular, Japan's new fuel economy standards announced that it would use vehicle fuel economy corrected using the Well-to-Tank efficiency of the fuel production stage. Accordingly, in Korea, it is necessary to predict and evaluate the effects of applying life cycle analysis results on fuel economy regulation and greenhouse gas regulation.

There are two main reasons why the consideration of the fuel production process, especially upstream of electricity, is needed. First, the demand for electricity will increase as demand for electric vehicles increases in the future. Second, greenhouse gas emissions during the electricity production process are depending on the type of power generation. In this situation, life cycle analysis can be used as a tool to quantitatively evaluate the environmental friendliness of various fuels and vehicles. Well-to-wheel (WTW) analysis refers to the life cycle analysis of automotive fuels and represents the life cycle process, from oil production to the vehicle operation. The life cycle process of the electric vehicle includes the vehicle driving process, the power generation process, and the production process of power generation raw materials. For the sake of a fair comparison, the internal combustion engine car includes all related fuel production processes such as gasoline and diesel, just like electric vehicles.

In this study, I proposed the life-cycle GHG regulation regulated based on the life-cycle GHG emission value of automobile fuel and evaluated the effect of the new GHG standards on the vehicle market and stakeholders. It also showed that the national energy policy could be linked to the automobile policy through Well-to-wheel standards. The research order of this study is as follows. First, a life cycle analysis of automobile fuels in Korea was performed, and future life cycle greenhouse gas emissions were predicted. Next, the GHG emission regulations and penalties for life cycle regulation were established, and a model was designed to predict the mutual influence between the government, consumers, and automobile manufacturers based on the actor-based model. Using this model, the vehicle market prediction model can be used to predict how a car manufacturer will set a price for a product and what product a consumer will buy. Third, I analyzed the social phenomena that apply life cycle GHG regulations to the life cycle analysis results and automobile market prediction model.

The automotive GHG life cycle analysis is divided into the well-to-tank (WTT) process, which means the process from raw material extraction to refueling or filling the car, and the tank-to-wheel (TTW) process, which means the car driving process. For gasoline cars, hybrid cars, plug-in hybrid cars, and electric cars, the GHGs emitted during the TTW process are 138.7, 94.6, 13.2, and 0 g-CO_2-eq./km, respectively. The WTW GHG emissions were calculated for four vehicles in the order of 160.9, 109.9, 89.3, 85.0 g-CO_2-eq./km. The difference in TTW GHG emissions between gasoline vehicle and electric vehicle is 138.7 g-CO2-eq./km, but the difference in WTW GHG emissions is 75.9 g-CO2-eq./km.

Next, I used an agent-based model to design a model that predicts the automotive market for 2030. An agent-based model is an analytical technique used to predict decision-making of actors that influence and influence each other in socio-economic environments. In this study, the government, consumers, and automobile manufacturers were selected as agents involved in the vehicle market. The goal of the GHG emission regulation is set by comprehensively considering the national GHG reduction target, the potential reduction in the transport sector, and the manufacturers' interests. The GHG standard in Korea has announced its targets by 2020, and no future targets have been announced. Therefore, the average TTW and WTW emissions are inferred from the goal of alternative vehicle supply in Korea in 2030. The target value of original GHG standards is 62.2 g / km, and the target value of proposed GHG standards is 109.2 g / km. Penalty rates for failure to achieve GHG regulations were set at 50,000 won when exceeding 1 g/km. Consumers and manufacturers make decisions to increase the utility of car purchases and the net profit from car sales, respectively. Consumers determine their utility in consideration of the price, fuel economy, fueling cost, charging time, and total driving distance of their vehicles. The automaker's net profit is determined by retail prices, production costs, regulatory costs, and research and production facility costs. The vehicle market prediction model was designed to calculate the optimal product price and the market share according to the mutual influence between consumers and manufacturers. Third, I analyzed the impact that would occur when implementing GHG standards on the vehicle market by applying WTW emissions to GHG regulation. In order to effectively observe the effects of greenhouse gas emissions during the fuel production phase, I have focused on the electricity generation process in which the impact is prominent. Assessing how life-cycle greenhouse gas emissions vary from zero to 1068 g/kWh, resulting in changes in greenhouse gas emissions by vehicle type, resulting in product prices and sales rates in the automotive market, total cost of ownership for consumers, and gross government revenues. As a result, the vehicle market applying the WTW standards has the following characteristics.

First, the vehicle market is directly affected by the upstream emissions of the fuel. The original standard regulates the vehicle's Tank-to-Wheel GHG emissions, and the proposed standard regulates the vehicle's Well-to-Wheel GHG emissions. Thus, when the GHG emissions of the electricity production process change, the proposed standard is affected, but the original standard is not. In this study, the regulation cost is determined by the difference between the vehicle's GHG emissions and the GHG target value. The regulation cost is included in the vehicle retail price, which means that the price of the vehicle may change in the proposed standard. As a result, changes in market share due to changes in upstream emissions helped to reduce or offset the increase in total GHG emissions. Sales of PHEV and BEV declined as upstream GHG increased, while sales of PHEV and BEV increased as upstream GHG decreased. In this study, the vehicle market responded flexibly to changes in upstream emission under proposed standards.

Second, when the generation mix is the same as Korea's development plan for 2030, the total GHG emissions of the proposed standard will be greater than that of the original standard. This is because the gap between ICEV and BEV is reduced when regulating WTW emissions of vehicles rather than regulating TTW emissions. As a result, sales volume of ICEV and HEV increased, and the sales volume of PHEV and BEV decreased in the proposed standard. In this study, four scenarios are proposed to solve the problem of increasing greenhouse gas emissions under the proposed standard. The four methods are to increase the penalty rate, improve engine efficiency, improve the ratio of PHEV and BEV, and reduce battery price. Besides, this study evaluated the impacts of consumers

and governments on four scenarios. The impact of each agent on GHG standards is expressed in terms of TCO and GOV income.

The results of this study have the limitation that the total GHG emissions under the WTW standard are higher than those under the TTW standard at the power generation mix level in Korea in 2030. This result arises the concern that the WTW standard are less effective than the TTW standard to reduce the GHG emissions. To solve this concern, this study suggests the development of vehicle technology, reduction of battery price, and increase of penalty rate. However, there are two problems: 1. Difficulty of direct intervention through the policy, 2. GHG reduction effect is greater in TTW regulation with the new technology. Therefore, there is a need to make meaningful suggestions for the phenomenon that seems to increase GHG emission due to the proposed standard. I suggested the two power generation mixes that represent important features.

Keywords: Greenhouse gas emissions, Well-to-wheel analysis, Greenhouse gas standards, Vehicle market prediction, Well-to-wheel standards

Student Number: 2013-20686

Table of Contents

List of Figures

List of Tables

Nomenclature

ASC	Alternative Specific Constant
c_i	Manufacturing cost
CT_i	Charging time
DR_i	Driving range
fc_i	Fuel cost
FE_i	Fuel economy
FXC_i	Fixed cost
G_i	Greenhouse gas emission
G_{std}	Standard target value
n	Number of vehicle manufacturers
p_i	Retail price
Q	Total sales volume
q_i	Market share
u_i	Utility

Greek Letters

Π_j	Total profit of manufacturer
β_i	Coefficients of attribute
η	Efficiency
ρ	Penalty rate

Subscripts

i	Index of powertrains (1: ICEV, 2: HEV, 3: PHEV, 4: BEV)
j	Index of manufacturer
std	Standard

Abbreviations

ASC	Alternative Specific Constant
BEV	Battery Electric Vehicle
CAFE	Corporate Average Fuel Economy
CARB	California Air Resources Board
CD	Charge-Depleting
CI	Carbon Intensity
COG	Coke Oven Gas
EER	Energy Economy Ratio
EF	Emission Factor
FCEV	Fuel-Cell Electric Vehicle
FQD	Fuel Quality Directive
GHG	Greenhouse Gas
GJ	Giga Joule
GOV	Government
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
HEV	Hybrid Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
LCA	Life Cycle Analysis
LCFS	Low Carbon Fuel Standard
LDV	Light-Duty Vehicle
LFG	Landfill Gas
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas

METI	Ministry of Economy, Trade and Industry (JAPAN)
MPGe	Mile Per Gallon equivalent
MSRP	Manufacturer's Suggested Retail Price
MY	Model Year
NG	Natural Gas
NHTSA	National Highway Traffic Safety Administration
PHEV	Plug-in Hybrid Electric Vehicle
RED	Renewable Energy Directive
SAFE	Safer Affordable Fuel-Efficient vehicle
SMR	Steam Methane Reforming
SUV	Sport Utility Vehicle
TCO	Total Cost of Ownership
TTW	Tank-to-Wheel
U.S. EPA	U.S. Environmental Protection Agency
U.S. RFS2	U.S. Renewable Fuel Standard Extended
VKT	Vehicle Kilometer Traveled
WTT	Well-to-Tank
WTW	Well-to-Wheel
ZEV	Zero Emission Vehicle

Chapter 1. Introduction

1.1. Research background

Energy resource depletion and climate change have become global issues, mainly caused by the increased use of fossil fuels and accompanying greenhouse gas (GHG) emissions. One of the most responsible causes is the rapid growth in energy use in the transportation sector [1].

Korea and other countries around the world are enacting regulations on fuel economy or greenhouse gas emissions of automobiles to reduce greenhouse gas emissions in the transportation sector. Figure 1.1 shows the average GHG emissions, average fuel economy change and future target value of light-duty-vehicle by country [2]. In Korea, fuel economy or carbon dioxide regulations have to be met, depending on the vehicle's average curb weight. The United States regulates fuel economy and carbon dioxide based on footprints. Footprint means the bottom area of the car. In Europe, China, and Japan, regulations on carbon dioxide, fuel consumption, and fuel economy are based on vehicle curb weights, respectively.

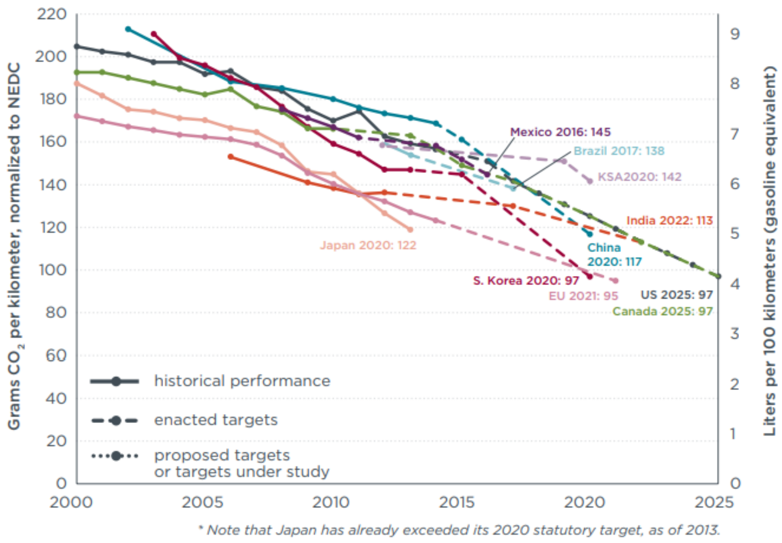

Figure 1.1 Historic records and future targets of GHG emissions for LDVs in selected countries [g-CO_2-eq./km] [2]

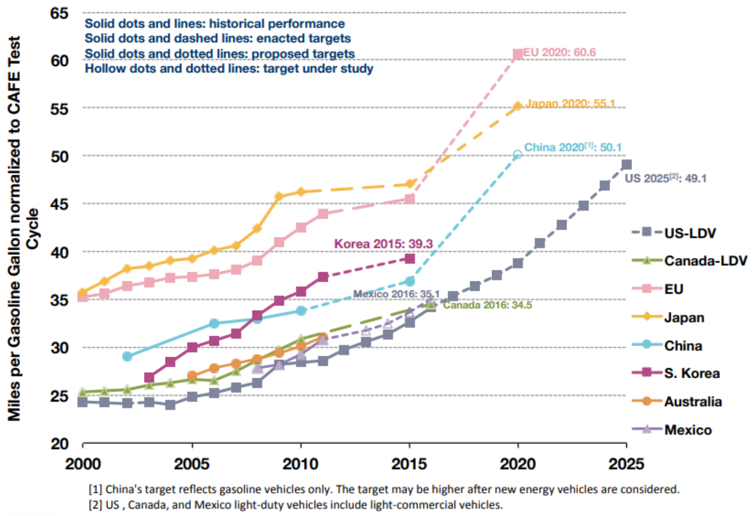

Figure 1.2 Historic records and future targets of Fuel economies for LDVs in selected countries [MPGe] [2]

In addition to these regulations for automotive manufacturers, there are also regulations for fuel suppliers who sell transportation fuels. Subsequent regulations are fuel regulations that actively use fuel life cycle assessments. The U.S. Renewable Fuel Standard Extended (U.S. RFS2) regulations classify renewable fuels into four categories based on raw materials, fuel types, and life cycle GHG reduction effects, and disclose annual mandatory mix ratios [3]. Life cycle GHG emission is evaluated using GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model of Argonne National Laboratory for biofuel and renewable energy of various kinds and various raw materials. The entire life cycle of fuel includes agricultural impacts, land use change, feedstock transport, fuel production, distribution and use. RFS2 does not consider fossil fuels other than gasoline and diesel, such as natural gas, propane, and fossil fuel-based electricity.

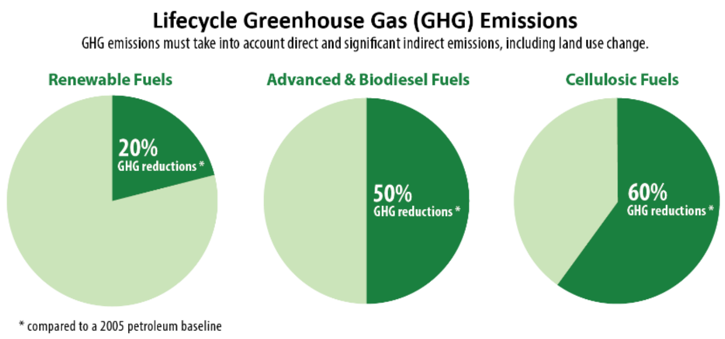

Figure 1.3 U.S. EPA. Renewable Fuel Standard Program

- Life cycle GHG reduction effect according to four fuel classifications [3]

TABLE I.B.6–1—FINAL 2019 PERCENTAGE STANDARDS

	Final percentage standards
Cellulosic biofuel	0.230
Biomass-based diesel	1.73
Advanced biofuel	2.71
Renewable fuel	10.97

Figure 1.4 U.S. RFS2 – Renewable volume obligations [3]

The state of California, USA, is a leader in various environmental regulations and has implemented many regulations. Among them, the low carbon fuel standard (LCFS) is a trading system for greenhouse gas emissions of fuels implemented by the California Air Resources Board (CARB) [4]. Depending on the carbon intensity calculated using the GREET-CA model, the fuel is given credit or deficit, and the fuel supplier can either trade with another fuel supplier or carry over to the next year. Unlike RFS2, LCFS includes a variety of fuels, including gasoline, diesel, natural gas, liquefied petroleum gas, electricity and hydrogen. The carbon intensity of the fuel is adjusted according to the following equation, which is modified using the fuel economy of the vehicle using that kind of fuel.

$$(\text{EER Adjusted CI})_{\text{X}} = \frac{CI_X}{EER_X}$$

(EER: Energy Economy Ratio, gasoline=1, electricity=3, hydrogen=2.3)

Since 2017, the trading price of LCFS credits has been rising and is currently trading at $ 200 per metric ton in 2019 [5].

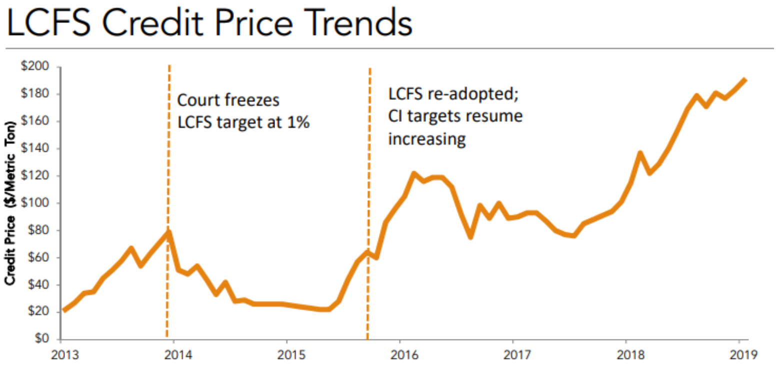

Figure 1.5 LCFS Credit Price Trends [5]

The European Union regulates fuel suppliers through the fuel quality directive (FQD) and renewable energy directive (RED) policies, both of which have separate targets for the transport sector. The FQD aims to reduce the life cycle emissions of the transport sector by 6% by 2020. The average GHG intensity is calculated and regulated according to the ratio of the life cycle GHG intensity given to each fuel and the fuel yield. Fuel suppliers can achieve their targets by increasing the production of low GHG intensity fuels such as biofuels and electricity, or by reducing flaring and venting in the upstream process of fossil fuels. RED, which is being applied along with the FQD, has announced a goal to increase the ratio of renewable energy to more than 10% of the energy used by the transport sector by 2020 [6].

Recently, the US Trump administration proposed a Safer Affordable Fuel-Efficient vehicle (SAFE) regulation aimed at easing the regulation of current CAFE standards. Following the fuel economy targets proposed by the existing CAFE standard by 2020, freezing the target by MY 2026 is expected to save more than $ 500 billion in social costs. As a result, companies that had to meet the average fuel economy of 54.5 MPGe by MY 2025 will change to 46.7 MPGe by MY 2026 [7]. However, during the comment period, differences in modeling tools, input data, and key assumptions between CAFE and SAFE led to the controversy that it was difficult to directly compare the costs or environmental impacts of the two regulations. The California government sued the Trump administration to provide data and analytical methods used to benefit from the SAFE proposal. In addition, Unite Auto Workers, including 17 automakers including General Motors, Volkswagen, and Toyota, issued a statement opposing the revised fuel economy regulations, stating that long-term litigation and industry uncertainties could limit company growth. Eventually, the EPA's internal agency, the Science Advisory Board, announced that it would postpone the decision to finalize the SAFE amendment and re-examine its environmental and cost impacts.

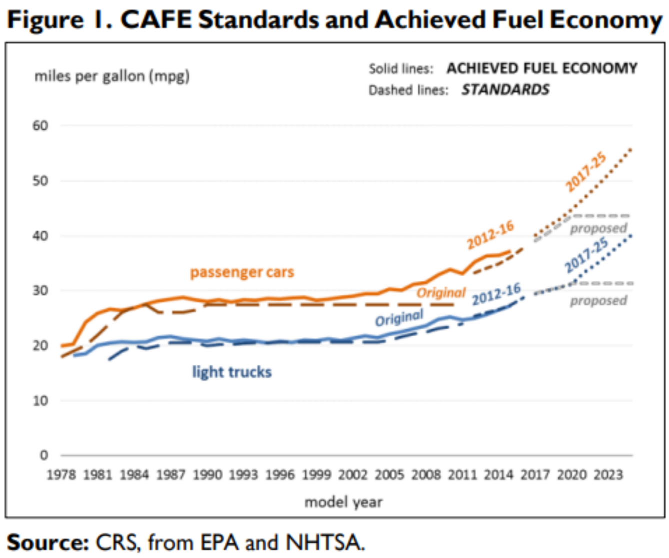

Figure 1.6 U.S. Fuel Consumption Targets Suggested by SAFE [MPGe] – Gray Dotted Line [7]

Japan's Ministry of Economy, Trade and Industry (METI) announced in 2018 that it would achieve Well-to-Wheel (WTW) Zero Emission by 2050 as a long-term goal through the Trend of Next Generation/Zero Emission Vehicle and Policy in Japan. Conceptually, it is intended to reduce WTW emission by 80% through innovation of vehicle usage methods such as automobile fuel economy, sharing service, connecting service, and greenhouse gas reduction in energy supply process [8].

In the policies as mentioned above in the world, the reduction of greenhouse gas in the transportation sector has two main directions. One is to reduce GHG emissions through improved fuel economy and power generation, while the other is to reduce GHG emissions through the production and supplement of low-carbon fuels. However, the policies, as mentioned above, have limitations in quantitatively evaluating both the effects of vehicle technology development and the use of low carbon fuel.

Besides, fuel economy standards and GHG standards, and Zero emission vehicle (ZEV) policies are favorable policies for electric vehicles that do not generate greenhouse gases while driving. However, these regulations do not consider greenhouse gases generated during the upstream process. Fuel regulations such as LCFS, RFS, and FQD reflect the impact of fuel economy on automobiles using simple coefficients. However, since this is a coefficient obtained by calculating a representative fuel economy by fuel, it is difficult to reflect the diversity of powertrain technology and increase or decrease fuel economy.

In many countries, various environmental regulations are being implemented in the transportation sector. Two representative policies are GHG standard and fuel economy standards, such as CAFE (Corporate Average Fuel Economy) standard in U.S. These regulations require automakers to meet their regulatory targets for GHG emissions or fuel economy averaged with their sales volume during a year.

In particular, these policies estimate that there are no tailpipe emissions during electric driving mode for electric vehicles. Furthermore, regulators give some incentive or bonus for these ZEVs to promote the development and sales of more battery vehicles. According to U.S. CAFE standard, fuel economies of battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) are converted to MPGe by energy content and then divided by 0.15. U.S. GHG standard estimates GHG emissions as 0 g/mile for the CD modes of BEV and PHEV [9]. The fuel economy regulation and greenhouse gas regulation in Korea, ZEV is recognized that three units are sold per unit and there are no GHG emissions for ZEV [10]. This has led to the development of non-conventional fuels and energy conversion systems for automotive applications, which require new judgment tools to better compare them with their conventional counterparts in terms of environmental friendliness or energy efficiency. In addition, the ZEV mandatory sales policy in many countries regulates mandatory sales of cars without tailpipe emission over a certain percentage. These regulations are driving the development and sale of more battery-powered vehicles, and pursuing policies to further promote them.

