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EVALUATION OF NEW GREENHOUSE GAS EMISSION STANDARDS FOR LIGHT DUTY VEHICLES THROUGH A WELL-TO-WHEEL ANALYSIS

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ABSTRACT

Well-to-wheel analysis can be used to quantitatively compare the impact electric vehicles has on global warming with conventional internal combustion vehicles. In this study, we performed a well-to-wheel analysis in Korea in 2030. Furthermore, we evaluated the impact of the WTW standard from the perspective of the government, the manufacturer and the consumer. The government adjusts the penalty rate to present a new GHG standard scheme for the same amount of WTW greenhouse gases, and the vehicle market shares move from PHEVs and BEVs to HEVs and ICEVs depending on the manufacturer's suggested retail price and consumer choice.

Keywords: greenhouse gas, vehicle emission standard, well-to-wheel analysis, vehicle market prediction, agent-based model, alternative vehicle

NOMENCLATURE

Abbreviations	
BEV 100	Battery electric vehicle (driving range: 100 miles)
CAFE	Corporative average fuel economy
GHG	Greenhouse gas
HEV	Hybrid electric vehicle
ICEV	Internal combustion engine vehicle
PHEV	Plug-in hybrid electric vehicle
TTW	Tank-to-Wheel
WTW	Well-to-Wheel
Symbols	
c	Manufacturing cost
CT	Charging time
DR	Driving range
FE	Fuel economy
GHG_{std}	Greenhouse gas standard target
i	Index of powertrains
n	Number of manufacturers
p	Retail price
q	Market share
Q	Total sales volume
u	Utility
ρ	Penalty rate
Π	Total profit
$X\|_{eq}$	X value at Nash equilibrium

1. INTRODUCTION

1.1 Background

Various environmental regulations are being implemented in the transport sector around the world to solve the global warming problem. Examples include the CAFE standard in California, U.S., and the GHG standard and framework act on low carbon and green growth in Korea. These regulations require automakers to meet their regulatory targets for average GHG emissions or fuel economy. In particular, these regulations estimate that there are no GHG emissions for BEVs and PHEVs in the charge depleting mode, which promotes the development and sales of more automobiles using batteries. [1]

The current GHG standard would be effective in reducing GHG emissions in the transport sector through the expansion of electric vehicles, but if the amount of GHG emissions from the power generation process increases further, it is difficult to say whether the standard would be successful. The WTW analysis evaluates not only the GHGs generated during vehicle

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operation but also the emissions generated during the fuel life cycle. This life cycle analysis has the advantage of being able to more effectively manage nationwide GHG emissions and, more broadly, to manage global GHG emissions. Therefore, applying the WTW analysis to vehicle GHG emission standards allows you to assess actual GHG emissions from vehicle sales.

1.2 Research objective

The aim of this study is to evaluate new GHG standards for light-duty vehicles through WTW analysis. More specifically, we quantitatively analyze the impact of changes in GHG policy on vehicle manufacturers, consumers, and governments.

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
- Seven powertrains: ICEV-gasoline, ICEV-diesel, HEV-gasoline, PHEV-gasoline, BEV 100, BEV 200, and BEV 300
- 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)

2. WELL-TO-WHEEL ANALYSIS

2.1 Well-to-wheel analysis approach

First, we analyze the well-to-wheel GHG emissions of various automotive fuels in Korea. WTW analysis is a methodology for analyzing the entire process of the fuel life cycle. Petroleum-based fuels, such as gasoline and diesel, begin with crude recovery, import, refining and distribution to gas stations throughout the country. Electricity is the secondary form of energy that is generated from various raw materials, such as coal, natural gas, and uranium. Therefore, the producing and transporting processes of raw materials are also included in the WTW cycle of electricity.

We used the GREET program developed by the U.S. Argonne National Laboratory as a tool for WTW analysis. [2] We collected input data for the domestic situation, input it into the GREET model, and added new pathway and calculation formulas to obtain Korean WTW GHG results. For detailed, please refer to our previous study. [3], [4]

2.2 Future predictions

Most recently, we presented the predicted WTW results by 2030. [5] Future WTW results are calculated by predicting the fuel economy and power generation mix, which are the most sensitive parameters. Fuel economy data were obtained from Autonomie data [6] 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. [7] Figure 1 shows the WTW results. 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 emissions generated from the feedstock and fuel production processes, the results are WTW emissions.

3. AGENT-BASED MODEL

3.1 Agent-based model approach

Agent-based models are used to predict the selection and behavior of various decision makers affected by sociotechnical systems. Each agent moves according to a specified decision rule and is affected by

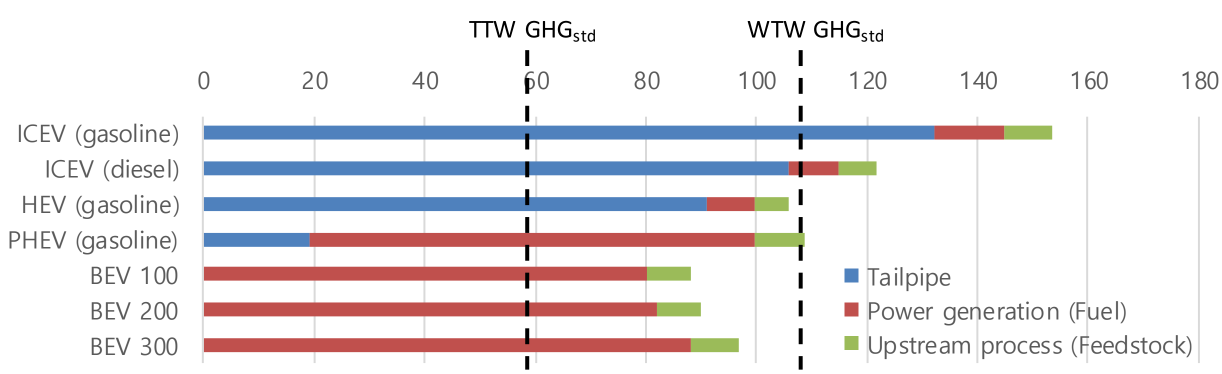

Fig 1 WTW GHG emissions of passenger vehicles in 2030 in Korea [g-CO_2-eq./km]

different agents. [8] In our study, government, manufacturer and consumer agents were selected to analyze the influence of GHG standards. Figure 2 shows the determinants of each agent, decision rules and the interacting factors with each other. Details are described in the following sections.

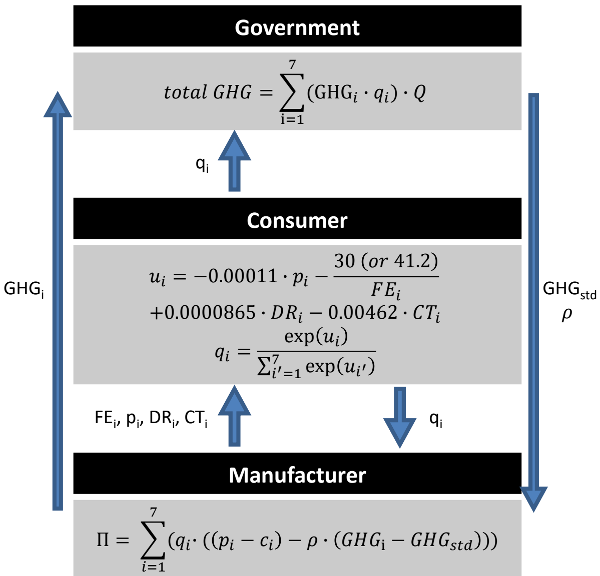

Fig 2 Agent-based model schematic

3.2 Government agent

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 follows.

$$\text{total GHG} = \sum_{i=1}^{7} (\mathrm{GHG_i} \cdot \mathrm{q_i}) \cdot \mathrm{Q}$$

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. [9] The determined TTW standard target is 58.2 g/km, and the WTW standard target is 108.3 g/km.

The penalty rate of the GHG standard is \$45/(g-CO_2-eq./km).

3.3 Manufacturer agent

The vehicle manufacturer sets up a strategy to maximize the total profit of its company. To achieve maximum profits, the manufacturer determines the fuel economy, retail price, and performance of the product. The total profit of the vehicle manufacturer can be expressed in the form of the following equation. [10]

$$\Pi = \sum_{i=1}^{7} (q_i \cdot ((p_i - c_i) - \rho \cdot (GHG_i - GHG_{std})))$$

The profit is determined by the retail price (p_i), manufacturing cost (c_i), penalty according to the GHG standard, and the market share (q_i). Manufacturing cost (c_i) is correlated with the fuel economy, and we used the modified Autonomie data[6] by referring to the current BEV prices. Investment cost and research cost were ignored. The manufacturers that emit average GHGs less than the target value sell carbon credits at \$45/(g-CO_2-eq./km).