However, there is a lot of controversy about treating GHG emissions of vehicles running in electric mode as zero. According to U.S. EPA and NHTSA (National Highway Traffic Safety Administration), they said in the Final rule for GHG and CAFE standard, “There is no such comprehensive program addressing upstream emissions of GHGs, and the upstream GHG emissions associated with production and distribution of electricity are higher, on a national average basis than the corresponding upstream GHG emissions of gasoline or other petroleum-based fuels.” [11] This passage mentions the need for a program to consider comprehensively the greenhouse gases generated from the upstream of the fuel. The European Commission has written articles with the following headings and points: “GHG policy should cover 'upstream' electric vehicle emissions - This would help ensure that vehicle emissions regulations are placed on a sound scientific basis, manufacturers continue to improve the efficiency of electric vehicles, and the full benefit of regulations to limit GHG emissions from vehicles are realized.” [12] The article noted that, given the upstream GHG emissions of electricity, automakers have incentives to improve fuel economy. However, CARB recently announced that “Simplify compliance by removing the requirement to consider upstream GHG emissions associated with the production of the electricity used by electric vehicles when calculating the GHG emissions for a car maker's fleet.” [13] They said it agreed not to consider upstream GHGs to simplify regulation.

Japan also introduced a well-to-wheel approach to the new regulations by announcing new fuel economy regulations to improve fuel economy by 25.4 km/L by 2030. [14] The new fuel economy standards estimate the energy consumption of the domestic fuel production stage in the form of WTT efficiency, and multiplies the fuel economy or fuel consumption by the normalized WTT efficiency for gasoline cars to obtain a total fuel economy. The newly defined fuel economy is expressed as a formula as follows.

$$\text{Total FE}\left[\frac{\text{km}}{\text{L}_{\text{eq}}}\right]$$

$$= \text{gasoline equivalent TTW FE} \times \left(\frac{\text{WTT efficiency}_{\text{fuel}}}{WTT\ efficeincy_{gasoline}}\right)$$

WTT efficiency uses the calculated value as shown in Figure 1.7, and this value is multiplied by the energy efficiency of the process occurring in Japan.

	Refining	Distributing	Refueling	Total upstream efficiency
Gasoline	92.9%	99.5%	99.5%	92%
Diesel	93.9%	99.5%	99.5%	93%

	Refining	Generation efficiency	Electric generation fraction	Distributing	Total upstream efficiency
Electric	99.8%	44.3%	56%	90.4%	71.4%

Figure 1.7 Assumptions and calculation of well-to-tank (WTT) efficiency of fossil fuels and electricity [14]

In summary, automotive greenhouse gas regulations and fuel economy regulations in the United States, Europe, and Japan continue to address the need to consider the upstream of fuel, and this interest is becoming increasingly material.

1.2. Research objectives

There are two main reasons for this discussion of the upstream process of electricity. First, demand for electricity will increase as sales volume of electric vehicles increases. As a simple example, the energy consumption of Hyundai Kona electric is 5.6 km/kWh, and assuming 15,000 km of annual mileage, one Kona consumes 2321.4 kWh per year. When the cumulative sales of electric vehicles reach 2.5 million, electric vehicles consume 5803.5 GWh per year. For comparison, some figures show that the total power generation in 2018 in Korea is 570,674 GWh, and the annual power generation of six coal-fired power plants in Samcheonpo is 21,448 GWh.

The second reason for discussing upstream of electricity is that GHG emissions in the power generation process vary greatly depending on the power source. There are various types of power generation sources such as fossil fuels used in fired plants such as coal, natural gas and heavy oil, renewable energy such as wind, solar, and water, and nuclear. Therefore, it is possible to determine whether the greenhouse gas emissions due to the electricity used by the electric vehicle are larger or smaller than those of the internal combustion engine, depending on which power source is used to produce electricity.

Thus, new judgment tools are needed to compare the upstream GHG emissions of various powertrain and alternative fuel vehicles. In this situation, quantitative comparison is possible through Well-to-wheel analysis. In the WTW analysis, in addition to the greenhouse gases produced during the combustion of fuel consumed when driving a car, the greenhouse gas emissions generated during fuel production are also evaluated. The life cycle analysis is meaningful in that it is more comprehensively assessed when looking at greenhouse gas emissions across the country and, more broadly, when viewed as ‘global’ greenhouse gas emissions. Therefore, applying WTW analysis to the regulation of automobiles' greenhouse gas emissions can help assess actual greenhouse gas emissions from vehicle sales and set reduction targets.

Therefore, the objective of this study is to propose a WTW standard that can quantitatively evaluate greenhouse gas emissions from the development of automobile technology and the use of low carbon fuels to complement the limitations of existing greenhouse gas reduction policies. Figure 1.8 shows the range covered by the proposed standard. The original standard only handled tailpipe emissions from the vehicles. In contrast, the proposed standard regulates greenhouse gases using the entire process, including upstream, that is, WTW GHG emissions. In the proposed standards, as well as including the upstream of electricity, upstream of gasoline, diesel and the like which are conventional fuels are all included. This research evaluates the impact of upstream GHG emissions on the vehicle market and stakeholders under the new GHG standard. Also, in the new GHG standards, national energy policy can be linked to automotive policy through WTW standard. (ex. Basic Plan for Long-term Electricity Supply and Demand)

Figure 1.8 Proposed standard reflecting upstream GHG

The research was conducted in the following order.

(1) Well-to-wheel analysis (Chapter 2)

- Well-to-wheel analysis of automotive fuels in Korea

- Future prediction of Well-to-wheel GHG emissions in 2030

(2) Policy-setting and vehicle market prediction (Chapter 3)

- Set target value and penalty rate for 2030 GHG standards

- An agent-based modeling approach to predict the impact of GHG standard on vehicle market

(3) Evaluation of the impact of WTW GHG standards (Chapter 4)

- Using the WTW results and agent-based model, predict market changes driven by GHG standards changes

- Evaluate the reaction of the manufacturer, consumer, and government due to the increase and decrease of Well-to-Wheel greenhouse gases

First, I performed a Well-to-Wheel analysis of various automobiles in Korean cases. This analysis was conducted in 2017 to analyze the current situation, followed by future forecasts for 2030. The WTW analysis covers all automotive fuels and powertrains used in Korea and includes petroleum-based fuels, electricity, and hydrogen.

Second, establish new greenhouse gas standards and develop a model to predict the future automotive market. The government seeks to manage and reduce the country's greenhouse gases comprehensively. Accordingly, the government has the authority to set the target value and penalty rate of vehicle standards. To assess the impact of policy on the automotive market, the agent-based modeling approach assesses the decisions made and impacted by vehicle manufacturers, consumers, and governments. The in-house model was designed to predict the sales price and market share of the vehicle.

Third, based on the WTW results, the new GHG standards, and the automotive market prediction model, it was analyzed how the market share changed when applying the WTW analysis to the existing automobile greenhouse gas regulation.

Someone can have a question of why the vehicle manufacturers are penalized for the greenhouse gases generated during the WTT process. However, as TTW standards are changed to WTW standards, the regulation target values are also adjusted, and thus, responsible for GHG emissions in the process of consuming fuel and producing it for sale of automobiles. Therefore, the contribution of this study is to present the WTW GHG emission standard for the first time and to evaluate its impact quantitatively.

1.3. Research scope

The research scope is set as follows.

- Model year: 2030

- Only to the compact car market and the total market size is 500,000
example: Hyundai Avante, Ioniq, Kia K3, Chevrolet Cruze etc.
(Curb weight (2016, Argonne Autonomie): 1180~1460 kg at 2015, 950~1220 kg at 2030)

- Four kinds of powertrains are on the market:
ICEV (gasoline), HEV (gasoline), PHEV (gasoline), BEV (200 mile)

The compact car market is sensitive to the vehicle retail price, [15] and is likely to be applied to electric car technology. For ICEV, gasoline cars account for most of the market share. Passenger car sales volume per year in 2015, 2016, 2017, and 2018 remained stable at 1.53 million units. In addition, the passenger car market share of compact cars and small sport utility vehicles (SUVs) is about 28.2%. [16] In the future, as the number of single-person households increases, the small car market is expected to become more active. Thus, in this study, the annual sales volume of compact cars in 2030 is assumed to be 500,000 units.

Chapter 2. Well-to-Wheel analysis

2.1. Introduction

Life cycle analysis (LCA) is a method that estimates the energy use and GHG emissions associated with a product during all stages of its life, e.g., recovery of raw materials, production, use, and discarding of the product. Therefore, the overall environmental impacts of the product can be estimated. Specifically, as a part of LCA for automotive fuels, well-to-wheel (WTW) analysis has been given significant attention and can be divided into two groups of processes: well-to-tank (WTT) and tank-to-wheel (TTW) processes. WTT includes processes such as feedstock recovery, fuel production, fuel storage, distribution to fueling stations, and refueling. TTW represents vehicle operation whereby fuel is consumed to power the vehicle.

2.2. Previous researches

Several research groups have performed WTW analysis, mostly in the U.S., Canada, Europe Union (EU), and Japan. Argonne National Laboratory (ANL), located in the US, developed spreadsheet-based software, GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation), to perform WTW analysis of automotive fuels in the U.S.[17]. GHGenius is another spreadsheet-based software and includes a WTW database of automotive fuels for Canada, the U.S., Mexico, and India [18]. JEC (Joint Research Centre – EUCAR – CONCAWE collaboration) is a collaboration among the European Commission's Joint Research Centre, the European Council for Automotive R&D (EUCAR), and Conservation of Clean Air and Water in Europe (CONCAWE), and it publishes European well-to-wheel reports [19]. BioGrace is a GHG calculation tool for biofuels, developed under the Intelligent Energy Europe program and used in the European Union Renewable Energy Directive program [20].

The most recent works of literature on comparative evaluation of FCEV and other vehicles using WTW analysis mainly deal with electrolysis, coal gasification, and steam methane reforming (SMR) processes. Wang performed a WTW analysis to help select fuel for fuel-cell electric vehicle (FCEV), SMR process, and electrolysis process using various electric power generation mixes that were selected and analyzed as H_2 production process [21]. Ramsden et al. investigated the cost, WTW energy use and emissions for ten pathways of H_2 production. Steam reforming of natural gas (NG) and ethanol, electrolysis, biomass gasification, and coal gasification technologies were analyzed in this research [22]. Pereira and Coelho performed WTW analysis of FCEV in Portugal in the case of H_2 production by SMR, coal gasification, and electrolysis [23], and Larsson et al. analyzed on those three technologies for FCEV in Sweden [24]. Bicer and Dincer also analyzed the WTW emissions for SMR, coal gasification and electrolysis and compared with methanol and electric vehicles [25].

2.3. Well-to-Wheel processes approach and methodology

The GREET model [17] was adopted as a base calculation tool, but the detailed parameters and some of the calculation methods were modified for our own purposes. To apply for the GREET program, the term efficiency (η) of each process is defined as follows:

$$\eta = \frac{Output\ Energy}{Input\ Energy}$$

$$= \frac{Product\ energy}{Feedstock\ energy + Feed\ loss + Process\ fuel\ energy}$$

The input energy is equal to the sum of the feedstock energy, feed loss, and process fuel energy. In the definition above, the feedstock energy has the same value as the product energy. Some feedstock is lost in the form of leakage and evaporation or is used as a process fuel of the byproduct. These energy losses are represented as a feed loss and are distinct from feedstock energy.

Process fuel is the energy source required to supply heat or steam and convert the feedstock into the product. The output energy is the specific product energy from a process such as the H_2 energy from the SMR process and the naphtha energy from the refining process.

Raw data for calculating each process efficiency were collected through both domestic and foreign literature surveys and the support of related associations. If there are several applicable references for one parameter, the mean value is selected as a representative value, and the minimum and maximum values are used to produce the error bars. Meanwhile, if there is a domestic, official reference on a certain parameter, it is regarded as the representative value of that parameter, and the other values are selectively included in the error bars to consider the uncertainty of such representative data. The year 2017 was the base year of the data collection.

The total WTW GHG emissions consist of three parts. (1) The GHG emissions from process fuel combustion are calculated as the product of the amount of process fuel energy and the emission factor (EF). EFs for overseas production sites and some domestic plants were obtained from the IPCC [26] and the U.S. EPA [27]. We also obtained and applied Korean EFs to analyze the refining, power generation, and TTW processes. (2) The upstream GHG emissions of the process fuel, from the feedstock recovery process to the transportation are included. (3) Finally, non-combustion GHG emissions through leakage, evaporation, chemical reaction and physical processes are also included. Here, leakage means the leaking of gaseous fuel into the atmosphere, and evaporation means the evaporating of liquid fuel into the atmosphere.

The quantity of GHG emissions in this paper is presented in g-CO_2-eq./GJ. Here, the unit means the number of grams of CO_2-equivalent GHGs emitted to produce 1 GJ of product. Additionally, the WTW results are expressed in units of g-CO_2-eq./km, which means the amount of CO_2-equivalent GHGs emitted when a vehicle travels 1 km. We use global warming potentials of 25 and 298 to convert CH_4 and N_2O emissions into CO_2-equivalents, respectively, based on the 100-year time horizon [28].

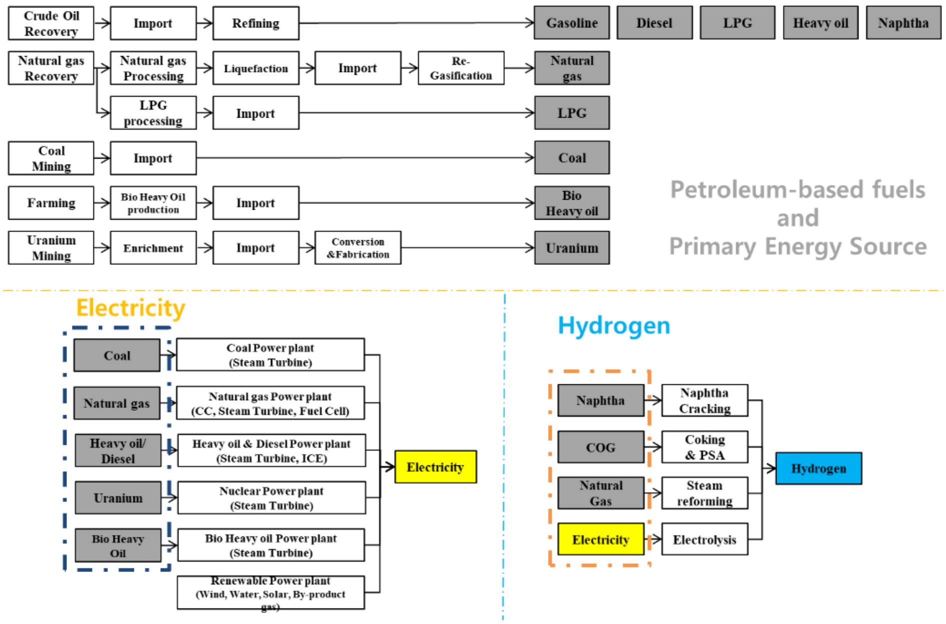

Figure 2.1 Well-to-Wheel processes of automotive fuels in Korea

Our research team's study covers all available fuels and powertrains options in South Korea. Figure 2.1 shows the well-to-wheel processes for all fuels analyzed in this study. Petroleum-based fuels include gasoline, diesel, LPG, heavy oil, naphtha, pet coke, and refinery still gas, etc. which are produced through the crude oil refining process. In addition, fuel production cycle of natural gas, coal, and uranium was analyzed. Primary energy and petroleum-based fuels are used as automotive fuels or as resource for electricity generation and hydrogen production. I analyze the GHG emissions from every single process. For the fuel used as the process fuel in the individual processes, the calculation was iterated to include the greenhouse gas emitted in the whole process.

2.4. Well-to-Wheel analysis of automotive fuels in Korea

This section summarizes the analysis methods, key parameters, assumption, and results of the well-to-wheel analysis of automotive fuels used in Korea. In addition to petroleum-based fuel and natural gas, major parameters and production processes are introduced in Section 2.4.1 to Section 2.4.2 and Section 2.4.3 for raw materials of electricity and hydrogen such as coal, uranium and renewable energy. In particular, the well-to-wheel analysis of hydrogen was explained in detail in 2.4.4. The analysis of hydrogen was published in a journal [29]. Finally, the WTW GHG results for the present and future in Korea are presented in Section 2.5 and 2.6.

2.4.1. Petroleum-based fuel

The upstream process begins with a crude recovery process. All the crude oil used in Korea is extracted from the wells of overseas production areas. In this recovery process, crude oil extraction, processing, and storage are included. The key parameters are the GHG emissions from the use of process fuels for crude oil extraction and processing, and from flaring and venting in the oil fields. Firstly, the share of crude oil import from various countries of origin is provided by Korea Petroleum Association, and the usage of process fuels and accompanying GHG emissions in each of these countries are based on GREET and GHGenius data. Secondly, the raw information on flaring and venting is referred to in the reports from NOAA and EIA, and the associated GHG emissions for crude oil imported into Korea are calculated by weight-averaging the raw data above with the share of the country of origin [30, 31]. To estimate GHG emissions from the ocean tanker, its power [J/s], payload [ton], and speed [km/s] should be informed. With these values, the energy consumption to deliver 1 ton of crude oil per 1 km [J/ton·km] by the ocean tanker can be evaluated by dividing power by payload and speed. Then, the GHG emissions are calculated by multiplying the energy consumption by averaged transporting distance [km] and emission factors [g/J]. The averaged transportation distance (11,745 km) is calculated by the share of import quantity and the distance from each country. With the information on ocean tankers from GREET [17], the GHG emissions during import are calculated [32].

Then, petroleum products, such as gasoline, diesel, LPG, residual oil, pet coke, and refinery still gas, are produced during the refining process. The production energy of the refining process is allocated to each product through the refinery-level allocation. The production efficiencies of gasoline and diesel are 93.0% and 94.1%. For domestic distribution to fueling stations, barge and truck and pipeline are major transport methods. By using similar information as for the ocean tanker, the GHG emissions can be calculated.

For details, the readers can refer to our previous paper, which is on the WTW analysis of petroleum-based fuels. [32]

2.4.2. Natural gas

There are two major sources of natural gas used in Korea. One source is imported natural gas, the life cycle of which starts from recovering raw natural gas at overseas production sites. In this recovery process, the average flaring quantity is evaluated by weight-averaging the flaring amount in each country of origin with the share of LPG import quantity in Korea. [30, 31] This corresponds to 228.07–242.32 g-CO2/GJ. In addition, we use 39.24 g-CO2/GJ for CO_2

venting, and 377.95 g-CH_4/GJ for CH_4 leakage. [33] In the process of NG processing, the raw natural gas is cleaned and treated to produce dry NG.

After that process, NG is liquefied in the form of liquefied natural gas (LNG), imported into Korea using LNG carriers, re-gasified, and distributed to various domestic factories, power plants, and gas stations in Korea. The readers can refer to our previous work to obtain more details about the WTW analysis of natural gas in Korea. [34]

The other source of natural gas is landfill gas. The landfill gas is generated by decomposing waste buried in the ground. This gas mainly consists of CH_4, CO_2, and small amounts of N_2, O_2, and H_2S. [35] The upstream process starts with the landfill gas (LFG) collection process. Next, the impurities are removed, and methane, the primary component of natural gas, is extracted. During the NG processing process, 2% of fuel leaks to the atmosphere and the amount of CH_4 emission due to this leakage is 400.0 g/GJ. [17]

It is noted that there is a carbon credit associated with using LFG to produce natural gas. Typically, the LFG should be extracted and burned from the landfill, and GHG emissions are generated during this flaring process. However, once natural gas is produced using landfill gas, greenhouse gas emissions from flaring are not emitted, and thus, this amount of GHG emissions during the flaring process is considered as a credit and is deducted from the total amount of GHG emissions for the LFG (on-site) pathway. [36] Greenhouse gas emissions by flaring were calculated using the EPA emission factor [27], and the calculated value is 68,138 g-CO_2 eq./GJ.

2.4.3. Electricity

The upstream process begins with the feedstock recovery process, followed by the production of the sources of electricity and their transportation to the power plants, with the final step being the electric power generation process. The domestic electric power generation mix for 2017 is shown in Table 2.1. Coal-fired power plants account for the highest percentage, 40.1%, followed by nuclear power plants, 31.4%, and natural-gas-fired power plants, 23.0%. According to the national government classification, renewable energy uses hydropower, wind power, solar photovoltaic, and by-product gas accounts for 1.3%, 0.3%, 0.7%, and 1.8%, respectively. [37] Detailed data about domestic power generation were collected by referring to the report from KEPCO (2018), which includes power generation efficiency and emission factors for each power generation technology, power generation mix, and transmission and distribution losses. The transmission and distribution loss is 3.6% on a yearly average. Based on these data, we calculated the GHG emissions, 52.7 g-CO_2-eq./kWh during the upstream process for power generation and 525.1 g-CO_2-eq./kWh during the power generation process. Detailed research data can be found by referring to our companion paper regarding the WTW analysis of electric vehicles in Korea. [38]

Fuel (power generation technology)	Generation mix (%)	Efficiency (%)
Coal (steam turbine)	43.46	35.1
Coal (IGCC)	0.18	39. 9
Natural gas (steam turbine)	0.04	33.9
Natural gas (combined cycle)	23.56	45.1
Natural gas (fuel cell)	0.27	47.0
Heavy oil (steam turbine)	0.82	34.2
Diesel and heavy oil (internal combustion engine)	0.10	33.7
Uranium	26.78	8.99 (MWh/g-U235)
Renewables	4.77	-
Total	100	

Table 2.1 Major parameters of electric power generation in 2017 [37]

- In 2017, the share of bituminous coal and anthracite coal for power generation are 97.9% and 2.1%, respectively. [37]

- The unit *MWh/g-U235* of the efficiency of uranium represents the conversion factor for the nuclear power plant.

- Renewable energy uses 1.4% of hydropower, 0.4% of wind power, 1.2% of solar photovoltaic, and 1.8% of by-product gas. [37]

Fuel	Process	Parameter	Det.	Min	Max	Unit	Ref.
Coal	Coal mining	Coal mining efficiency	99.3	99.4	99.3	%	
		CH_4 leakage	119.9	117.9	131.9	g-CH_4/GJ_P	
	Coal import	Coal import distance	2113			km	
Petroleum	Crude recovery	Crude recovery efficiency	98.9	99.0	98.7	%	
		CH_4 emission from flaring and venting	59.5	57.1	61.6	g-CH_4/GJ_p	
		CO_2 emission from flaring and venting	1,059	1,016	1,102	g-CO_2/GJ_p	
	Crude import	Crude oil import distance	4782			km	
	Refining	Refining efficiency for naphtha	95.1	95.6	94.1	%	[32]
Natural gas	Raw natural gas recovery	Recovery efficiency	98.4	99.0	97.5	%	
		CH_4 leakage during recovery	77.4	11.9	192.0	g-CH_4/GJ_p	
		Energy amount of flaring	8,657	7,535	9,780	kJ/GJ_p	

	NG processing	Processing efficiency	98.1	99.0	97.4	%	
		CH_4 leakage during processing	33.2	30.5	43.8	g-CH_4/GJ_p	
		CO_2 venting during processing	1,525	1,135	1,916	g-CO_2/GJ_p	
	Liquefaction	Liquefaction efficiency	92.7	94.3	91.0	%	
	NG import	NG import distance	3542			km	
	Regasification & distribution	Regasification & distribution efficiency	99.3	99.4	99.2	%	
		CH_4 leakage in Korea	8.2	6.6	9.9	g-CH_4/GJ_p	
Landfill gas	NG processing	NG processing efficiency	83.5			%	[17]
		Energy amount of CH_4 leakage	20,000			kJ/GJ_p	[17]

Table 2.2 Major parameters of upstream processes [38]

- *Reference* in Table 2.2 means the reference for each parameter, if the reference cell is empty, the values of that parameter are calculated by Choi and Song (2017), which is our previous paper.

- For each parameter on the table, *Det.* means the determined value, *Min* means the value where the final GHG emissions result is minimum, and *Max* means the value at which the final result is maximum. If only one reference is found or an exact value can be obtained, only the *det.* value is entered. *Min* and *Max* values are used to representing the error bars.

- The unit $/GJ_p$ means per 1 GJ of a product under a certain process.

2.4.4. Hydrogen

The annual production of H_2 in Korea is 2.1 million tons, with 1.4 million tons of by-product H_2 [39]. Naphtha cracking is the main technology for H_2 production for sale in Korea. It is noted that the gross production rate from COG (coke oven gas) is 2.1 million m^3/hr from the Korean steel industries, although only 300 m^3/hr is available for sale.

Figure 2.2 shows the hydrogen production pathways in Korea. In this study, the H_2 production processes are classified by their feedstock (COG, naphtha, NG, or electricity). Off-site production corresponds to the situation whereby H_2 is produced at a location distant from where it is used, typically with a relatively large production capacity, and then distributed to a gas station for final usage.

The 'Upstream process' in Figure 2.2 represents the processes that are associated with producing the feedstock for each H_2 production process. Another dashed line box indicates the H_2 production process from each feedstock. COG is a byproduct gas of the coking process, which transforms coal into coke to use in steel making processes. Thus, the upstream process starts with coal mining and cleaning at overseas coal mines. Because naphtha is a petroleum-based fuel, the upstream process begins with a crude recovery process. In petrochemical plants, naphtha is decomposed into several products and the main products of the naphtha cracking process are ethylene and propylene; H_2 only accounts for ~1 wt.% of the total product. Assuming energy-based allocation, the H_2 production efficiency is 88.0%, and considering the confidence interval, the efficiency is set to 86.9 – 89.1%. I presented the details on the efficiency of the naphtha cracking process in the previous work [40]. When H_2 is produced through the SMR process, NG is used as both a feedstock and a process fuel. NG, which is supplied as a feedstock, reacts with steam to produce mainly H_2 and CO_2, and small amounts of CO, H_2O, and CH_4 either are produced or remain. In the case of Elec. (off-site), the first process is 'upstream for feedstock.' There are several types of resources for power generation, e.g., coal, NG, uranium, residual oil, and renewable energy. The pathways producing each resource are grouped together as 'upstream for feedstock,' detailed descriptions of these upstream processes were given in Section 2.4.3.

The two processes following the H_2 production process are the compression and distribution processes. The distribution process is the process of transporting the H_2 produced in the plant to the industrial plants as a stationary fuel, which is only applicable for off-site-produced H_2. The compressors used by the H_2 plant and distribution company are NG compressors, while the compressors used at the gas station are electric compressors [40].

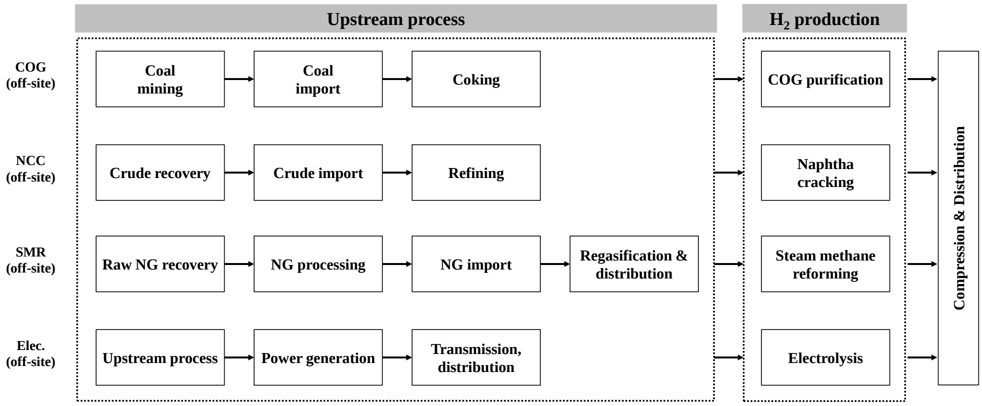

Figure 2.2 Hydrogen production pathways in Korea

For the four pathways in Figure 2.2, the life cycle greenhouse gas emission (white bar) results per GJ of H_2 are shown in Figure 2.3. Error bars are used to reflect the influences of the uncertainty of each variable used in the analysis or the range of the values of multiple references. The following summarizes the major points for the individual pathways.

- COG (off-site): The upstream process, including the coal mining and coking processes, represents the largest portion of the WTW greenhouse gas emissions. The carbon component of the COG is ultimately used as the process fuel for steel mill processes and is not released in the form of GHGs during the H_2 production process. All the GHGs emitted during H_2 production are due to the consumption of process fuels.

- Naphtha (off-site): The H_2 production efficiency is the highest among the technologies considered, and thus, the amount of GHG emitted during the H_2 production process is small. All the carbon component contained in the feedstock, naphtha, is converted to other petrochemicals and is not emitted as greenhouse gases. Overall, the total life cycle GHG emissions of this pathway are the lowest among four H_2 production pathways.

- NG (off-site): In addition to the GHG emissions from the use of process fuels, there are large amounts of CO_2 emissions in the product gas, which originate from the carbon contained in the feedstock NG. This accounts for more than 81% of GHG emissions during the H_2 production process.

- Elec. (off-site): There are no GHG emissions during the H_2 production because the process fuel is 100% electricity. It is noted that the generation mix used in this study is the Korean mainland mix, where thermal power generation, i.e., coal and NG, accounts for 67.5% of the total generation mix. As a result, the total amount of life cycle GHG emissions per unit H_2 production is the highest in electrolysis with the Korean grid mix pathway. Some studies report that H_2 production using electrolysis is considered promising when it is combined with renewable sources, e.g. wind or photovoltaic power generation [22, 41]. In these cases, there are no GHGs during upstream process and the total WTW GHG emissions of electrolysis pathways will decrease to only ~20,000 g-CO_2 eq./GJ.

Among the life cycle processes, the GHG emissions from H_2 distribution, compression and refueling are rather high. For example, greenhouse gas emissions from these processes account for 51.9% of the WTW GHG emissions in the Naphtha (off-site) pathway. For reference, the corresponding processes of the WTW results for gasoline vehicles account for only ~2%, which is mainly attributed to the characteristics of the liquid fuel [32].

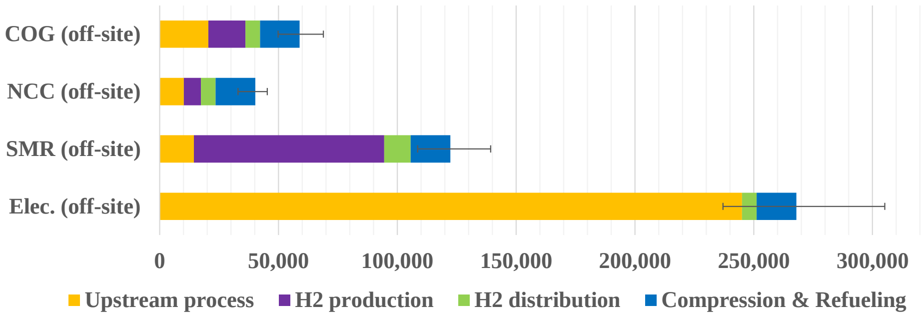

Figure 2.3 Life cycle GHG emissions per GJ of hydrogen [g-CO_2 eq./GJ]

2.5. WTW GHG emissions results in 2017

The major parameters and data analysis of the life cycle pathways of the various fuels and energy sources were explained from the section 2.4.1 to the section 2.4.4. Figure 2.4 shows the WTW GHG emissions by incorporating vehicle technologies, including the results for ICEV, HEV, PHEV, and EV. The fuel economy of the ICEV (gasoline), HEV, PHEV, and EV used in this calculation is the weighted average based on the sales volume of all passenger cars sold in Korea in 2017 [42]. Table 2.3 shows the fuel economy for each vehicle type. The unit of [km/$L_{eq.}$] means gasoline-equivalent fuel economy. The utility factor of PHEV implies the share of driving range between charge-depleting (CD) operation and charge-sustaining (CS) operation.

Vehicle Types	Fuel economy [km/Leq.]
ICEV (gasoline)	11.9
ICEV (diesel)	11.1
HEV (gasoline)	16.8
PHEV (gasoline) (Utility factor: 86%)	48.6 (CD mode, 5.8 km/kWh) 18.7 (CS mode)
BEV	49.2 (5.8 km/kWh)

Table 2.3 Fuel economy for each vehicle type in 2017 [42]

In Figure 2.4, the ‘Upstream process (feedstock)’ represents the processes including the raw material recovery, the production of feedstock, and the transport of feedstock to the fuel production site. ‘Fuel production’ refers to the processes from the production of the vehicle fuel to the charging of the vehicle fuel tank at the fuel station. In the case of BEVs, the ‘Fuel production’ stage includes the electric power generation, transmission, distribution, and charging processes. Finally, The WTW results of BEVs depend on the power source during the upstream process and power generation process. 'Vehicle operation' represents GHGs emitted during the vehicle operation phase, where BEVs do not generate GHGs.

During the WTW processes for ICEVs, HEVs, PHEVs, and BEVs, the highest portion of the greenhouse gas emissions is emitted during the conversion of fuel chemical energy into mechanical energy or electrical energy through the combustion of fuel. This corresponds to the vehicle operation phase for ICEVs and HEVs with internal combustion engine operation and the fuel production phase for BEVs with fossil-fueled power plant operation.

PHEV is equipped with a battery that can be externally charged in the existing HEV to extend the range of driving, and selected as the representative model of the extended-range electric vehicle (EREV) PHEV vehicle that uses electricity only in the charge-depleting mode. After calculating the WTW GHG emissions for electricity and gasoline, the WTW GHG emissions per distance of PHEV were calculated by multiplying the energy consumption ratio of electricity and gasoline in PHEV.

The results of BEVs are indicated by the power sources in Figure 2.4, and the representative value (*Korea mainland Avg*) is weight-averaged with the power generation mix in Korea in 2017. Most of the greenhouse gases came from the combustion of fossil fuels during power generation process, such as coal, natural gas, and petroleum-based fuel. The GHG emissions of by-product gas is noteworthy. The 'By-Product gas' in Figure 2.4 refers to boil-off gas (BOG) from the steel mill plant. The emission factor of the BOG is higher than other fossil fuel because BOG contains large amounts of carbon monoxide and hydrogen, so the heating value is low. The result value of ‘renewable’ is composed with 3.0% of WWS and 1.8% of by-product gas.

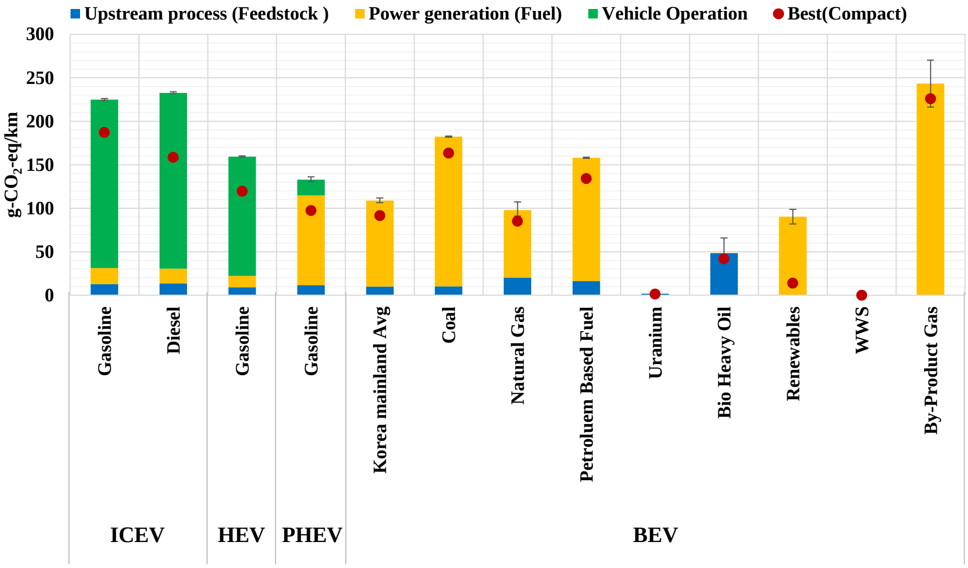

Figure 2.4 Well-to-Wheel GHG emissions per km of driving distance [g-CO2 eq./km]

2.6. Future prediction

Most recently, we presented the predicted WTW results by 2030. [43] Future WTW results are calculated by predicting the fuel economy and power generation mix, which are the most sensitive parameters for future prediction of ICEV, HEV, PHEV, and BEV. Fuel economy data were obtained from Autonomie data [44] scaled by the highest fuel economy for vehicles sold in Korea in 2017. The power generation mix, which has a significant impact on the WTW results of electric vehicles, is obtained based on the 8th national plan for power supply and demand in Korea. [45] The 8th Basic Plan for Long-term Electricity Supply and Demand, released in Korea in 2017, refers to the power supply and demand forecast for the next 15 years by 2031. In this report, nuclear power plants and coal are being phased out, and renewable energy is expanded significantly. Figure 2.5 shows the 2017 power mix of Korea and the target power mix of 2030. The graph shows that the ratio of coal and uranium decreases and that of NG and WWS increases in 2030 compared to 2017. In particular, WWS shows a 14% p increase in the total generation from 2.7% in 2017 to 16.7% in 2030. Etc. includes thermal power generation using petroleum-based fuels and byproducts.

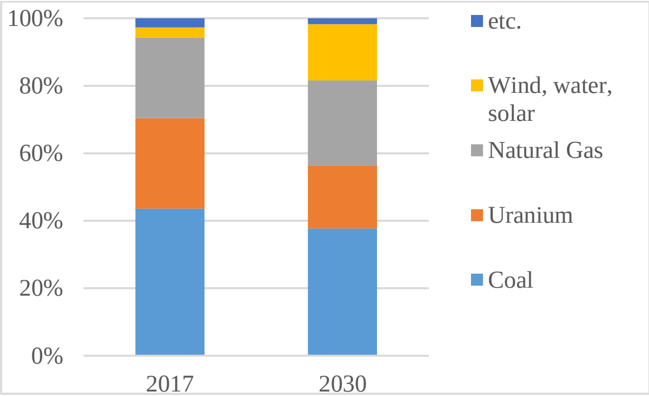

Figure 2.5 Power generation mix in Korea in 2017 and 2030

Just as changes in the power mix will have a huge impact on future upstream greenhouse gas emissions, fuel economy is a parameter that will have a significant impact on future tailpipe GHG emissions. As institutions around the world tighten their GHG regulations, the level of technology for automobiles will increase, which will lead to a higher fuel economy. In this paper, we decided to use the fuel economy predicted by Autonomie data. [46] The reason for using Autonomie data is that it is possible to obtain the predicted fuel economy by segment and to obtain corresponding manufacturing cost data. This is suitable for use in Chapter 3, model for predicting future car market. Since the fuel economy of Autonomie data is laboratory-measured FE, it was converted to 5-cycle. In addition, Autonomie classifies achievable fuel economy of 10%, 50% and 90% into high, medium and low tech, respectively, according to the probability of achieving the technological advancement level. In this study, med-tech fuel economy was used as a representative value, and in section 4.3, high-tech fuel economy was used to see the change according to the technology level of the vehicle.

	2015	2020	2025	2030	2030 (high tech)	2030 (low tech)
ICEV (gasoline)	12.3	14.3	14.8	16.6	18.5	14.6
HEV (gasoline)	17.5	20.4	21.6	24.3	28.4	20.7
PHEV (gasoline)	41.7	49.6	51.6	57.3	73.5	45.5
BEV (200mile)	47.0	51.1	53.5	55.6	61.1	50.8

Table 2.4 Predicted fuel economies of compact cars [km/Leq.] [46]

Figure 2.6 shows the WTW results of four kinds of powertrain vehicles in 2030. The unit g-CO_2-eq./km, which is the unit of the result, is the CO_2 equivalent of greenhouse gases emitted when driving a vehicle for 1 km. Tailpipe emissions are the same as the TTW GHG emissions, and by adding the WTT emissions generated from the feedstock and fuel production processes, the results are WTW emissions. The low, med, and high marks for each powertrain indicate the technology development level for each powertrain. The higher the tech, the better the fuel economy, the lower the greenhouse gas emissions.

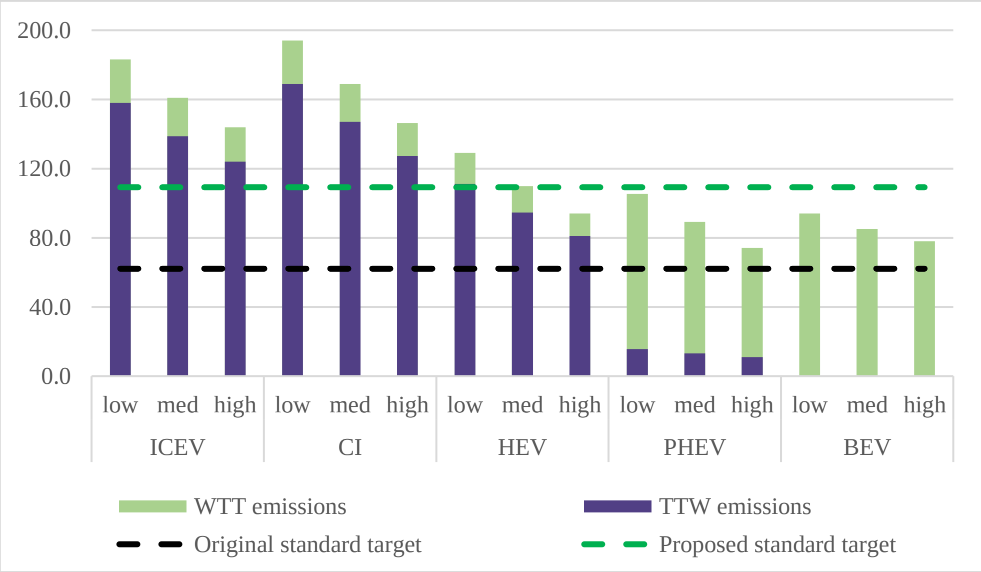

Figure 2.6 WTW GHG emissions of passenger vehicles in 2030 in Korea [g-CO2-eq./km]

The purple bars in Figure 2.6 are the TTW GHG results for four powertrains in 2030. It is evident that the tailpipe emissions of BEV are zero. The TTW emissions of 2030 were compared to the target values of the original standard. (The target value will be explained in detail in section 3.3.1.) The GHG emission of gasoline vehicles is 77g/km higher than the target value, and the GHG emissions of BEV are 62g/km lower than the target value.

The green bars are the WTT results in 2030. The WTT emissions indicated with green bars are added to the tailpipe emission. The WTW GHG emissions of BEV were determined by the power generation mix in 2030. Also, GHG change due to fuel economy is amplified more than TTW GHG. Like the TTW GHG, we compared the target value of the WTW standard with the GHG emissions of the four powertrains. The GHG difference between ICEV and BEV is reduced. In addition, the over and under-achieve amounts against the target value are decreased, compared to the original standards. To compare with 2017, the WTW GHG emissions of ICEV-gasoline and BEV decrease about 60 g/km, 20 g/km, respectively. The gap between the ICEV and BEV also decreases in 2030.