3.4 Consumer agent

Consumers decide to buy high-utility products. The discrete choice model is used to quantify utility and analyze consumer purchasing trends. Utilities vary depending on the attributes of the product and the usage environment. [11]

In this study, the utility is expressed quantitatively by the following formula.

$$u_i = -0.00011 \cdot p_i - \frac{30 \ \ (or \ \ 41.2)}{FE_i} + 0.0000865 \cdot DR_i - 0.00462 \cdot CT_i + \varepsilon_i$$

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. Y. Kwon et al. conducted a survey on EV owners in Korea, and we expected that this analysis reflects the psychology of Korean consumers. [12] The coefficients given in their study are modified to match the unit of the attribute in the utility equation. The coefficients of 1/FE are -29.7, -31.4 and -41.2 for gasoline, diesel, and electric vehicles, respectively, because their utility in fuel economy depends on the fuel prices.

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. [10]

$$q_i = \exp(u_i) / \sum_{i'=1}^{7} \exp(u_{i'})$$

4. RESULTS AND DISCUSSION

4.1 Mathematical approach and results

In Nash equilibrium, the company makes the best decision in consideration of the best strategies of other competitive companies. [13] Applying this theory to the vehicle market, all manufacturers at the Nash equilibrium point determine the price and performance of the product to maximize their profit. Assuming that it is a pure oligopoly market, all companies have the same manufacturing costs, FE, DR, and CT, for their powertrains. This method also assumes that the FE, DR, and CT are fixed in a given vehicle category. Thus, the retail price is the only parameter adjusted by the manufacturer.

Based on these assumptions, the derivative of the firm's profit to each product price in the Nash equilibrium state is zero. The result is simply summarized as follows.

$$\frac{\partial \Pi}{\partial \mathrm{p_i}} = 0 \quad (\text{for } \mathrm{i} = 1\sim7)$$

$$\Pi|_{eq} = -\frac{1}{n-1}\frac{1}{(-0.00011)}$$

$$\mathrm{p_i}|_{eq} = -\frac{n}{n-1}\frac{1}{(-0.00011)} + c_i + \rho(G_i - G_{std})$$

From this mathematical approach, the following information is available. First, profit is affected only by the number of manufacturers (n) and the coefficient for the retail price in the utility equation. As the number of competing companies increases, the maximum profit that a company can achieve is reduced. Furthermore, consumer sensitivity to prices also affects their profitability. The GHG standard does not affect the total profit because of the assumption that the total sales volume (Q) in the vehicle market is fixed.

Second, the price is affected by the manufacturing cost (c_i) and the number of manufacturers (n). In particular, all profit and loss due to GHG standards are reflected in the vehicle price. This price adjustment allows manufacturers to control the reduced sales of vehicles with higher GHGs and the increased sales of those with lower GHGs.

4.2 Discussion

Assuming that there were five manufacturers, we calculated the market share of 7 powertrains in 2030 when the number of manufacturers was five (n=5). Figure 3 shows the market share results in four scenarios of GHG standards. The four scenarios represent no GHG standard, the TTW GHG standard (current policy), the WTW GHG standard with same penalty rate as the TTW standard, and the WTW GHG standard with a modified penalty rate.

When other conditions 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.

(No regulation) Consumers prefer to buy ICEVs at a cheap price and with weak constraints on the driving range (DR) and charging time (CT). In this scenario, the resulting average GHG emissions were 62.0 g/km for TTW and 110.7 g/km for WTW.

(TTW standard) In the TTW standard, which regulates vehicle tailpipe emissions, PHEV and BEVs occupy the largest share of the four scenarios, and ICEVs and HEVs occupy the lowest share. The average GHG emissions were 48.3 g/km for TTW and 105.3 g/km for WTW. The manufacturer undertakes a strategy that results in more bonuses by emitting average GHGs approximately 10 g/km below the aforementioned TTW GHG standard.

(WTW standard) The market share of BEVs and PHEVs with the TTW standard moved toward the market share of ICEVs and HEVs when WTW regulation was applied. This is because the difference in penalty due to

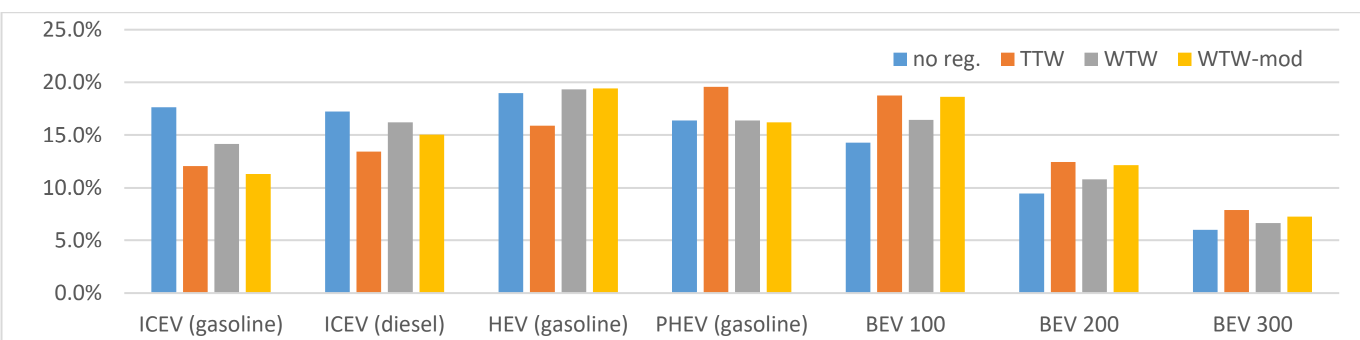

Fig 3 Vehicle market shares according to the GHG standard scenario in 2030

the GHG standard between the former and the latter was reduced. However, when the same penalty rate was applied, the market shares were balanced at the point where total WTW GHGs increased instead of the TTW standard. The average GHG emissions were 56.6 g/km for TTW and 107.9 g/km for WTW.

(Modified WTW standard) In this last 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 1.97 times compared to that of the TTW standard. In the modified WTW standard, the BEV market share slightly decreased by ~3%, and the HEV share increased by ~22% compared to the TTW standard. The average GHG emissions were 51.6 g/km for TTW and 105.3 g/km for WTW.

5. CONCLUSION

In this study, the effects of WTW GHG standards were quantitatively evaluated to help policymaking and marketing strategies. This study shows how consumers, governments, and producers react in applying the WTW standard and how GHG emissions and market shares change. For the WTW standard, the proportion of BEVs in the market decreased compared to the TTW standard. In particular, it was shown that the sales of HEVs could be an effective alternative to responding to the GHG standard from a WTW perspective.

Through these analyses, we have discussed the meaning of the WTW standard. First, it is possible to assess the GHG emissions quantitatively for the electric driving mode of alternative vehicles. Second, WTW analysis and application may affect future vehicle market shares, even though the total WTW GHG emissions have not changed.

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REFERENCES

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

[2] U.S. Argonne National Lab. GREET1 (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) Transportation Fuel Cycle Analysis Model Version 2012 rev2. 2012.

[3] Jang JJ, Song HH. Well-to-wheel analysis of 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):1102-1116.

[4] Choi W, Song HH. 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 2018;230:135-147.

[5] Choi W, Yoo E, Jang JJ, Seol E, Kim M, Song HH. Well-to-Wheel Greenhouse Gas Emissions of Current (2017) and Future (2030) Passenger Vehicle Pathways : A South Korean Case Study. in Appllied Energy Symposium: MIT A+B (AEAB2019) 2019. MIT, Boston, USA.

[6] Moawad A, Kim N, Shidore N, Rousseau A. 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).

[7] Minister of Trade, Industry and Energy. The 8th Basic Plan for Long-term Electricity Supply and Demand (2017 - 2031). 2017.

[8] Dam van KH, Nikolic I, Lukszo Z. Agent-based modelling of socio-technical systems. Vol. 9. Dordrecht: Springer; 2012.

[9] Korea Environment Corporation. Establishment of an alternative vehicle supply roadmap in 2030. (not open to the public), 2018.

[10] Michalek JJ, Papalambros PY, Skerlos SJ. 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):1062-1070.

[11] Train KE. Discrete choice methods with simulation. 2nd ed. New York: Cambridge; 2009.

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

[13] Jehle GA, Reny PJ. Advanced microeconomic theory. 3rd eq. Harlow: Pearson; 2001.