Chapter 3. Agent-based analysis

3.1. Introduction

An agent-based model is used to predict the decision-making and behavior of various agents, who are the decision-makers, that influence each other in socio-technical system. It is used as a tool to comprehensively analyze the influence of various technical attributes such as socio-economic characteristics such as individual, age, gender and income, and specific quality and price of alternative. [47] In this study, three agents, government, manufacturer and consumer, were established to analyze the impact of the automotive GHG standard. The parameters that can be determined by each agent and the elements on which interaction occurs are shown in Figure 3.1.

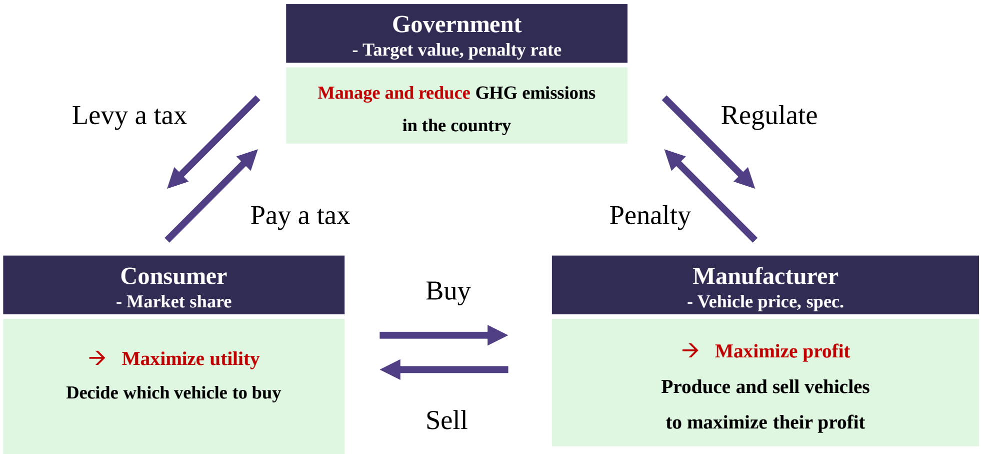

Figure 3.1 Three agents related with vehicle market

The government wants to manage and reduce GHG emissions across the country. Thus, the government can decide the target value of the regulation and the penalty rate. Consumer decides which vehicle to buy and the decisions of many consumers are going to compose the market share. The manufacturers produce and sell vehicles and they want to maximize their profit. Also, the manufacturers can suggest the affordable price of the vehicle.

Each agent interacts with each other. For a simple example, consumer buy, and manufacturer sell vehicles. The government regulates the manufacturer and if the company couldn't meet the regulation, they should pay penalty for that. The government and consumers give and take the incentive and tax. The consumer can decide which car to buy based on his preference. The vehicle manufacturer can decide which car to develop, the level of fuel economy, whether to increase or decrease production costs and the selling price. The government can determine the incentives for electric vehicles, fuel taxes, regulation levels, and penalty rates. Each agent's decision is mutually affected. The consumer decides which car to buy based on the price, fuel economy, determined by the vehicle manufacturer, and incentive, and charging infrastructure, determined by the government. The vehicle manufacturer establishes a sales strategy that takes into consideration consumer purchasing sentiment and government regulations and sets fuel economy and price accordingly. The government decides on the strength of regulation, taking into account tax revenues and national greenhouse gas emissions.

The following assumptions are used to quantitatively predict the impact of WTW GHG standards in simplified market conditions.

- Model year: 2030
- Only to the compact car market, fixed total sales volume (0.5 million)
- Four powertrains: ICEV-gasoline, HEV-gasoline, PHEV-gasoline, BEV (driving range: 200 miles)
- Three agents: government, consumer, and manufacturer
- Nash equilibrium, pure oligopoly (a small number of firms produce homogeneous products), and non-cooperative markets (no price fixing)

3.2. Previous researches

Agent-based models are used in various studies to analyze the market adoption of alternative fuel vehicles such as PHEV and BEV. Burak Sen et al. used ABM to analyze the effect of CAFE regulation and government incentive on EV market penetration. [48] In the paper, the author selected scenarios that considered incentive and CAFE standards, and predicted how the vehicle sales mix of ICEV, HEV, PHEV, EREV, and BEV would change.

A paper by T. Krause et al. explains the difference between Nash equilibria analysis and agent-based modeling. [49] According to the Nash equilibrium analysis, the strategy of each agent is the best response to the strategy of other agents. Thus, equilibrium is achieved when all agents make the best choice. [50] Agent-based modeling allows you to apply reactions by interactions with other agents when one agent makes decisions by some set of rules.

Jeremy J. Michalek, et. al. analyzed the effects of emissions policy on optimal vehicle design decisions using a mathematical model. In the study, gasoline and diesel vehicles were analyzed. [51] Through the study (Michalek 2004), they analyzed how the design variables of engine type, engine size and shape, price, and engine performance mpg, time 0-60 are decided for each scenario according to the level of GHG standards and fuel economy standards. Based on these previous studies, an in-house vehicle market prediction model was designed in this analysis. The consumer acts according to the consumer choice model, and the vehicle manufacturer pursues maximum profit under the Nash equilibrium assumption. Section 3.3 and Section 3.4 provide a detailed explanation of the vehicle market prediction model that will be used in this analysis. The model that used in this study refers to Michalek's model [52], which is designed to analyze the WTW GHG standard by modifying the greenhouse gas emissions of the vehicle and the target values of the GHG standards. There has been no research on how consumers and manufacturers respond to the WTW GHG standard, there is a novelty of this study in the analysis considering the consumer choice and profit of the automaker for the first time. More previous studies on consumer choice analysis are listed in Table 3.2.

3.3. Methodology – Key parameters and assumptions

3.3.1. Policymaker – Manage the nationwide greenhouse gas emission standard

The role of government is to manage and reduce GHG emissions across the country. To fulfill this role, the government sets the target value and the penalty rate for the GHG standard. Total GHG emissions from the vehicle market are determined as equation below.

$$\text{total GHG} = \sum_{i=1}^{4} (\text{GHG}_i \cdot q_i) \cdot \text{VKT} \cdot \text{Q}$$

The goal of the GHG emission regulation is set by comprehensively considering the national GHG reduction target, the potential reduction in the transport sector, and the manufacturers' interests. The GHG standard in Korea has announced its targets by 2020, and no future targets have been announced. Therefore, the average TTW and WTW emissions are inferred from the goal of alternative vehicle supply in Korea in 2030. [53] According to the roadmap, the vehicle supply targets for 2030 are ICEV 20%, HEV 34.3%, PHEV 15.2%, and BEV 30.5%. Assuming that the market share of compact cars in 2030 has the same ratio, the average TTW GHG emissions and WTW GHG emissions were set as target values. The determined TTW standard target is 62.2 g/km, and the WTW standard target is 109.2 g/km. These regulation targets represent the greenhouse gas targets that the Korean government wants to achieve in 2030. In addition, the same criteria can be used to set the goals of TTW regulation and WTW regulation.

The penalty rate of the GHG standard is 50,000 KRW per 1 g-CO_2-eq./km excess. In addition, the carbon credit can be sold if the manufacturer emits less amount of GHGs than the target value. This is specified in Korean regulations.

> "Where any motor vehicle manufacturer's average quantity of greenhouse gas emissions or efficiency of average energy consumption of the relevant year is in compliance with the permissible greenhouse gas emission levels or the efficiency standards for average energy consumption, it may use the difference between those quantities and the permissible average emission quantities from the following year by carrying it forward for the period prescribed by Ordinance of the Ministry of Environment or trade in it with another motor vehicle manufacturer, and where its average quantities of greenhouse gas emissions or efficiency of average energy consumption of the relevant year are in noncompliance with the permissible levels of greenhouse gas emissions or the efficiency standards for average energy consumption, it may redeem the portion that exceeds the permissible average emission quantities or the average energy consumption required from the following year for the period prescribed by Ordinance of the Ministry of Environment."
>
> - Ministry of Environment, CLEAN AIR CONSERVATION ACT, Article 76-5 [10]

3.3.2. Manufacturer – Decision of vehicle fuel economy and price to maximize profit

Vehicle manufacturers establish strategies to maximize their total profits. The analysis of this study assumes that each manufacturer sells only compact cars, and analyzes the situation of selling ICEV gasoline, HEV gasoline, PHEV 30 gasoline, and BEV 200. The manufacturer can determine the fuel economy, production cost and selling price for each product it sells. First, data range of three parameters was collected.

First, the data related to the forecast fuel economy and production cost until 2030 were used for Autonomie data of Argonne National Laboratory. [54] In ANL, large-scale simulation of five vehicle classes, six timeframes, five powertrains, and four fuels is used to predict the future vehicle specification, energy consumption, and cost. Each input parameter for prediction has three risk levels, resulting in three outcomes: high tech, med tech, and low tech with 10%, 50%, and 90% chances of achieving a certain level of technology.

Figure 3.2 shows the relationship between fuel economy and manufacturing cost for compact cars in 2030. [54] The following are the characteristics of this graph. First, the correlation prediction between manufacturing cost and fuel economy shows an approximately linear relationship. In the case of ICEV gasoline, ICEV diesel, and HEV, manufacturing cost increases as fuel economy increases. To produce higher fuel economy vehicles, manufacturing costs increase. In addition, when the same amount of fuel economy is increased, the increased rates of manufacturing cost of ICEV and HEV are higher than those of PHEV and BEV.

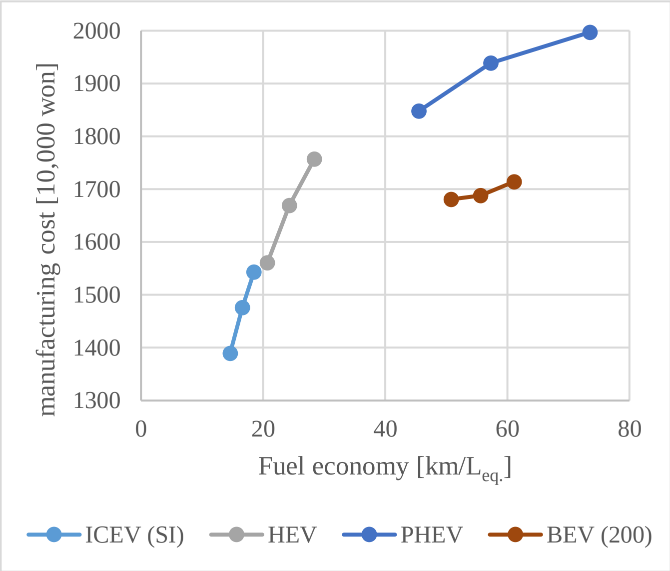

Figure 3.2 Correlation between fuel economy and manufacturing cost in 2030

The total profit of vehicle manufacturer j can be expressed as the following equation. $i = 1 \sim 4$ represents the type of vehicle powertrains; ICEV, HEV, PHEV, and BEV. q_i denotes the sales volume ratio of the vehicle i, p_i denotes the retail price and c_i indicates the manufacturing cost. In other words, for all of the vehicle $i = 1 \sim 4$, the amount obtained by multiplying the difference between the retail price and the manufacturing cost by the market share becomes the income of the vehicle manufacturer. However, manufacturers may earn a lower total profit due to penalties according to the GHG standard. The penalty for the GHG standard is equal to the difference between the corporate average GHG emissions and the GHG standard target, multiplied by the total number of units sold (Q_j) and the penalty rate (ρ). Section 3.4.2 assumes that the vehicle investment cost is not taken into account. In Section 3.4.3, the equation was developed to include the investment cost.

$$\Pi_j = \sum_{i=1}^{4}(Q_i \cdot (p_i - c_i)) - \rho \cdot Q_j \cdot (GHG_{avg,j} - GHG_{std})$$

According to the Clean Air Conservation Act in Korea, the penalty rate for unachieved GHG standard is 50,000 KRW per 1 g/km access after 2020, and GHG emissions can be carried over to next year or can be traded between vehicle companies. In this study, it is assumed that excess achievements can be sold through trading.

The market share (q_i) of each vehicle is determined by the probability of consumer choice. The consumer decides which vehicle to buy by considering various parameters such as the price and fuel economy of the vehicle. The determination of q_i is described in Section 3.3.3.

3.3.3. Consumer – Select the vehicle with the highest utility

The consumer choice model was used to analyze which of the various products the consumer would choose. The consumer's decision rule is utility maximization. The consumer selects a vehicle that can obtain the maximum utility by comprehensively evaluating the utility of attributes such as price, fuel economy, driving distance, and charging time. To quantitatively represent the utility, we used a logit model of discrete choice analysis. [55] Several previous studies that predicted vehicle sales volume through the consumer choice model considered the following parameters. Physical parameters include car prices, fuel prices, 0 to 100 acceleration, subsidy, incentive, charging infrastructure and environmental regulation. Some studies also consider socio-states such as income, education level, gender, and family type. [48, 56, 57] In this study, the utility of vehicle i is represented as follows.

$$u_i = -\beta_1 \cdot p_i - \frac{\beta_2}{FE_i} \cdot (\mathrm{fc_i}) + \beta_3 \cdot DR_i + \beta_4 \cdot CT_i + (\mathrm{ASC_i}) + \varepsilon_i$$

As expressed in the equation above, the attributes to be considered when evaluating a given vehicle's utility are the price (p_i), fuel economy (FE_i), driving range (DR_i), charging time (CT_i), and alternative specific constant (ASC_i). The Error term (ε_i) is assumed to be independently identically-distributed extreme value. A detailed description of each attribute follows.

Attributes	Nomenclature	Description	Unit
Price	p	The price a consumer pays for a vehicle (= MSRP – incentive)	10^4 KRW
Fuel cost	fc	Refueling cost or charging costs	KRW/L or KRW/kWh
Fuel Economy	FE	km per gasoline equivalent liter	km/L_{eq}
Driving range	DR	Driving distance with a full charge	km
Charging time	CT	The time required for a full charge	min
Preference	ASC	Alternative specific constant	-

Table 3.1 Attributes that determine the utility of the consumer

First, price p_i is the price paid by consumers when they buy a vehicle, minus the incentives provided by the government from the manufacturer's retail price. The term $\frac{\beta_2}{FE_i} \cdot fc_i$, expressed as the inverse of fuel economy and fueling cost, deals with the cost of fuel used to drive a vehicle. The fuel cost per kilometer was calculated according to the fuel type and fuel consumption level of each vehicle by multiplying the fuel cost of gasoline or the charging cost of electricity. The driving range and charging time are characteristics that vehicle users who use batteries are sensitive to. *DR* refers to the distance that can be driven after full charge of fuel or electricity, and *CT* refers to the time required for full charge. Unlike the four attributes described above, *ASC* is a constant introduced to reflect the consumer's subjective purchasing tendency. *ASC* is an indicator of which powertrain is preferred when price, fuel economy, *DR* and *CT* are all the same. Every powertrain has its own *ASC*. When new technology is introduced in automobiles, purchase decisions include the risk-taking of goods that the consumer is not familiar with and the concerns about infrastructure.

The coefficient multiplied by each attribute is an indicator of how sensitive the consumer is to that attribute. Many researchers have analyzed the relationship between their willingness-to-pay and attributes through a survey of real consumers. [47, 56-60] The previous studies are summarized in the table below.

Authors	Year	Country	data type, analysis method
Andre Hackbarth, Reinhard Madlener	2013	Germany	Multinomial logit, Mixed logit Willing-to-Payness
William Sierzchula SjoerdBakker, KeesMaat, BertvanWee	2014 (2012)	30 countries	beta, OLS regression using collected data
Michael K. Hidrue, GeorgeR. Parsons, Willett Kempton, Meryl P.Gardner	2011	US	MNL model, parameters implicit attribute values Questionnaire for a given budget range, given two EV models
Makoto Tanaka, Takanori Ida, Kayo Murakami, Lee Friedman	2014 (2012)	US, Japan	mixed logit, coeff., Willing-to-Payness
Yeongmin Kwon, Sanghoon Son, Kitae Jang	2018 (2015)	Korea (Jeju)	Survey for EV owners
Andre Hackbarth, Reinhard Madlener	2016	Germany	Multinomial logit, Willing-to-Payness
Hocheol Jeon	2017	Korea	Mixed logit model, Latent class model

Table 3.2 Previous researches of the consumer choice model in vehicle market

Among the preceding studies, Y. Kwon et al. set up coefficients by conducting a survey of Korean EV owners. [57] However, the paper only surveyed the owners of electric vehicles, and the survey's options also consisted of answers to the purchase of electric vehicles. Therefore, there is a limit to use as a utility function covering ICEV, HEV, and PHEV in this study.

The coefficients of utility for my study were selected from the results of the Policy Research Report by the Korea Economic Institute. [60] In the report, the choice experiment was used to estimate the utility function. Jeon obtained a total of 1187 response samples from an online survey and estimated the mixed logit model and latent class model. According to various assumptions, there are four types of mixed logit models and three types of latent class models. To predict the automotive market in 2030 in this study, the segment 2 coefficient of the latent class model was selected from the seven factors presented in the above report.

In order to show that the selected coefficients are suitable for use in our model, I examined the characteristics of the segment 2 population. Latent class analysis is a research method that analyzes the data collected through the questionnaire and divides the population into a group of finite classes with similar propensities through statistical procedures rather than a group with homogeneous characteristics. Individuals belonging to an individual class will have different coefficients for each class when selecting a vehicle. In the latent class model, the probability of consumer choice is calculated in the form of conditional probability considering both the probability of belonging to a specific segment and the probability that an individual belonging to the segment selects product.

I only use the coefficients for segment 2. The limitation is that selecting only the coefficients of some segments can reflect the intention of the researcher. However, it is hard to accurately determine the preference of the future consumer from the current survey results. Therefore, coefficients were selected based on following assumptions and the consumers in segment 2 judged to reflect consumer tendency of 2030 well. According to Jeon's report, consumers in segment 2 are not likely to be residents of Jeju Island and they are sensitive to the price, fueling cost and fuel economy of the vehicle. In addition, the preference for HEV and PHEV is not high, and for the BEV, there is an intermediate preference. [60]

The utility is expressed quantitatively by the following formula.

$$u_i = -0.149 \cdot p_i - \frac{0.00375 \cdot fc_i}{FE_i} + 0.115 \cdot DR_i - 0.001 \cdot CT_i + ASC_i + \varepsilon_i$$

$$(ASC_{SI} = 1.428,\ ASC_{HEV} = 0.904,\ ASC_{PHEV} = -1.265,\ ASC_{BEV} = 0.172)$$

Consumers evaluate the vehicle utility by comprehensively evaluating the price (p_i), fuel economy (FE_i), driving range (DR_i) and charging time (CT_i) attributes. The coefficients multiplied by each attribute are indicators of how sensitive the consumer is to their attributes. H. Jeon conducted a survey on vehicle buyers in Korea, and we expected that this analysis reflects the psychology of Korean consumers. [60] The coefficients given in their study are modified to match the unit of the attribute in the utility equation. The consumer chooses the vehicle that has the maximum utility, but there is an error term in the utility equation due to imperfect knowledge, such as unobserved attributes and measurement errors. Because of this error, the consumer's choice is expressed as a probability of purchase. Therefore, the market share (q_i) is calculated as the ratio of the exponential utility. [61]

$$q_i = \frac{\exp(u_i)}{\sum_{i'=1}^{4} \exp(u_{i'})}$$

3.4. Responses of the agents to the GHG emission standard - Mathematical approach

3.4.1. Nash equilibrium

In a Nash equilibrium, every company makes the best decision in consideration of given the strategies of other competitive companies. When every company's strategy reaches a certain point, every company has no incentive to change its choice, which looks like an equilibrium state. [50] Applying this theory to the vehicle market, all manufacturers at the Nash equilibrium point determine the price and the vehicle performance of the product to maximize their profit.

Assuming that it is a pure oligopoly market, all companies have the same manufacturing costs, fuel economy, driving range, and charging time, for their powertrains. This study also assumed that the *FE*, *DR*, and *CT* are fixed in given powertrains. Thus, the retail price is the only parameter adjusted by the manufacturer.

3.4.2. Mathematical approach (1) – Excluding the fixed cost

In order to quantitatively assess the impact of the WTW GHG standard, we will explain it through a mathematical approach. First, let's assume that there are two companies (j = 1, 2) that sell two vehicle models (i = 1, 2) by simplifying the system. In the Nash equilibrium, all firms set prices for their products to maximize their profits. In other words, the derivative of the firm's profit by the product price is zero. The profit of firm 1 (Π_1) can be expressed as equation below. Profit is the sales profit of the product minus the regulation cost and the greenhouse gas penalty.

$$\Pi_1 = q_{11}(p_{11} - c_{11}) + q_{21}(p_{21} - c_{21}) - \rho(q_{11}(G_{11} - G_{std}) + q_{21}(G_{21} - G_{std}))$$

$$\frac{\partial \Pi_1}{\partial p_{11}} = \frac{\partial q_{11}}{\partial p_{11}}(p_{11} - c_{11}) + q_{11} + \frac{\partial q_{21}}{\partial p_{11}}(p_{21} - c_{21}) - \rho\left(\frac{\partial q_{11}}{\partial p_{11}}(G_{11} - G_{std}) + \frac{\partial q_{21}}{\partial p_{11}}(G_{21} - G_{std})\right)$$

The above equation is differentiated profit by price (p_{11}) with all other parameters fixed (*FE, CT, DR,* p_{21}, p_{12}, p_{22}). As utility u_{11} changes as p_{11} changes, the market share of vehicles on the market may change. That is q_{21}, as well as q_{11}, are affected by the price change of p_{11}. This is because u_{11} is included in the denominator of the expression representing q_{21}.

$$v_i = \beta_1 \cdot (Price_i - incentive_i) + \beta_{2i} \cdot \frac{fuel\ cost_i}{Fuel\ economy_i} + \beta_{3i} \cdot (Acpt.) + \beta_{4i} \cdot DR_i + \beta_{5i} \cdot CT_i$$

$$\frac{\partial v_{11}}{\partial p_{11}} = \beta_1$$

$$q_{11} = \frac{\exp(v_{11})}{(\exp(v_{11}) + \exp(v_{21}) + \exp(v_{12}) + \exp(v_{22}))}$$

$$q_{21} = \frac{\exp(v_{21})}{(\exp(v_{11}) + \exp(v_{21}) + \exp(v_{12}) + \exp(v_{22}))}$$

Therefore, q_{11} and q_{21} can be expressed as follows by partial differentiation for p_{11}.

$$\frac{\partial q_{11}}{\partial p_{11}} = \frac{\frac{\partial v_{11}}{\partial p_{11}} \exp(v_{11}) \left(\sum\sum v_{ij}\right) - \exp(v_{11}) \exp(v_{11}) \frac{\partial v_{11}}{\partial p_{11}}}{\left(\sum\sum v_{ij}\right)^2}$$

$$= \frac{\partial v_{11}}{\partial p_{11}} q_{11}(1 - q_{11}) = \beta_1 q_{11}(1 - q_{11})$$

$$\frac{\partial q_{21}}{\partial p_{11}} = -\frac{\exp(v_{21}) \exp(v_{11}) \frac{\partial v_{11}}{\partial p_{11}}}{\left(\sum\sum v_{ij}\right)^2} = -\frac{\partial v_{11}}{\partial p_{11}} q_{11} q_{21} = -\beta_1 q_{11} q_{21}$$

Substitute this into the equation $\frac{\partial \Pi_1}{\partial p_{11}}$

$$\frac{\partial \Pi_1}{\partial p_{11}} = \beta_{1,i=1} q_{11}(1 - q_{11})\big((p_{11} - c_{11}) - \rho(G_{11} - G_{std})\big) + q_{11}$$

$$- \beta_{1,i=1} q_{11} q_{21}\big((p_{21} - c_{21}) - \rho(G_{21} - G_{std})\big) = 0$$

$$divide\ by\ \beta_1 q_{11},$$

$$(1-q_{11})\big((p_{11}-c_{11})-\rho(G_{11}-G_{std})\big)+\frac{1}{\beta_1}$$
$$-q_{21}\big((p_{21}-c_{21})-\rho(G_{21}-G_{std})\big)=0$$

$$p_{11}=\Pi_1|_{eq}-\frac{1}{\beta_1}+c_{11}+\ \rho(G_{11}-G_{std})$$

$$Likewise,\ p_{21}=\Pi_1|_{eq}-\frac{1}{\beta_1}+c_{21}+\ \rho(G_{21}-G_{std})$$

$$put\ p_{11},\ p_{21}\ into\ the\ \Pi_1\ equation,$$

$$\Pi_1=q_{11}\left(\Pi_1|_{eq}-\frac{1}{\beta_1}\right)+q_{21}\left(\Pi_1|_{eq}-\frac{1}{\beta_1}\right)$$

$$q_{11}+q_{21}=0.5\ \ (\because pure\ oligopoly)$$

$$\Pi_1|_{eq}=-\frac{1}{\beta_1}$$

Given the equation, the manufacturer's profit on the Nash equilibrium is represented by $-\frac{1}{\beta_1}$, and the price of each vehicle is defined as

$$p_{ij}=\Pi_j|_{eq}-\frac{1}{\beta_1}+c_{ij}+\ \rho\big(G_{ij}-G_{std}\big)$$

Now, if we expand the vehicle market to *m* vehicle models, *n* manufacturers, profits, and prices can be expressed as follows.

$$p_{11}=\Pi_1|_{eq}-\frac{1}{\beta_1}+c_{11}+\ \rho(G_{11}-G_{std})$$

$$p_{21} = \Pi_1|_{eq} - \frac{1}{\beta_1} + c_{21} + \rho(G_{21} - G_{std})$$

$$\vdots$$

$$p_{m1} = \Pi_1|_{eq} - \frac{1}{\beta_1} + c_{m1} + \rho(G_{m1} - G_{std})$$

$$put\ p_{11},\ p_{21},\ \ldots,\ p_{m1}\ into\ the\ \Pi_1\ equation,$$

$$\Pi_1 = q_{11}\left(\Pi_1|_{eq} - \frac{1}{\beta_1}\right) + q_{21}\left(\Pi_1|_{eq} - \frac{1}{\beta_1}\right) + \ \ldots + q_{m1}\left(\Pi_1|_{eq} - \frac{1}{\beta_1}\right)$$

$$q_{11} + q_{21} + \cdots + q_{m1} = \frac{1}{n}$$

$$\Pi_1|_{eq} = -\frac{1}{n-1}\frac{1}{\beta_1}$$

$$p_{ij} = -\frac{n}{n-1}\frac{1}{\beta_1} + c_{ij} + \rho\left(G_{ij} - G_{std}\right)$$

The information that can be grasped through the expansion of the equation and the result is as follows. Profit of the manufacturer is only affected by the number of vehicle company *n* and β_1, a coefficient for the utility price. As the number of competitors increases, the maximum profit that the manufacturer can earn decreases. Also, the more sensitive consumers are to price, the lower the profits of a company. This means that when Nash equilibrium is formed at a certain price, the more sensitive the consumer is to price, the more difficult it is to raise the price.

The retail price of a vehicle is determined by the manufacturing cost of each vehicle, greenhouse gas emissions, total profit, number of firms, and beta 1. The price increases as the manufacturing cost increases and as the total profit of the manufacturer increases. As with the profit, the more price-sensitive the consumer is, the lower the price of the vehicle. In addition, the penalty from greenhouse gas emissions is reflected in the price as it is.

For gasoline vehicles, the number of firms was changed from 2 to 50, confirming that the price converged through iteration. When the number of firms increased from four to five, the price decrease rate was -2.66%, and when the number of firms increased from 19 to 20, the price decrease rate was -0.01%. Considering the convergence of prices, it is assumed that there are 10 manufacturers in the market in this study.

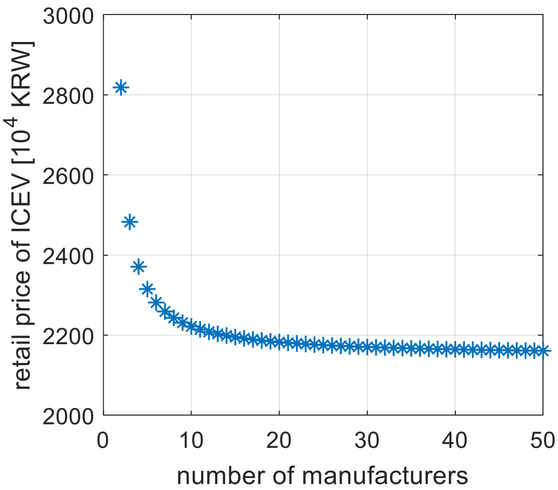

Figure 3.3 price changes of ICEV according to the number of manufacturers

3.4.3. Mathematical approach (2) – Including the fixed cost

This section further considers fixed costs that are independent of sales volume, such as the R&D cost and facility installation cost, when calculating the profits of a vehicle manufacturer. The fixed cost for model *i* of company *j* is represented by FXC_{ij}.

As in Section 3.4.2, the following equation is developed for the situation where two manufacturers produce two vehicle models. The profit Π_1 of the firm is added with a term for FXC_i that is independent of the market share q_i. Deriving Π_1 from the price p of the product disappears the *FXC* term and produces the same result as section 3.4.2.

$$\Pi_1 = q_{11}(p_{11} - c_{11}) + q_{21}(p_{21} - c_{21}) - \rho\big(q_{11}(G_{11} - G_{std}) + q_{21}(G_{21} - G_{std})\big) - (\mathrm{FXC}_{11} + FXC_{21})$$

$$\frac{\partial \mathit{\Pi}_1}{\partial p_{11}} = \frac{\partial q_{11}}{\partial p_{11}}(p_{11} - c_{11}) + q_{11} + \frac{\partial q_{21}}{\partial p_{11}}(p_{21} - c_{21}) - \rho\left(\frac{\partial q_{11}}{\partial p_{11}}(G_{11} - G_{std}) + \frac{\partial q_{21}}{\partial p_{11}}(G_{21} - G_{std})\right)$$

As calculated in section 3.4.2, the above equation is differentiated profit by price (p_{11}) with all other parameters fixed (*FE, CT, DR,* p_{21}, p_{12}, p_{22}).

$$v_i = \beta_1 \cdot (Price_i - incentive_i) + \beta_{2i} \cdot \frac{1}{Fuel\ economy_i} + \beta_{3i} \cdot (Acpt.) + \beta_{4i} \cdot DR + \beta_{5i} \cdot CT$$

$$\frac{\partial v_{11}}{\partial p_{11}} = \beta_1$$

$$q_{11} = \frac{\exp(v_{11})}{(\exp(v_{11}) + \exp(v_{21}) + \exp(v_{12}) + \exp(v_{22}))}$$

$$q_{21} = \frac{\exp(v_{21})}{(\exp(v_{11}) + \exp(v_{21}) + \exp(v_{12}) + \exp(v_{22}))}$$

q_{11} and q_{21} can be expressed as follows by partial differentiation for p_{11}.

$$\frac{\partial q_{11}}{\partial p_{11}} = \frac{\frac{\partial v_{11}}{\partial p_{11}} \exp(v_{11}) \left(\sum\sum v_{ij}\right) - \exp(v_{11}) \exp(v_{11}) \frac{\partial v_{11}}{\partial p_{11}}}{\left(\sum\sum v_{ij}\right)^2}$$

$$= \frac{\partial v_{11}}{\partial p_{11}} q_{11}(1 - q_{11}) = \beta_1 q_{11}(1 - q_{11})$$

$$\frac{\partial q_{21}}{\partial p_{11}} = -\frac{\exp(v_{21}) \exp(v_{11}) \frac{\partial v_{11}}{\partial p_{11}}}{\left(\sum\sum v_{ij}\right)^2} = -\frac{\partial v_{11}}{\partial p_{11}} q_{11} q_{21} = -\beta_1 q_{11} q_{21}$$

Substitute this into the equation $\frac{\partial \Pi_1}{\partial p_{11}}$

$$\frac{\partial \Pi_1}{\partial p_{11}} = \beta_{1,i=1} q_{11}(1 - q_{11})\left((p_{11} - c_{11}) - \rho(G_{11} - G_{std})\right) + q_{11}$$

$$- \beta_{1,i=1} q_{11} q_{21}\left((p_{21} - c_{21}) - \rho(G_{21} - G_{std})\right) = 0$$

$$divide\ by\ \beta_1 q_{11},$$

$$(1-q_{11})\big((p_{11}-c_{11})-\rho(G_{11}-G_{std})\big)+\frac{1}{\beta_1}$$

$$-q_{21}\big((p_{21}-c_{21})-\rho(G_{21}-G_{std})\big)=0$$

$$add\ (FXC_{11}+FXC_{21})-(FXC_{11}+FXC_{21})\ to\ both\ sides,$$

$$p_{11}=\Pi_1|_{eq}-\frac{1}{\beta_1}+c_{11}+\ \rho(G_{11}-G_{std})+(FXC_{11}+FXC_{21})$$

$$Likewise,\ p_{21}=\Pi_1|_{eq}-\frac{1}{\beta_1}+c_{21}+\ \rho(G_{21}-G_{std})+(FXC_{11}+FXC_{21})$$

$$put\ p_{11},\ p_{21}\ into\ the\ \Pi_1\ equation,$$

$$\Pi_1=q_{11}\left(\Pi_1|_{eq}-\frac{1}{\beta_1}+(FXC_{11}+FXC_{21})\right)$$

$$+q_{21}\left(\Pi_1|_{eq}-\frac{1}{\beta_1}+(FXC_{11}+FXC_{21})\right)-(FXC_{11}+FXC_{21})$$

$$q_{11}+q_{21}=0.5\ \ (\because\ pure\ oligopoly)$$

$$\Pi_1|_{eq}=-\frac{1}{\beta_1}-(FXC_{11}+FXC_{21})$$

Now, if we expand the vehicle market to *m* vehicle models, *n* companies, profits, and prices can be expressed as follows.

$$p_{11}=\Pi_1|_{eq}-\frac{1}{\beta_1}+c_{11}+\ \rho(G_{11}-G_{std})+(FXC_{11}+FXC_{21}+\cdots+FXC_{m1})$$

$$p_{21}=\Pi_1|_{eq}-\frac{1}{\beta_1}+c_{21}+\ \rho(G_{21}-G_{std})+(FXC_{11}+FXC_{21}+\cdots+FXC_{m1})$$

$$\vdots$$

$$p_{m1} = \Pi_1|_{eq} - \frac{1}{\beta_1} + c_{m1} + \ \rho(G_{m1} - G_{std}) + (FXC_{11} + FXC_{21} + \cdots + FXC_{m1})$$

$put\ p_{11},\ p_{21},\ \ldots,\ p_{m1}\ into\ the\ \Pi_1\ equation,$

$$\begin{aligned}\Pi_1 = q_{11}&\left(\Pi_1|_{eq} - \frac{1}{\beta_1} + (FXC_{11} + FXC_{21} + \cdots + FXC_{m1})\right)\\ &+ q_{21}\left(\Pi_1|_{eq} - \frac{1}{\beta_1} + (FXC_{11} + FXC_{21} + \cdots + FXC_{m1})\right) + \ \ldots\\ &+ q_{m1}\left(\Pi_1|_{eq} - \frac{1}{\beta_1} + (FXC_{11} + FXC_{21} + \cdots + FXC_{m1})\right)\\ &- (FXC_{11} + FXC_{21} + \cdots + FXC_{m1})\end{aligned}$$

$$q_{11} + q_{21} + \cdots + q_{m1} = \frac{1}{n}$$

$$\Pi_1|_{eq} = -\frac{1}{n-1}\frac{1}{\beta_1} - (FXC_{11} + FXC_{21} + \cdots + FXC_{m1})$$

$$p_{ij} = -\frac{n}{n-1}\frac{1}{\beta_1} + c_{ij} + \ \rho\left(G_{ij} - G_{std}\right)$$

3.5. Model validation and sensitivity analysis

Using the parameters described in Section 3.3.1 to Section 3.3.3 and selected coefficients, I designed an in-house model to predict the vehicle market in 2030. Before using the model, the market prediction model developed in this study should be validated. Since the vehicle market prediction model is a future prediction model, it is impossible to validate with the actual data. Therefore, model validation was performed by comparing the market share in 2030 predicted using this model with the future prediction results of other research institutions. Therefore, validation was performed for two situations as follows.

First, for validation of the coefficients of the consumer choice model, I calculated how the market share for the automobile market in 2017 was calculated with this model. At this time, the attributes used to determine the utility utilized the specifications of ICEV (SI), HEV, PHEV, and BEV cars, which are the highest-sold in the compact car market in Korea in 2017. Representative models selected based on 2017 sales volume are Avante, Ionic HEV, and Ionic BEV. In 2017, PHEV, which had a low sales volume in Korea, selected Ionic PHEV as a representative model in accordance with the equity of other models. The retail price is the lowest trim price of the model. In addition, it is assumed that there are 9 gas stations and 0.8 electric stations in 10 km^2.

	SI	HEV	PHEV	BEV
Price [104 KRW]	1394	2197	3230	3840
Incentive [104 KRW]	0	100	500	1,900
Fuel Economy	13.5 km/L	22.4 km/L	20.5 km/L	6.3km/kWh
Drive Range [km]	740	1,100	1,000	191
Charge Time [min]	5	5	180	300
Market share [%]	70.4	24.7	0.8	4.1

Table 3.3 Vehicle specification for validation in 2017

The 2017 market share results show the propensity of consumers to have the utilities selected in Section 3.3.3.

The vehicle market shares in 2017 are calculated with the agent-based model. It is assumed that there are no GHG standards. Figure 3.4 compares the market share of passenger cars sold in 2017 in Korea with the calculation results of this study. According to this study results, the sales volume of HEV and BEV are higher than actual data in 2017. This is linked to the characteristics of consumers in segment 2 in the Jeon study. [60] All consumers who buy a car in 2017 have a lower preference for electric vehicles. However, consumers of Segment 2 tend to be less reluctant to use new technologies such as HEV, PHEV, and BEV. It is assumed that the preference of segment 2 will be similar to that of consumers in 2030.

The results of the sensitivity analysis for 2017 are as follows. Sensitivity is defined as the rate of change in market share.

$$S = \frac{\left(q_i - q_{i,baseline}\right)}{q_{i,baseline}}$$

i: vehicle index (ICEV, BEV)

q: market share

$q_{i,\ baseline}$: market share of vehicle *i* in 2017 without GHG standard

S: Sensitivity [%] = change rate in market share

Figure 3.5 shows that consumers in 2017 are most sensitive to price when buying BEVs. Also, consumers who buy ICEVs do not change their intention to buy even if the prices or specifications of ICEV change.

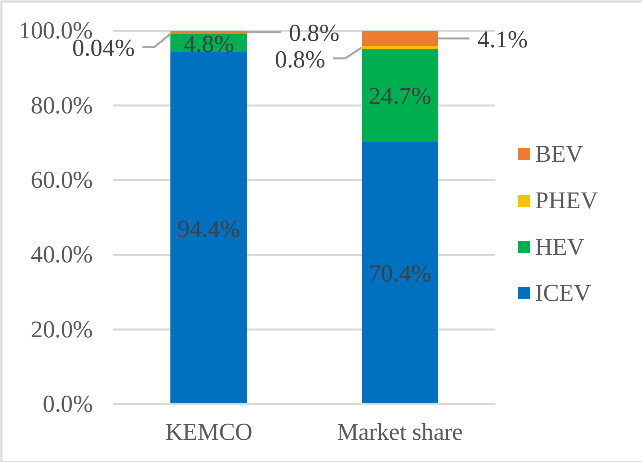

Figure 3.4 Validation of market prediction model in 2017

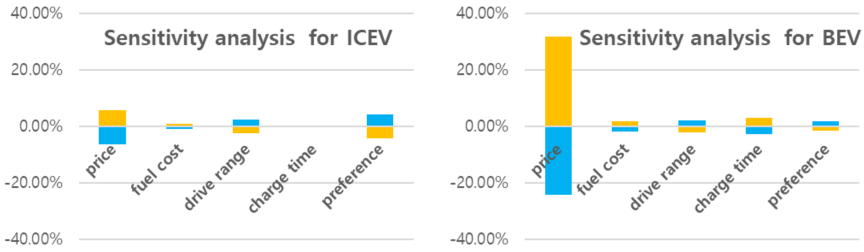

Figure 3.5 Impact on market share by ±10% change in vehicle attributes in 2017

	SI	HEV	PHEV	BEV
Manufacturing cost [10^4 ₩]	1480	1670	1940	1690
Incentive [10^4 ₩]	0	0	0	0
Fuel Economy	16.6 km/L	24.3 km/L	42.5 km/L	6.3km/kWh
Drive Range [km]	825	1,200	900	320
Charge Time [min]	5	5	90	180
TTW GHG [g-CO_2-eq./km]	138.7	94.6	13.2	0
WTW GHG [g-CO_2-eq./km]	160.9	109.9	88.4	85.0

Table 3.4 Vehicle specification for future prediction in 2030 (This study)

Validation was made for 2030 by comparing the automotive market forecasts of other research institutes with the results from this model in Figure 3.6. It is assumed that the TTW standard is applied to the vehicle market in 2030 and the detailed specifications of the vehicles are shown in Table 3.4. For the vehicle market in 2030, forecasts vary by analyst. [53, 62-65] Predicted market share ranges are from 35% to 41% for ICEVs and 14.1% to 37.5% for BEVs. The large share of electric vehicles in this study results is considered a characteristic of the compact car market. The 2030 roadmap (Korea) is also the value that was used to set the target values in Section 3.3.1. The consumer pattern predicted in this study was found that ICEV is preferred over HEV and BEV is preferred over PHEV.

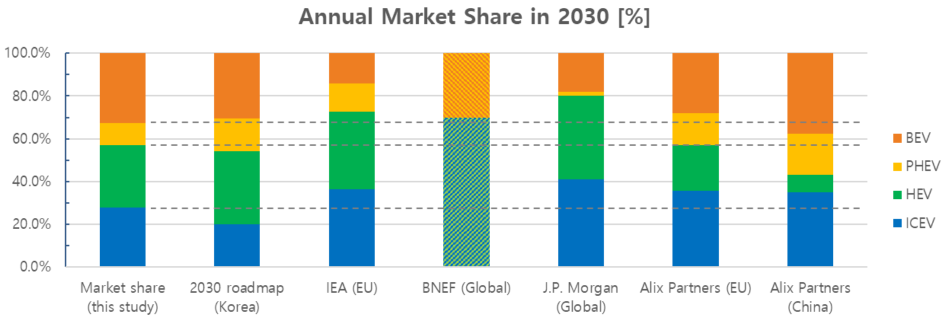

Figure 3.6 Validation of market prediction model in 2030

Figure 3.7 shows that consumers in 2030 are still most sensitive to price when buying ICEVs and BEVs. Unlike in 2017, ICEV's price sensitivity has increased significantly. This means that if the price of an ICEV rises by 10%, consumers are willing to buy another powertrain. In addition, the sensitivity trends of ICEV and BEV are similar in 2030. This means that consumers in 2030 can easily change their choices based on the attributes of the vehicle.

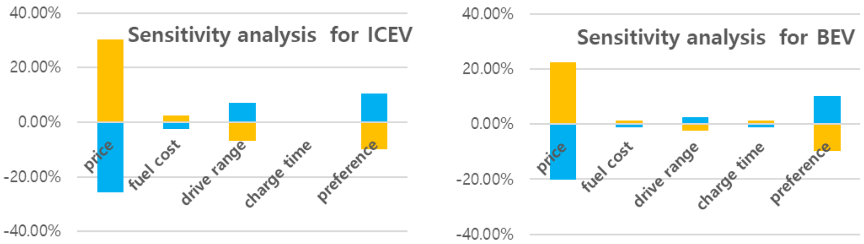

Figure 3.7 Impact on market share by ±10% change in vehicle attributes in 2030

Chapter 4. Results and Discussion

4.1. Evaluation of WTW GHG standards using the WTW results and market prediction model

4.1.1. How to read the results graphs

The research objectives of this study are to evaluate the impact of upstream GHG emissions on the vehicle market and stakeholders under the new GHG standard. In this section, the market changes caused by the upstream GHG emissions of electricity were analyzed. As mentioned in the research motivation, demand for electricity will increase as sales volume of electric vehicles increases. By scanning for the upstream emissions of electricity, which was previously treated as zero, we can continuously analyze the impact of various power generation mixes. The x-axis of the results in this chapter represents the amount of greenhouse gas emitted in the life cycle process of obtaining 1 kWh of electricity, includes resource production, power generation, transmission and distribution processes. If the power mix is 100% renewable, this value is zero. And if the power mix is 100% coal, this value becomes 1067.7 g/kWh. If the power mix is same as a 2030 mix, this value becomes 561.9 g/kWh.

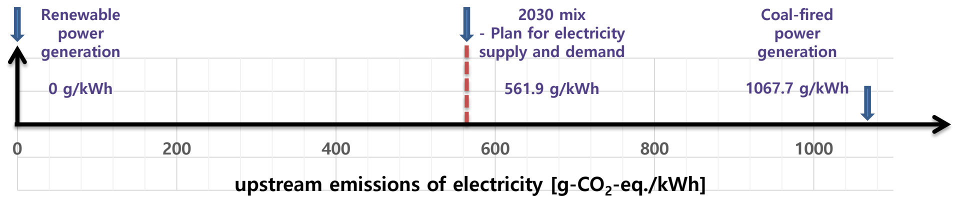

Figure 4.1 x-axis represents upstream GHG emissions of electricity

The following six parameters were selected to examine the market changes caused by the upstream change in electricity: a. GHG emissions of each vehicle

(GHG_i), b. price of each vehicle (p_i), c. market share of each vehicle (q_i), d. consumer's total cost of ownership (TCO_{avg}), e. government net income (GOV income), f. total GHG emissions (GHG_{tot})

Parametric studies were conducted on three cases of the GHG standard in the vehicle market. Assuming that there were ten manufacturers, I calculated the market share of 4 powertrains in 2030 when the number of manufacturers was ten (n=10). Table 4.1 shows the market share results in four scenarios of GHG standards. The three cases represent no GHG standard, the TTW GHG standard (current policy), and the WTW GHG standard with the same penalty rate as the TTW standard. When other vehicle specifications remain the same, the change in GHG standard affects the value of (GHG_i - GHG_{std}) in the price equation, resulting in a different market share of the vehicle.

	Penalty rate [KRW/(g/km)]	Target values [g/km]	Subject of GHG standards
No standard	0	-	-
Original standards	50,000	62.2	Tank-to-Wheel emissions
Proposed standards	50,000	109.2	Well-to-Wheel emissions

Table 4.1 Three cases of GHG standards

4.1.2. Definition of six results parameters - No standard case

First, let me explain how the six parameters are predicted when there is no greenhouse gas standard in the vehicle market in 2030. The definition of the six parameters and the calculation method will also be explained in this section.

a. GHG emissions of each vehicle (GHG_i)

The TTW GHG emissions and WTW GHG emissions of each vehicle were analyzed. Tailpipe emissions are not affected by the generation mix. In other words, regardless of whether electricity generated from coal or electricity generated from solar power is used, TTW greenhouse gas emissions from electric vehicles are zero. (Figure 4.2 - Left)

On the other hand, changes in upstream GHG will affect the WTW emissions of the vehicles. In the case of ICEVs and HEVs, some of the electricity was used as a process fuel in the fuel production process, but the resulting change in WTW emissions was less than 1%. Therefore, there is almost no difference according to the change in the power generation mix. Since PHEV and BEV use electricity as their main power source, the effect of the upstream change of electricity is large to their WTW GHG emissions. As the life cycle greenhouse gas emissions of electricity increase, the difference between ‘PHEV, BEV’ and ‘ICEV, HEV’ decreases. (Figure 4.2 - Right)

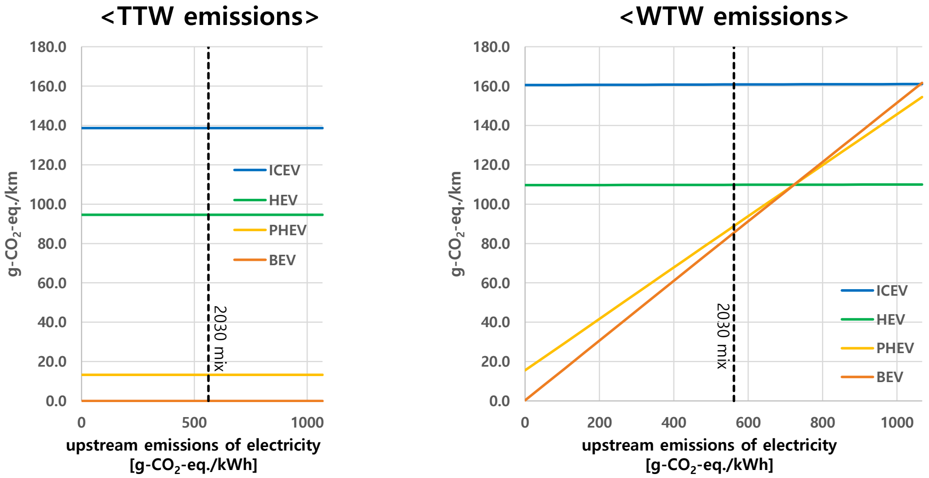

Figure 4.2 GHG emissions of each vehicle [g-CO_2-eq./km]

(Left: TTW emissions, Right: WTW emissions)

b. Price of each vehicle (p_i)

Second, changes in vehicle prices due to changes in power generation mix can be predicted through the equation obtained in Section 3.4.3. The price of the vehicle includes the regulation cost in the term of $\rho\left(G_{ij} - G_{std}\right)$. This analysis assumes a pure oligopoly market in which 10 manufacturers produce and sell vehicles of the same specification. Substituting the equation for n = 10 and price independent of j, we can obtain the below equation.

$$p_i[10^4 \text{ KRW}] = 746 + c_i + \rho(G_i - G_{std})$$

The manufacturing cost (c_i) for each powertrain and the TTW GHG or WTW GHG (G_i) are listed in Table 3.4. In the no standard case, the penalty rate is zero, so the vehicle prices do not include the regulation cost. In other words, the price of the vehicles is determined by the production cost.

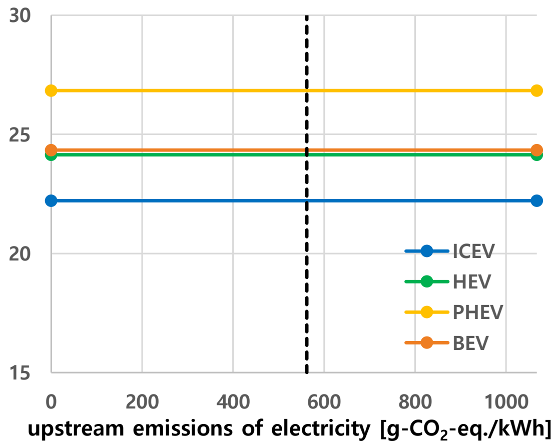

Figure 4.3 No standard – Price of each vehicle [10^6 KRW]

c. Market share of each vehicle (q_i)

Consumer decides which vehicle to buy and the decisions of many consumers are going to compose the market share. The market share is determined by the utility of the four powertrains. In this study, only the price of the vehicle affects the utility due to the upstream change in electricity. Because it assumes that all attributes other than price are fixed. Therefore, the market share can be calculated by substituting the vehicle price and the remaining vehicle specification. The market share is shaped by the probability of a consumer choice, with individual consumers choosing a vehicle to buy from four types of powertrains. This analysis assumes that there is no 'opt-out' option. 'Opt-out' means that a consumer gives up purchasing a car, or chooses a different vehicle, or a different classification, or a different price point that out of the options. If the price increases as a result of the intensity of the GHG standard, more people will choose to ‘opt-out.’

$$q_i = \frac{\exp(u_i)}{\sum_{i'=1}^{4} \exp(u_{i'})}$$

$$u_i = -0.149 \cdot p_i - \frac{0.00375 \cdot fc_i}{FE_i} + 0.115 \cdot DR_i - 0.001 \cdot CT_i + ASC_i$$

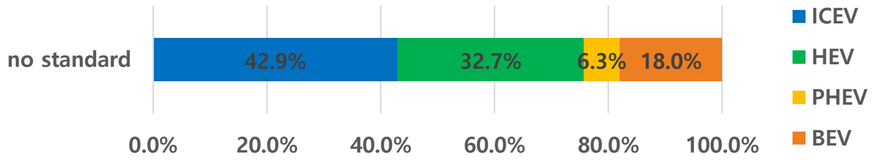

Figure 4.4 No standard - Market share of each vehicle [%]

d. Consumer's total cost of ownership (TCO_{avg})

A total cost of ownership (TCO) is an indicator of how consumers will be affected in the new regulations. The total cost of ownership of a consumer is the cost of the total lifetime of buying and using a vehicle. TCO includes the purchase price of the vehicle, total fuel cost and maintenance costs, such as repair, maintenance, insurance, battery replacement, and personal charger installation. For the cost of each category for the calculation of the average TCO, I referred the report of Brennan et al. [66] The report assumes a vehicle lifetime of 150,000 miles and in this study, it was adjusted to 150,000 km. The average TCO of consumers who bought a car in 2030 will be calculated and compared with those of other scenarios.

Cost [10^6 KRW]	ICEV	HEV	PHEV	BEV
Maintenance cost	10.8	10.8	13.1	16.7
Vehicle purchase cost	Calculated in this study			
Fuel cost [67]	Gasoline: 1500 KRW/L Electricity: 313 KRW/kWh			

Table 4.2 Cost categories of the total cost of ownership [66]

e. Government net income (GOV net income)

Government net income (GOV income) is an indicator of how the government will be affected by the new standards. The government can make income from fuel taxes and GHG penalties for the vehicle market, and spend money on installing electric charging stations, represented in Table 4. GOV income included all costs incurred over a 15,000 km traveled by 500,000 vehicles sold in 2030.

Fuel tax [67]	
gasoline	Electricity
700 KRW/L	90 KRW/kWh
Installation of charging infrastructure	
2.39 [10^6 KRW per 1 EV unit]	
GHG penalty	
Calculated in this study	

Table 4.3 Cost categories of GOV net income

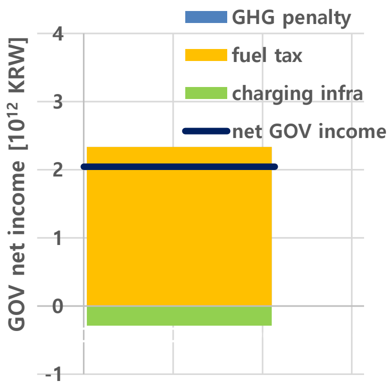

Figure 4.5 No standard – GOV net income [10^{12} KRW]

f. Total GHG emissions (GHG_{tot})

Finally, total GHG emissions are the sum of the WTW GHGs emitted over the lifetime of vehicles sold in 2030. In other words, total GHG is the sum of both tailpipe emissions from vehicle sales and upstream emissions from the production of fuel for the vehicle. How the total GHGs caused by vehicle GHG standards are changing will be evaluated in the following Section 4.2.

$$\text{total GHG} = \sum_{i=1}^{4} (\text{GHG}_i \cdot q_i) \cdot \text{VKT} \cdot Q$$

4.2. Comparison of the effect of original standard (TTW standard) and proposed standard (WTW standard)

In this section, six results parameters of the original standard and the proposed standard were compared.

a. GHG emissions of each vehicle (GHG_i)

All the different results between the original standard and the proposed standard are derived from here. The effect of the upstream emissions of electricity depends on whether the government regulates TTW emissions or WTW emissions of the vehicles. Changes in the upstream emissions of electricity do not affect tailpipe emissions. Therefore, in the original standard, manufacturers should pay penalty for ICEVs and HEVs, could sell carbon credits for PHEVs and BEVs regardless of the power mix. On the other hand, in the proposed standards, as the upstream emissions increase, PHEVs and BEVs shifts from the credit region to the penalty region.

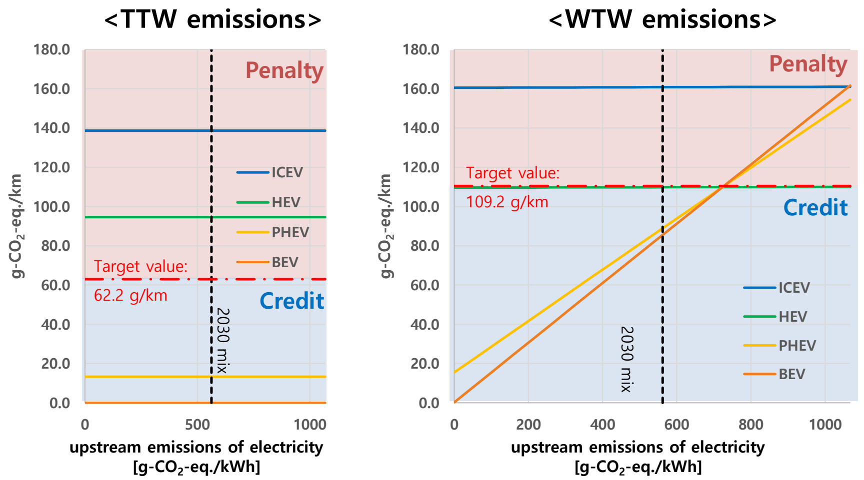

Figure 4.6 Penalty region and credit region due to the GHG standard

b. Price of each vehicle (p_i)

Comparing with the no GHG standard case, the change in results comes from the regulation cost. The penalty rate of the original standard is 50,000 KRW/(g/km) and the target value G_{std} is 62.2 g-CO_2-eq./km. Therefore, the price of ICEV and HEV, which has a higher TTW GHG than the target value, rises, and the price of PHEV and BEV, which has a lower TTW GHG, decreases. Unlike the original standard, the target value G_{std} is 106.2 g-CO_2-eq./km and the GHG emissions of each vehicle G_i are not fixed value. The WTW GHG emissions of PHEVs and BEVs change with the upstream of electricity, which is different from the WTW standard target value, which is reflected in the vehicle price due to regulation penalty or carbon credit. Therefore, the trend of the vehicle price graph is similar to the trend of the WTW GHG graph in the proposed standard.

$$p_i\ [10^4\ \mathrm{KRW}] = 746 + c_i + \rho(G_i - G_{std})$$

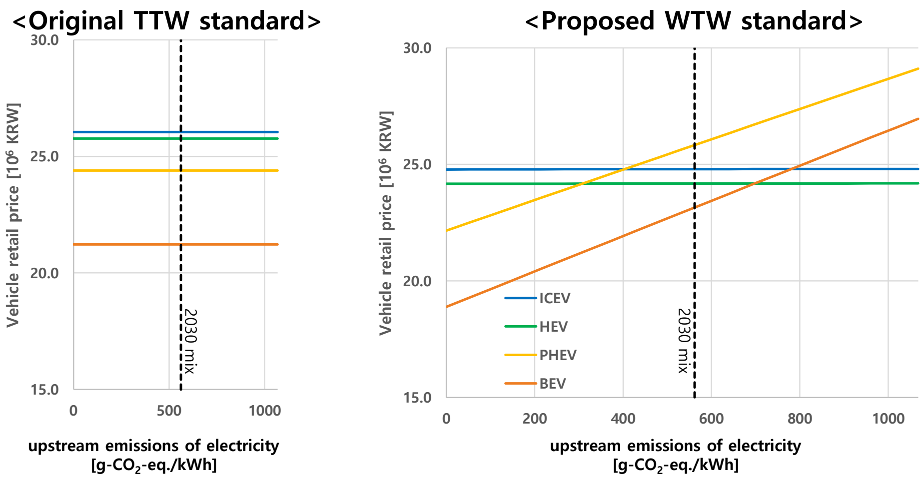

Figure 4.7 Retail prices of each vehicle [10^6 KRW]

c. Market share of each vehicle (q_i)

The changes in the vehicle price derive the changes in the market share. The market share is calculated by the probability of consumer choice, which depends on the vehicle price when the other factors remain the same. In the original standard, which regulates vehicle tailpipe emissions, PHEVs and BEVs occupy a large market share, and ICEVs and HEVs occupy a low market share.

Changes in vehicle prices due to upstream GHG emissions from electricity result in changes in market share. In the proposed standard, the market share varies according to the change of upstream GHG. Increasing prices of PHEVs and BEVs, driven by increased upstream GHGs, will lead to a decline in the market share of PHEVs and BEVs. As a result, the market share of ICEVs and HEVs increased. In particular, the market share of HEV is increasing rapidly, which indicates that consumers who have been thinking about purchasing PHEV and BEV are moving toward HEV due to the low price.

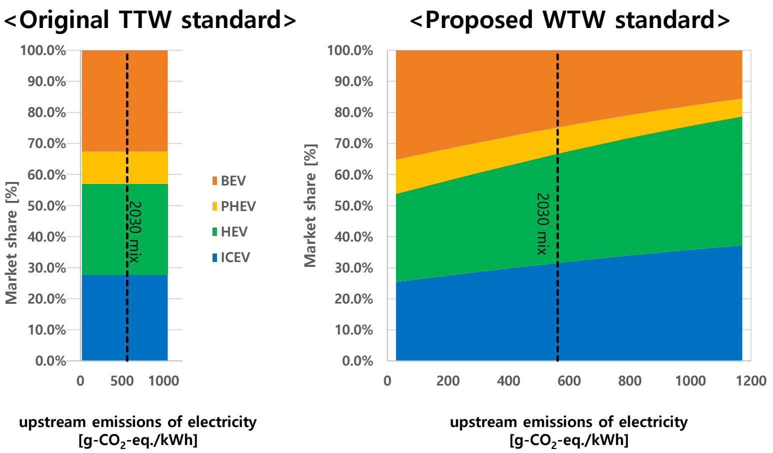

Figure 4.8 Market share of each vehicle [%]

d. Consumer's total cost of ownership (TCO_{avg})

The total cost of ownership is an indicator of how the consumer will be affected by the new standards. TCO_{avg} represents the average value of the total cost of ownership of all the consumers. As the upstream emission of electricity increases, the market share of BEVs and PHEVs decreases. As a result, the averaged vehicle purchase price and fuel cost increase, and the averaged maintenance cost decrease.

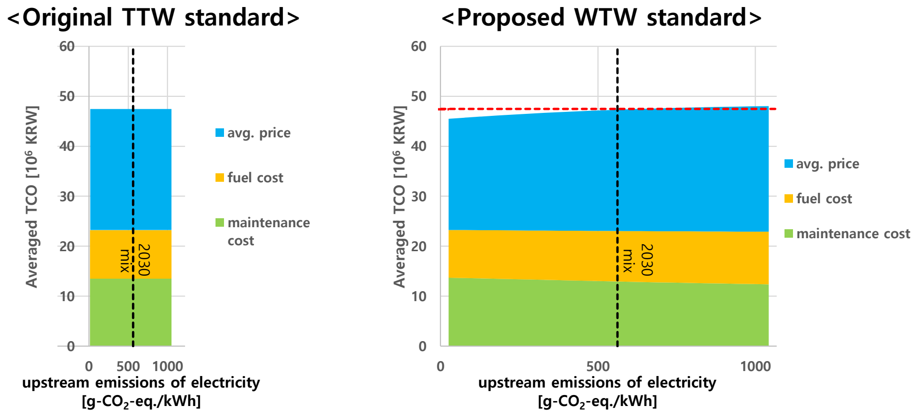

Figure 4.9 Averaged total cost of ownership [10^6 KRW per VKT]

(VKT = 150,000 km traveled)

e. Government net income (GOV net income)

Government net income is an indicator of how the government will be affected by the new standards. The government can make income from fuel taxes and GHG penalties for the vehicle market, and spend money on installing electric charging stations. GOV income included all costs incurred over a 15,000 km traveled by 500,000 vehicles sold in 2030. The cost for the charging infra is negative, so the thick line represents the net value. As the upstream emission of electricity increases, the market share of BEVs and PHEVs decreases. As a result, the fuel tax income and GHG penalty income increase, and the charging infrastructure installation cost decrease.

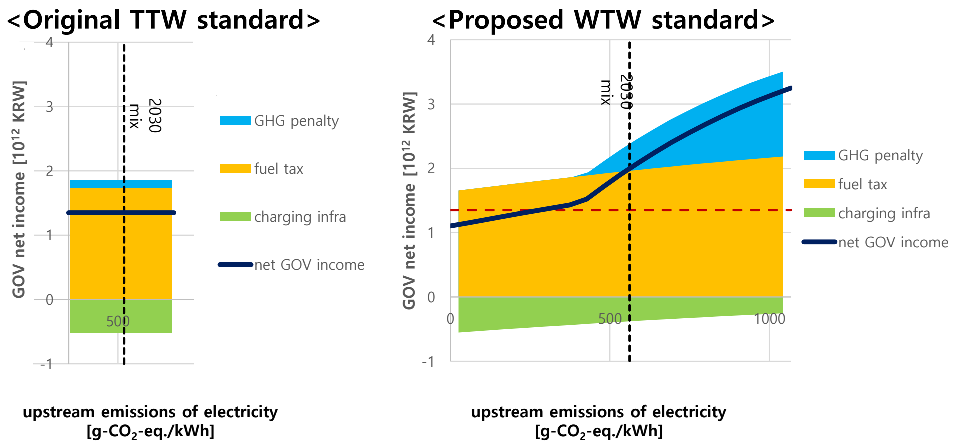

Figure 4.10 Government net income [10^{12} KRW per year]

f. Total GHG emissions (GHG_{tot})

Total GHG emissions are the sum of the WTW GHGs emitted over the lifetime of vehicles sold in 2030. In other words, total GHG is the sum of both tailpipe emissions from vehicle sales and upstream emissions from the production of fuel for the vehicle. In the formula below, VKT is 15000 km, Q is 500,000 units, and GHG_i is WTW emissions. When the life cycle GHG emissions of electricity change, only GHG_i changes under no standard and original standards, while GHG_i and q_i change under proposed standards.

$$\text{total GHG} = \sum_{i=1}^{4} (\text{GHG}_i \cdot q_i) \cdot \text{VKT} \cdot \text{Q} \tag{4.1}$$

Unlike the no standard case and the original standard case, the total GHG emissions in the proposed standards were curved shares. This means that if the upstream GHG emissions of the electricity decrease, the share of the electric vehicle will increase, thereby amplifying the GHG reduction effect. Likewise, increasing the greenhouse gas emissions of the life cycle of electricity has the effect of offsetting the increase in greenhouse gas emissions by reducing the share of electric vehicles. I also compared TCO and GOV net income of 3 cases to show how GHG standards affect consumers and government. Changes in TCO and GOV income were calculated on a 2030 power mix.

The average vehicle price is low because there is no regulation cost in the No standard. In addition, since there is no GHG credit given to EVs, market share is low due to the lack of incentives to attract consumers. The government has no income from the GHG penalty, but fuel tax is high and the expenditure of the installation of the charging station is low. In the original standard, TCO increased due to a rise in average price, and GOV income decreased as EV market share increased. In the proposed standard, the average price and fuel cost increase and maintenance costs decrease, resulting in a reduction in overall TCO. In addition, as the PHEV and BEV share decreases, resulting in increased GOV income.

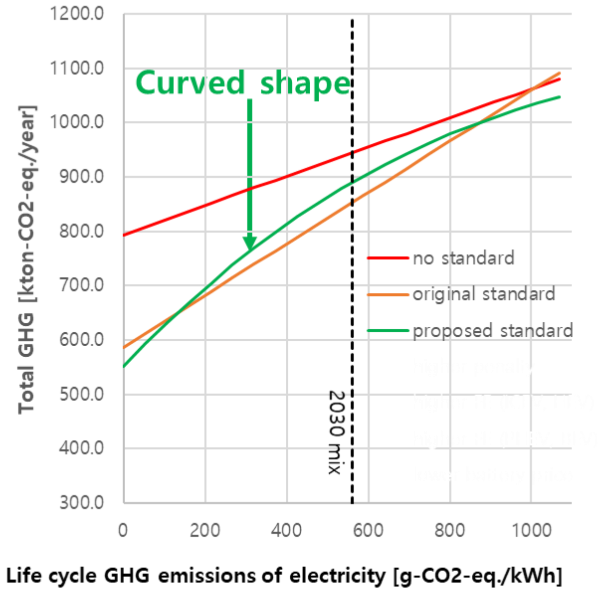

Figure 4.11 Total GHG emissions [kton-CO_2-eq./year]

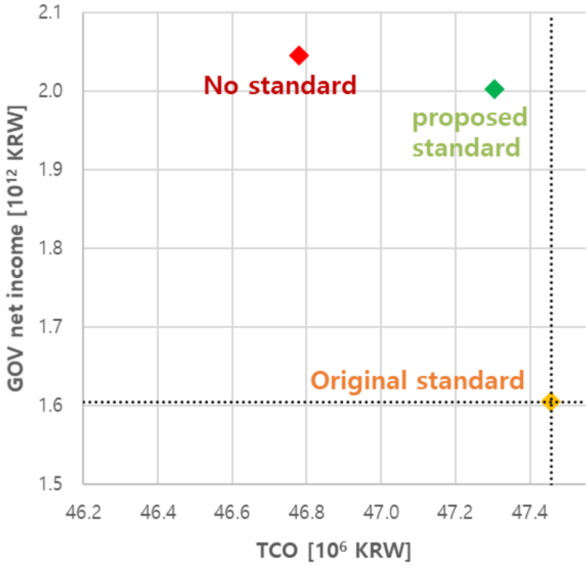

Figure 4.12 Impact of GHG standards on consumers and governments

4.3. How to reduce the total GHG emissions in 2030, with proposed standards

When the generation mix will be the same as Korea's development plan for 2030, the total GHG emissions of the proposed standard will be greater than that of the original standard. In this section, four scenarios are proposed to solve the problem of increasing greenhouse gas emissions under the proposed standard. The four methods are as follows.

a. Higher penalty rate

b-1. Higher technology level: Higher Fuel economy of ICEV and HEV

b-2. Higher technology level: Higher Fuel economy of PHEV and BEV

c. Lower manufacturing cost: battery cost reduction

In addition, this study evaluated the impacts of consumers and governments on four scenarios. The impact of each agent on GHG standards is expressed in terms of TCO and GOV income.

a. Higher penalty rate

In this scenario, the government adjusted the penalty rate to obtain the same amount of WTW GHG emissions as the TTW standard. The penalty rate should have been increased by 1.74 times compared to that of the TTW standard. With the higher penalty rate, the price gap between ICEV and BEV, which had been reduced under WTW standards, will widen again.

b. Higher technology level

During the WTW processes for every powertrain vehicles, the highest portion of the greenhouse gas emissions is emitted during the conversion of fuel chemical energy into mechanical energy or electrical energy through the combustion of fuel. This corresponds to the vehicle operation phase for ICEVs and HEVs with internal combustion engine operation and the fuel production phase for PHEVs and BEVs with fossil-fueled power plant operation. In the equation below, the price of the vehicle reflects the difference between the GHG emissions of each vehicle and the standard target value. This difference affects consumer choice and market share.

$$p_{ij} = -\frac{n}{n-1}\frac{1}{\beta_1} + c_{ij} + \rho\left(G_{ij} - G_{std}\right)$$

When the difference between $\left(G_{ij} - G_{std}\right)$ is positive, which means when the vehicle emits more greenhouse gas than the standard target, the penalty is reflected in the price, resulting in an increase in the vehicle price. Likewise, if the difference of $\left(G_{ij} - G_{std}\right)$ is negative, the vehicle price is decreased by the gain from selling carbon credit. Another characteristic is the difference between the $\left(G_{ij} - G_{std}\right)$ values from the TTW and WTW standards. $\left(G_{ij} - G_{std}\right)$ of ICEV and HEV increases from TTW standards to WTW standards, but $\left(G_{ij} - G_{std}\right)$ of PHEV and BEV decreases from TTW standards to WTW standards. Thus, the impact of increased fuel economy can be expected to be greater in ICEV and HEV vehicles under the proposed standards.

c. Lower manufacturing cost – battery cost

The battery price is one of the most important parameters when predicting the future of electric vehicles. Two main factors hinder the diffusion of electric vehicles: the high price and the charging problem. The figure below shows the estimated battery pack cost for various technical reports and automaker statements. The value used for analysis in this study is the value corresponding to BEV 200 extracted from ANL's Autonomie report. This value is more costly per unit of energy than other forecasts. The battery price affects the unit price of the car that makes up part of the selling price of the vehicle. In order to examine how the battery cost affects the market share and the total greenhouse gas emission, it is assumed that the battery price is lowered to $ 100 per kWh.

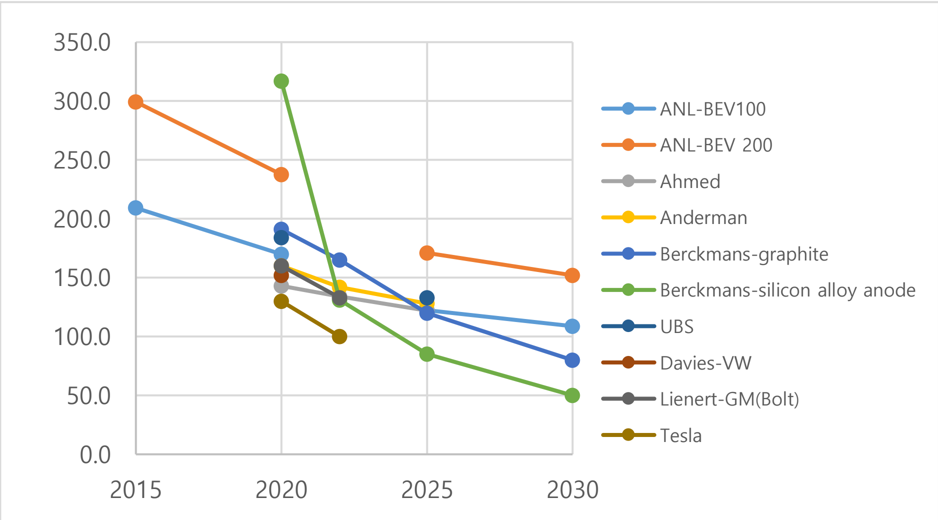

Figure 4.13 Battery pack cost [$/kWh]

The change in total GHG emissions, TCO and GOV income according to the four scenarios is shown in the figure below.

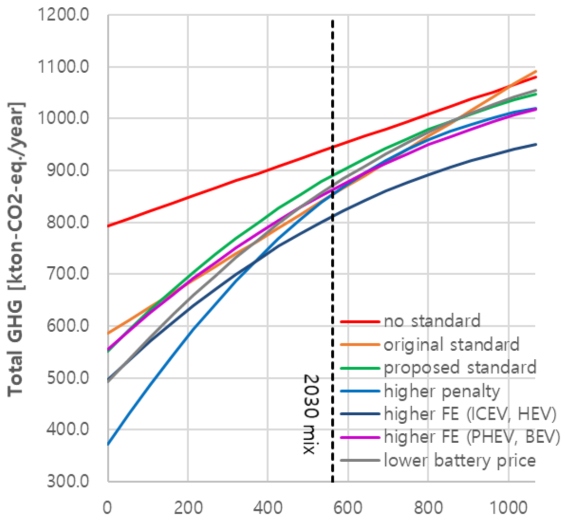

Figure 4.14 Total GHG emissions of 7 scenarios [kton-CO_2-eq./year]

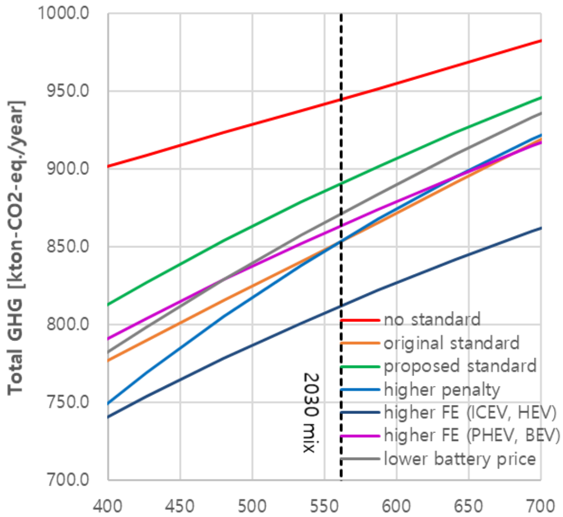

Figure 4.15 Total GHG emissions of 7 scenarios (zoom in) [kton-CO_2-eq./year]

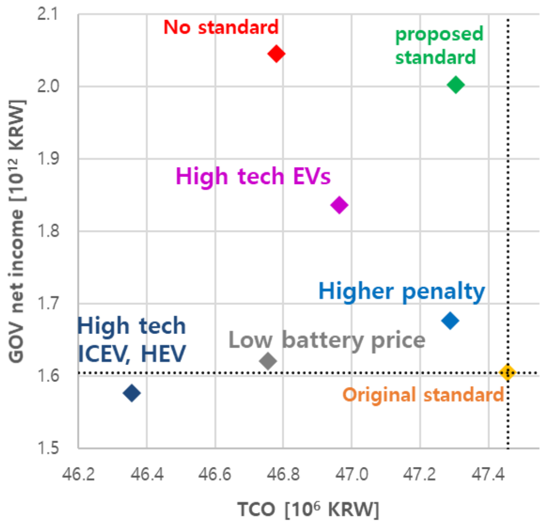

Figure 4.16 Impact of GHG standards on consumers and governments of 7 scenarios

Chapter 5. Conclusion

It is clear that the share of electric vehicles in the automobile market will gradually increase in the future. According to the present vehicle GHG emissions standards, the GHG emissions of electric vehicles are treated as zero. However, how about the upstream emissions of electricity? Upstream emissions of electricity are determined by the type of power source. Existing greenhouse gas standards do not reflect this difference in upstream emissions of electricity and other automotive fuels. These issues have been raised continuously. Recently, the Well-to-wheel concept has been applied to the new fuel economy standards in Japan, and the European Union is also considering introducing WTW CO_2 standards.

This study attempted to answer the following questions: How the GHG emitted during the upstream process affects the vehicle market based on the WTW standards. To obtain the answer, the following analysis was performed. First, I obtain the WTW results of automotive fuels in Korea in the present and the future. Second, I set the target value and penalty rate for 2030 GHG standards and the future prediction model is developed with the agent-based modeling approach. Third, based on the WTW results, the new GHG standards, and the vehicle market forecast model, I predicted how the vehicle market would change under the new GHG standards in various scenarios. As a result, the vehicle market applying the WTW standards has the following characteristics.

First, the vehicle market is directly affected by the upstream emissions of the fuel. The original standard regulates the vehicle's Tank-to-Wheel GHG emissions and the proposed standard regulates the vehicle's Well-to-Wheel GHG emissions. Thus, when the GHG emissions of the electricity production process change, the proposed standard is affected, but the original standard is not. In this study, the regulation cost is determined by the difference between the vehicle's GHG emissions and the GHG target value. The regulation cost is included in the vehicle retail price, which means that the price of the vehicle may change in the proposed standard. As a result, changes in market share due to changes in upstream emissions helped to reduce or offset the increase in total GHG emissions. Sales of PHEV and BEV declined as upstream GHG increased, while sales of PHEV and BEV increased as upstream GHG decreased. In this study, the vehicle market responded flexibly to changes in upstream emission under proposed standards.

Second, when the generation mix will be the same as Korea's development plan for 2030, the total GHG emissions of the proposed standard will be higher than that of the original standard. This is because the gap between ICEV and BEV is reduced when regulating WTW emissions of vehicles rather than regulating TTW emissions. As a result, the sales volume of ICEV and HEV increased and sales volume of PHEV and BEV decreased in the proposed standard. In this study, four scenarios are proposed to solve the problem of increasing greenhouse gas emissions under the proposed standard. The four methods are to increase the penalty rate, improve engine efficiency, improve the ratio of PHEV and BEV, and reduce battery price. In addition, this study evaluated the impacts of consumers and governments on four scenarios. The impact of each agent on GHG standards is expressed in terms of TCO and GOV income.

The results of this study have the limitation that the total GHG emissions under the WTW standard are higher than those under the TTW standard at the power generation mix level in Korea in 2030. This result raises the concern that the WTW standard is less effective than the TTW standard to reduce GHG emissions. To solve this concern, this study suggests the development of vehicle technology, reduction of battery price, and increase of penalty rate. However, there are two problems: 1. The difficulty of direct intervention through the policy, 2. GHG reduction effect is greater in TTW regulation with the new technology. Therefore, there is a need to make meaningful suggestions for the phenomenon that seems to increase GHG emissions due to the proposed standard.

The first suggestion is for a power generation mix level where the total GHG emissions under the WTW standard are lower than those under the TTW standard. It was explained that total greenhouse gas emissions have a curved shape due to changes in the power generation mix in the WTW standard. Due to the curved shape, we could find that the total GHG emissions of the TTW standard and the WTW standard are intersecting at the upstream emissions of electricity of 110 g/kWh and 850 g/kWh. Among them, 110 g/kWh, which is lower than the GHG emissions of the 2030 mix, could be proposed as a meaningful power generation mix. The upstream emissions of electricity are about 180 g/kWh in the EU 2030 mix. The Korean government has a goal to gradually increase the amount of renewable energy generation. Therefore, if WTW standard is introduced at the time when the power mix emits GHG emissions lower than 110 g/kWh, the GHG standard for the vehicle will effectively reduce the GHG emissions of the road transportation sector.

The second suggestion is for a power generation mix when the slope of the total GHG emissions under the WTW standard becomes equal to the slope of those under the TTW standard. The slope of the total GHG emissions represents the effect of the GHG emissions reduction on the power generation stage on the GHG emissions reduction in the road transport sector. Under the TTW standard, the graph of the total GHG emissions is the linear line. Under the WTW standard, the reduction of GHG emissions from the power generation stage has a combination of two effects: 1. reduction of GHG emissions from electric vehicles and 2. increase in sales of electric vehicles. As a result, the reduction of greenhouse gases at the power generation stage has the effect of increasing the slope of the total GHG emissions graph. At the point where the GHG emissions are about 450 g/kWh, the slope of GHG emissions under the WTW standard is equal to the slope of those under the TTW standard. This point means that the sensitivity of the total GHG emission reduction as the power generation mix changes is the same. Therefore, if the upstream GHG emissions of electricity are less than 450 g/kWh, the reduced amount of total GHG emissions is greater in the WTW standard with the same power mix change.

Bibliography

1. IEA, Energy and climate change, world energy outlook special report. 2015, OECD, IEA, Paris, France.

2. ICCT, *Global comparison of light-duty vehicle fuel Economy/GHG emissions standards*. 2013, Tech. rep., International Council on Clean Transportation.

3. U.S. EPA, *Renewable Fuel Standard Program: Standards for 2019 and Biomass Based Diesel Volume for 2020.* Federal Register, 2018. **83**(132): p. 32024-32060.

4. CARB, *Proposed RESO 15-36 Low Carbon Fuel Standard*. 2015, California Air Resources Board Sacramento, CA.

5. CARB, *Low Carbon Fuel Standard Workshop*. 2019; Available from: https://ww3.arb.ca.gov/fuels/lcfs/lcfs_meetings/040519handout.pdf.

6. The Council of the European Union, *COUNCIL DIRECTIVE (EU) 2015/652 of 20 April 2015.* Official Journal of the European Union, 2015.

7. NHTSA, *The Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule for Model Year 2021–2026 Passenger Cars and Light Trucks: Draft Environmental Impact Statement. Docket*. 2018, NHTSA-2017-0069, US Department of Transportation, 500 pp.

8. METI. *Long-Term Goal and Strategy of Japan's Automotive Industry for Tackling Global Climate Change*. 2018; Available from: https://www.meti.go.jp/english/press/2018/pdf/0831_003a.pdf.

9. Xie, F. and Z. Lin, *Market-driven automotive industry compliance with fuel economy and greenhouse gas standards: Analysis based on consumer choice.* Energy Policy, 2017. **108**: p. 299-311.

10. Ministry of Environment, K., *CLEAN AIR CONSERVATION ACT (대기환경보전법), Article 76-5*, R.o.K. Ministry of Environment, Editor. 2017.

11. U.S. EPA, *2017 and later model year light-duty vehicle greenhouse gas emissions and corporate average fuel economy standards; final rule.* Fed Reg, 2012. **77**(199): p. 62624-63200.

12. European Comission DG Environment News Alesrt Service, *Science for environment policy: GHG policy should cover 'upstream' electric vehicle emissions.* Science for Environment Policy, 2012(292).

13. CARB, *California and major automakers reach groundbreaking framework agreement on clean emission standards*, S. Young, Editor. 2019.

14. ICCT, *JAPAN 2030 FUEL ECONOMY STANDARDS.* POLICY, 2019.

15. Hahn, J.-s., *The Effects of Green Vehicle Incentives on Greenhouse Gas Reduction.* 2015.

16. MOLIT, *Total Registered Moter Vehicles*, Ministry of Land, Infrastructure and Transport, Republic of Korea, Editor. 2018.

17. ANL, *GREET1 (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) Transportation Fuel Cycle Analysis Model Version 2012 rev2*. 2012.

18. $(S\&T)^2$ Consultants, Inc., *GHGenius 4.03.* 2013.

19. Edwards, R., et al., *Well-to-wheels analysis of future automotive fuels and powertrains in the European context*, in *Well-to-tank report version 4.0*. 2013, Joint Research Centre of the European Commission.

20. $(S\&T)^2$ Consultants, Inc., *TRANSPORTATION FUEL LIFE CYCLE ASSESSMENT: VALIDATION AND UNCERTAINTY OF WELL-TO-WHEEL GHG ESTIMATES*, in *CRC Report No. E-102*. 2013, COORDINATING RESEARCH COUNCIL, INC.: Alpharetta, GA: Coordinating Research Council.

21. Wang, M., *Fuel choices for fuel-cell vehicles: well-to-wheels energy and emission impacts.* Journal of Power Sources, 2002. **112**(1): p. 307-321.

22. Ramsden, T., et al., *Hydrogen pathways: Updated cost, well-to-wheels energy use, and emissions for the current technology status of ten hydrogen production, delivery, and distribution scenarios*. 2013, National Renewable Energy Laboratory (NREL), Golden, CO.

23. Pereira, S.R. and M.C. Coelho, *Life cycle analysis of hydrogen–a well-to-wheels analysis for Portugal.* International Journal of Hydrogen Energy, 2013. **38**(5): p. 2029-2038.

24. Larsson, M., et al., *Energy system analysis of the implications of hydrogen fuel cell vehicles in the Swedish road transport system.* International journal of hydrogen energy, 2015. **40**(35): p. 11722-11729.

25. Bicer, Y. and I. Dincer, *Comparative life cycle assessment of hydrogen, methanol and electric vehicles from well to wheel.* International Journal of Hydrogen Energy, 2017. **42**(6): p. 3767-3777.

26. IPCC, *2006 IPCC guidelines for national greenhouse gas inventories*. 2006.

27. U.S. EPA, *Compilation of air pollutant emission factors*. 1995.

28. Solomon, S., *Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC*. Vol. 4. 2007: Cambridge University Press.

29. Yoo, E., M. Kim, and H.H. Song, *Well-to-wheel analysis of hydrogen fuel-cell electric vehicle in Korea.* International Journal of Hydrogen Energy, 2018. **43**(41): p. 19267-19278.

30. Briefing, U.S., *International energy outlook 2013.* US Energy Information Administration, 2013.

31. U.S. NOAA National Geophysical Data Center Global Gas Flaring Country Data. National Oceanic and Atmospheric Administration.; 2012

32. Jang, J.J. and H.H. Song, *Well-to-wheel analysis on greenhouse gas emission and energy use with petroleum-based fuels in Korea: gasoline and diesel.* The International Journal of Life Cycle Assessment, 2015. **20**(8): p. 1102-1116.

33. Burnham, A., et al., *Life-cycle greenhouse gas emissions of shale gas, natural gas, coal, and petroleum.* Environmental science & technology, 2011. **46**(2): p. 619-627.

34. Choi, W. and H.H. Song, *Well-to-wheel analysis on greenhouse gas emission and energy use with natural gas in Korea.* International Journal of Life Cycle Assessment, 2014. **19**(4): p. 850-860.

35. Larney, C., M. Heil, and G.-A. Ha, *Case Studies from the Climate Technology Partnership: Landfill Gas Projects in South Korea and Lessons Learned*. 2006, National Renewable Energy Laboratory (NREL), Golden, CO.

36. Mintz, M., et al., *Well-to-Wheels analysis of landfill gas-based pathways and their addition to the GREET model*. 2010, Argonne National Laboratory (ANL).

37. KEPCO, *Statistics of electric power in Korea (2017)*. 2018.

38. Choi, W. and Song, H.H., 2018. *Well-to-wheel greenhouse gas emissions of battery electric vehicles in countries dependent on the import of fuels through maritime transportation: A South Korean case study.* Applied energy, 230, pp.135-147.

39. MOTIE, Republic of Korea, *NEW & RENEWABLE ENERGY WHITE PAPER*. 2016.

40. Kim, M., E. Yoo, and H.H. Song, *Well-to-Wheel greenhouse gas emissions analysis of hydrogen fuel cell vehicle - Hydrogen produced by naphtha cracking.* The Korean Society of Automotive Engineers, 2017. **25**(2): p. 158.

41. McDowall, W. and M. Eames, *Forecasts, scenarios, visions, backcasts and roadmaps to the hydrogen economy: A review of the hydrogen futures literature.* Energy Policy, 2006. **34**(11): p. 1236-1250.

42. KEA, *2016 Vehicle Fuel Economy and CO2 emissions : Data and Analyses*. 2016.

43. Won Jae Choi, Eunji Yoo, Jae Jun Jang, Eunsu Seol, Myoungsoo Kim, Han Ho Song. *Well-to-Wheel Greenhouse Gas Emissions of Current (2017) and Future (2030) Passenger Vehicle Pathways : A South Korean Case Study*. in *Applied Energy Symposium: MIT A+B (AEAB2019)*. 2019. MIT, Boston, USA.

44. Moawad, A., et al., *Assessment of vehicle sizing, energy consumption and cost through large scale simulation of advanced vehicle technologies*. 2016, Argonne National Lab.(ANL), Argonne, IL (United States).

45. MOTIE, *The 8th Basic Plan for Long-term Electricity Supply and Demand (2017 - 2031)*, Minister of Trade, Industry and Energy, Republic of Korea, Editor. 2017.

46. Islam, E., et al., *An Extensive Study on Sizing, Energy Consumption, and Cost of Advanced Vehicle Technologies*. 2018, Argonne National Lab.(ANL), Argonne, IL (United States).

47. Van Dam, K.H., I. Nikolic, and Z. Lukszo, *Agent-based modelling of socio-technical systems*. Vol. 9. 2012: Springer Science & Business Media.

48. Sen, B., M. Noori, and O. Tatari, *Will Corporate Average Fuel Economy (CAFE) Standard help? Modeling CAFE's impact on market share of electric vehicles.* Energy Policy, 2017. **109**: p. 279-287.

49. Krause, T., et al., *A comparison of Nash equilibria analysis and agent-based modelling for power markets.* International Journal of Electrical Power & Energy Systems, 2006. **28**(9): p. 599-607.

50. Jehle, G.A., *Advanced microeconomic theory*. 2001: Pearson Education India.

51. Michalek, J.J., P.Y. Papalambros, and S.J. Skerlos, *A study of fuel efficiency and emission policy impact on optimal vehicle design decisions.* J. Mech. Des., 2004. **126**(6): p. 1062-1070.

52. Shiau, C.-S.N., J.J. Michalek, and C.T. Hendrickson, *A structural analysis of vehicle design responses to Corporate Average Fuel Economy policy.* Transportation Research Part A: Policy and Practice, 2009. **43**(9-10): p. 814-828.

53. Korea Environmental Corporation, *Establishment of an alternative vehicle supply roadmap in 2030 (not open to the public)*. 2018.

54. Islam, E., et al., *An Extensive Study on Sizing, Energy Consumption, and Cost of Advanced Vehicle Technologies*. 2017, Argonne National Lab.(ANL), Argonne, IL (United States).

55. Ben-Akiva, M.E., S.R. Lerman, and S.R. Lerman, *Discrete choice analysis: theory and application to travel demand*. Vol. 9. 1985: MIT press.

56. Sierzchula, W., et al., *The influence of financial incentives and other socio-economic factors on electric vehicle adoption.* Energy Policy, 2014. **68**: p. 183-194.

57. Kwon, Y., S. Son, and K. Jang, *Evaluation of incentive policies for electric vehicles: An experimental study on Jeju Island.* Transportation Research Part A: Policy and Practice, 2018. **116**: p. 404-412.

58. Tanaka, M., et al., *Consumers' willingness to pay for alternative fuel vehicles: A comparative discrete choice analysis between the US and Japan.* Transportation Research Part A: Policy and Practice, 2014. **70**: p. 194-209.

59. Hidrue, M.K., et al., *Willingness to pay for electric vehicles and their attributes.* Resource and energy economics, 2011. **33**(3): p. 686-705.

60. Jeon, H., *Analysis of Spatial Heterogeneity of Local Pollutants and Greenhouse Gas Emissions from the Electric Vehicles.* 2017. **2017**: p. 1-140.

61. Michalek, J.J., P.Y. Papalambros, and S.J. Skerlos, *A study of fuel efficiency and emission policy impact on optimal vehicle design decisions.* Transactions of the ASME-R-Journal of Mechanical Design, 2004. **126**(6): p. 1062-1070.

62. AlixPartners, *Betting Big in Electrification and Autonomous AlixPartners Global Automotive Outlook 2018 – EMEA Release*. 2018.

63. IEA, *Global EV outlook 2019.* International Energy Agency, France, 2019.

64. Morgan, J. *Driving into 2025: The Future of Electric Vehicles*. 2018; Available from: https://www.jpmorgan.com/global/research/electric-vehicles.

65. McKerracher, C., *Electric Vehicle Outlook 2019.* Bloomberg New Energy Finance, https://about.bnef.com/electric-vehicle-outlook/, 2019.

66. Brennan, J.W. and T.E. Barder, *Battery Electric Vehicles vs. Internal Combustion Engine Vehicles.* A United States-Based Comprehensive Assessment.

67. Kim, J., Study of the directions for the reform of the energy tax system in the transportation sector, KEEI, 2017.

국문 초록

전세계적으로 지구 온난화 문제를 야기하는 온실가스 배출을 줄이기 위한 다양한 규제가 시행되고 있다. 그 중에서도 도로 수송 분야에서는 연비 규제나 온실가스 규제를 통해 온실가스 배출량을 감축시키고자 한다. 이러한 규제의 특징은 전기 주행 모드의 자동차에 대해 배기구에서 발생하는 온실가스 배출량을 0 으로 산정하며, 이에 더불어 추가적인 인센티브를 부여한다는 점이다. 그런데 전기자동차가 차량 주행 시 온실가스를 배출하지 않지만, 차량 주행을 위해 필요한 전기를 얻기 위한 과정에서 온실가스가 발생한다. 그리고 이러한 상류 과정의 온실가스를 무시한 채 전기 주행 모드의 온실가스 배출량을 0 으로 산정하는 것에 대해 여러 논의가 이루어지고 있다.

특히 최근 들어 이러한 논의는 더욱 구체화되고 있다. 특히 일본의 새로운 연비 규제에서 연료 생산 단계의 효율을 이용하여 보정한 자동차 연비를 사용할 것이라고 발표하였다. 이에 따라 우리나라에서도 연비 규제와 온실가스 규제에 전과정 분석 결과를 적용하는 것에 대해 그 영향을 예측하고 평가할 필요가 있다.

이처럼 연료의 생산 과정, 특히 전기의 상류 과정에 대한 고려의 필요성이 이슈화되는 것에는 크게 두 가지 이유가 있다. 첫 째는 미래에 전기자동차의 수요가 증가함에 따라 전기의 수요가 증가할 것이기 때문이다. 둘 째는 전기 생산 과정의 온실가스 배출량은 발전원의 종류에 따라 달라지기 때문이다.

이러한 상황에서 전과정 분석은 다양한 연료와 자동차의 친환경성을 정량적으로 평가하기 위한 도구로 사용될 수 있다. Well-to-wheel

(WTW) 분석은 자동차 연료의 생애 전과정 분석을 의미하며, 원유 산지(Well)부터 자동차 주행 과정 (Wheel)에 이르기까지 전체 과정을 나타낸다. 전기차의 전과정에는 자동차 주행 과정과 발전 과정, 그리고 발전 원료의 생산 과정이 포함되어 있으며, 공정한 비교를 위하여 내연기관 자동차도 전기차와 마찬가지로 휘발유, 디젤 등의 연료 생산에 관한 모든 과정이 포함된다.

본 연구에서는 자동차 연료의 전과정 온실가스 배출량 값을 바탕으로 규제하는 전과정 온실가스 규제를 제시하고, 새로운 규제가 자동차 시장과 이해관계자들에게 미치는 영향에 대하여 평가하였다. 또한 자동차 전과정 온실가스 규제를 통해 국가의 에너지 정책이 자동차 정책과 연계될 수 있음을 보였다.

본 연구의 연구 순서는 다음과 같다. 먼저 우리나라의 자동차 연료에 대한 전과정 분석을 수행하고, 미래의 전과정 온실가스 배출량을 예측하였다. 다음으로 전과정 규제의 온실가스 배출량 규제치와 범칙금을 설정하고, 행위자 기반 모형을 바탕으로 정부와 소비자, 자동차 제작사 간의 상호 영향을 예측할 수 있는 모델을 설계하였다. 이를 통해서 얻은 자동차 시장 예측 모델을 이용하여 자동차 제작사가 제품의 가격을 어떻게 설정할 것인지 소비자는 어떠한 제품을 구매할 것인지를 예측할 수 있다. 마지막으로 전과정 분석 결과와 자동차 시장 예측 모델에 전과정 온실가스 규제를 적용하여 나타나는 사회적 현상에 대해 분석하였다.

본 연구의 분석 범위는 2030년의 준중형차 시장을 가정하였다. 이에 따라 2030년의 연간 준중형 자동차 판매량은 50만 대로 추산하였다. 준중형차 시장의 주 소비자는 가격에 민감하며, 준중형차는 전기 자동차의 기술을 적용하기 용이한 특징이 있다. 또한 본 분석의

자동차 시장에는 휘발유 내연기관 자동차, 휘발유 하이브리드 자동차, 휘발유 플러그인 자동차와 주행가능거리 200 마일의 전기자동차만 있다고 가정하였다.

자동차 온실가스 전과정 분석은 원료 추출 단계부터 자동차에 주유 또는 충전하기까지의 과정을 의미하는 Well-to-Tank (WTT) 과정과 자동차 주행 과정을 의미하는 Tank-to-Wheel(TTW) 과정으로 나뉜다. 분석을 위해 미국 아르곤 국가 연구소의 전과정 분석 프로그램을 이용하였으며, 한국의 실정에 맞도록 입력데이터와 연료 생산 경로를 모두 수정하여, 한국에서 사용하는 연료에 대한 전과정 분석 결과를 얻었다. 2030 년의 전과정 분석 결과를 얻기 위해 가장 중요한 요소는 미래의 연비와 발전 믹스이다. 여러 기관의 미래 예측 결과에 따르면 내연기관 자동차의 연비 향상율은 전기 자동차의 전비 향상율보다 높을 것으로 예상하고 있다. 또한 우리 나라의 2030 년 전력 수급계획은 원자력 발전량의 감축과 신재생 에너지 발전량의 증축이 핵심 목표이다. 2030 년의 전과정 분석 결과는 다음과 같다. 휘발유 자동차, 하이브리드 자동차, 플러그인 하이브리드 자동차, 전기자동차에 대해 먼저 자동차 주행 과정에서 배출되는 온실가스는 각각 138.7, 94.6, 13.2, 0 g-CO_2-eq./km 순으로 나타난다. 전과정 온실가스 배출량은 4 가지 자동차에 대해 160.9, 109.9, 89.3, 85.0 g-CO_2-eq./km 순으로 계산되었다. 휘발유 자동차와 전기 자동차의 주행과정의 온실가스 배출량 차이는 138.7 g-CO2-eq./km 이지만, 전과정 온실가스 배출량 차이는 75.9 g-CO2-eq./km 이며, 두 차종 사이의 간극이 좁혀지는 것을 확인할 수 있다. 또한 온실가스 배출량을 전과정적으로 계산하였을 때,

하이브리드 자동차와 플러그인 하이브리드 자동차의 온실가스 배출량 차이가 크게 감소하였다.

다음으로 행위자 기반 모형을 이용하여 2030 년의 자동차 시장을 예측하는 모델을 설계하였다. 행위자 기반 모형은 사회경제적 환경 속에서 서로 영향을 주고 받는 행위자들의 의사 결정을 예측하는 것에 사용되는 분석 기법이다. 본 연구에서는 자동차 시장에 연관된 행위자로 정부와 소비자, 자동차 제작사를 선정하였다.

먼저 우리나라의 자동차 온실가스 규제를 살펴보면 2020 년의 규제치까지 발표되었으며, 2030 년에 대해서는 발표된 바 없다. 따라서 동일 선상의 비교를 위하여 다음과 같은 가정을 통해 정부의 2030 년 온실가스 규제의 규제치와 범칙금 요율을 결정하였다. 기존의 규제 방법에 따른 온실가스 규제의 규제치는 62.2 g/km 이며, 전과정 온실가스 규제의 규제치는 109.2 g/km 이다. 온실가스 규제치를 달성하지 못할 경우에 대한 범칙금 요율은 현행 법의 2022 년 이후 시행안을 참고하여 1 g/km 초과 시 5 만원으로 설정하였다.

소비자와 자동차 제작사는 각각 자동차 구매에 따른 효용과 자동차 판매에 의한 순이익을 높이기 위한 의사결정을 한다. 소비자는 자동차의 가격과 연비, 주유비, 충전시간, 총주행거리 등을 고려하여 효용을 판단하며 제품의 효용이 높을수록 구매 확률이 높아진다. 4 가지 자동차에 대한 소비자의 구매 확률은 자동차의 판매율과 같다고 가정하였다. 자동차 제작사의 판매 순이익은 판매가와 생산 단가, 규제 비용, 연구 및 생산 시설 비용에 따라 결정된다. 이 중에서 자동차의 판매가를 결정할 때에는 가격이 올라갈수록 판매 이익이 증가하지만 소비자의 이탈이 일어나 판매율이 감소할 수 있다.

소비자와 자동차 제작사 간의 상호 영향에 따라 최적의 제품 가격과 이에 따른 자동차 시장의 점유율을 계산하는 모델을 작성하였다. 이를 통해 얻은 2030 년 준중형 자동차 판매 비율은 기존의 온실가스 규제가 적용된다고 가정하였을 때, 내연기관 27.7%, 하이브리드 29.3%, 플러그인 하이브리드 10.4%, 전기차 32.6%이다.

마지막으로 온실가스 규제에 전과정 배출량을 적용하여 시중의 자동차에 대한 규제를 시행할 때 나타나게 될 영향에 대해 분석하였다. 연료 생산 단계의 온실가스 배출량에 의한 영향을 효과적으로 관찰하기 위하여 해당 영향이 두드러지게 나타나는 전기 발전 과정에 대해 집중하여 살펴보았다. 발전 원료의 생산 과정과 발전, 송배전 효율을 모두 포함한 전기의 전과정 온실가스 배출량은 2030 년의 전력 수급계획을 기준으로 562 g/kWh 이다. 전기의 전과정 온실가스 배출량이 0 부터 1068 g/kWh 까지 변화할 때, 차종에 따른 온실가스 배출량과 이로 인한 자동차 시장의 제품 가격과 판매율, 소비자의 총 소유 비용, 정부의 총 수입이 어떻게 달라지는지 평가하였다. 주행 과정에서 주로 전기를 사용하는 플러그인 하이브리드 자동차와 전기 자동차는 발전단의 전과정 온실가스 배출량 변화에 큰 영향을 받게 된다. 전기의 전과정 온실가스 배출량이 700 g/kWh 에 이르면 전기차의 전과정 온실가스 배출량은 하이브리드 자동차와 비슷해진다. 또한 석탄 100%의 전력 믹스에서 전기차의 온실가스 배출량은 휘발유 자동차의 전과정 온실가스 배출량과 같다. 기존의 온실가스 규제에서 자동차 주행 단계의 온실가스 배출량에 대해서만 평가하였을 때에는 발전 믹스가 달라지더라도 자동차에서 배출되는 온실가스에는 전혀 영향이 없다. 이러한 차이는 자동차의 제품 가격에 영향을 미치게 된다. 자동차

제품 가격에는 규제 비용이 포함되어 있기 때문에, 온실가스 배출량이 높을수록 범칙금으로 인해 가격이 높아지며, 온실가스 배출량이 낮을수록 탄소 배출권 거래제에 따른 보상으로 제품 가격이 낮아진다. 이는 전과정 온실가스 규제에서 발전 믹스의 변화에 따라 전기차의 가격이 달라질 수 있음을 의미한다. 발전단의 온실가스 배출량이 작을수록 전기차의 가격이 더 낮아져, 시장 점유율이 높아질 것이며, 발전단의 온실가스 배출량이 커지면 전기차의 가격이 상승하면서 시장 점유율이 낮아지게 된다. 즉, 전과정 온실가스 규제에서는 연료의 생산 과정의 온실가스 배출량 변화가 자동차 시장의 점유율에 영향을 미치는 것을 의미한다. 새로운 전과정 온실가스 규제에서 준중형 자동차 시장의 판매 비율은 내연기관 25.4~37.2%, 하이브리드 자동차 28.3~41.5%, 플러그인 하이브리드 자동차 11.1~5.8%, 전기차 35.2~15.5%로 나타났다. 각 판매율의 범위는 전기의 전과정 배출량이 0 g/kWh 일 때부터 1068 g/kWh 일 때까지를 의미한다.

이러한 자동차 시장의 변화가 소비자와 정부, 온실가스 배출량에 미치는 영향을 분석하여 새로운 규제가 미치게 될 영향에 대해 평가하였다. 소비자의 총 소유 비용은 자동차 구입 가격과 소유 기간동안의 주유비, 유지비용, 보험 등을 포함하는 값이다. 2030 년에 자동차를 구매한 소비자 1 명의 총 소유비용은 기존의 온실가스 규제에서 평균 4750 만 원이며, 전과정 온실가스 규제에서는 4550~4800 만 원으로 나타났다. 자동차 판매에 따른 정부의 순 수입은 유류세 세입과 온실가스 범칙금으로 인한 세입의 합에 전기차 충전시설 건설에 따른 제한 비용으로 나타내었다. 2030 년에 자동차 50 만 대를 판매했을 때, 1 년 간 정부의 총 수입은 기존의 온실가스

규제에서 평균 1 조 6000 억 원이며, 전과정 온실가스 규제에서는 1 조 3700 억~3 조 3700 억 원으로 나타났다.

자동차의 온실가스 배출량은 평균 전과정 온실가스 배출량으로 나타내었다. 이는 2030 년에 판매된 자동차가 주행 과정에서 배출하는 온실가스 외에도 생산, 발전, 수입, 수송 단계에서 배출하는 모든 온실가스 배출량을 합산함으로써 국가 전체의 온실가스 감축 목표에 얼마나 영향을 미치는지에 대한 지표로써 활용할 수 있다. 기존의 온실가스 규제에서 42.8% 점유율을 차지하는 플러그인 자동차와 전기자동차의 온실가스 배출량이 발전 믹스의 변화에 따라 달라지기 때문에, 평균 온실가스 배출량 또한 78.2~145.6 g-CO_2-eq./km 로 변화한다. 그런데 전과정 온실가스 규제에서는 플러그인 차와 전기차의 온실가스 배출량 변화와 더불어, 자동차의 점유율이 함께 변하기 때문에 평균 온실가스 배출량은 73.7~139.6 g-CO_2-eq./km 로 변화하게 된다. 이를 통해 전과정 온실가스 규제에서 발전단의 온실가스 배출량이 감소하면 전기차의 점유율이 증가하여 온실가스 감축 효과를 증폭시키며, 발전단의 온실가스 배출량이 증가하면 전기차의 점유율이 줄어들면서 온실가스 배출량이 증가하는 것을 상쇄시키는 효과가 나타나는 것을 확인하였다. 이는 자동차 연료의 생산 과정에서의 온실가스 배출량이 달라짐에 따라 자동차 시장이 유동적으로 반응하는 전과정 온실가스 규제의 장점을 드러낸다.

주요어: 온실가스, 전과정 분석, 온실가스 배출량 규제, 자동차 시장 예측, 전과정 온실가스 규제

학번: 2013-20686