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Vehicle Life Cycle Analysis Considering Uncertain Driving Distance

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Vehicle Life Cycle Analysis Considering Uncertain Driving Distance

A Dissertation Submitted in Partial Fulfillment of the

Requirement for the Degree of

Ph.D. in Economics

Department of Economic Systems

Graduate School of Economics

Kyushu University

by

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Contents

Chapter 1. Introduction

1.1. Climate change

According to the Intergovernmental Panel on Climate Change (IPCC) Summary for Policymakers, in Global Warming of 1.5 °C, anthropogenic activity alone since the industrial revolution has caused a temperature rise of approximately 1 °C. It has been indicated that global increase in temperature may cause an increase in the frequency of fextreme weather events such as sea level rise, acidification, droughts, and floods. IPCC has projected that temperatures will rise by approximately 1.5 °C from 2030 to 2050 (Intergovernmental Panel on Climate Change: IPCC, 2018)) (Figure 1-1).

At COP26, 153 countries announced new climate change policies for net zero emissions (COP26, 2021). The definition of net zero emissions is that the amount of CO_2 emitted by anthropogenic activities is offset by the amount of CO_2 absorbed by the sea, forests, etc., such that CO_2 emissions become virtually zero. Therefore, to strive towards net zero emissions, accurately estimating CO_2 emissions from anthropogenic activities is necessary.

It is predicted in the INTERNATIONAL ENERGY OUTLOOK 2021 by International Energy Agency (IEA) (2021) that globally passenger vehicles and mileage demand will increase to more than double between 2020 and 2050. The spread of next-generation vehicles such as electric and fuel cell vehicles is being promoted, but the transport sector is still thought to be largely responsible for emissions (International Energy Agency, 2021b). The International Energy Agency (International Energy Agency, 2021a) mentions "Reducing CO_2 emissions in the transport sector over the next half-century will be a formidable task" in Energy Technology Perspective 2020.

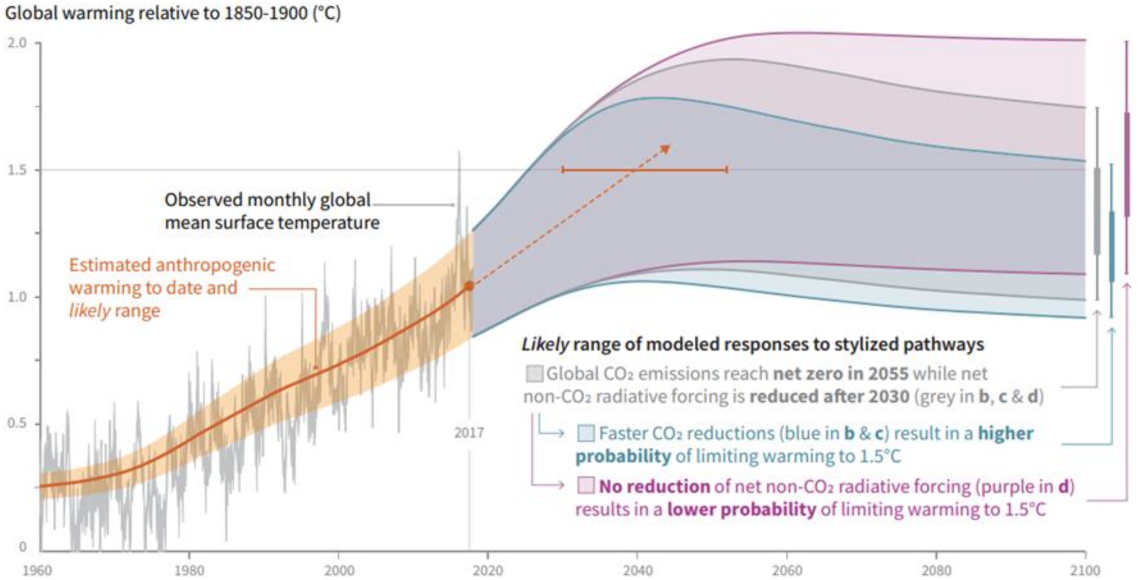


Figure 1-1. Human-induced global warming change above pre-industrial levels Source:

Summary for Policymakers in Global Warming of 1.5 °C (IPCC, 2018)

1.2. Structure of thesis

This Ph.D. thesis comprises 5 chapters (Figure 1-2). Chapter 2 is a comprehensive literature review focusing on Corporate Average Fuel Economy (CAFE) standard and Life Cycle Assessment. The research objectives and the contribution of this thesis are also presented in this chapter.

In Chapter 3, the actual 2015 sales volume and fuel economy data from seven Japanese automobile manufacturers (Toyota, Honda, Suzuki, Mazda, Subaru, Mitsubishi) are used to calculate the corporate average fuel economy standard (CAFE standard) achievement status of each company. Furthermore, not only were the optimal vehicle sales patterns estimated for each company when the constraints of CAFE standard are satisfied, but the life-cycle CO_2 emissions of each company were also analyzed based on the vehicle sales patterns.

Previous existing research on vehicle lifecycle analysis assumed that the annual mileage of a vehicle is invariant with vehicle age. In Chapter 4, the relationship between vehicle age and annual vehicle mileage is identified. Specifically, in Chapter 4, an assessment is conducted of how much annual vehicle mileage decreases as vehicle age increases for a specific engine type (e.g., gasoline engine) and a specific annual mileage stratum (i.e., annual mileage quantiles). Additionally, the impact of this uncertainty in driving propensity on CO_2 emissions during driving is evaluated.

Chapter 5 summarizes the analysis results obtained from Chapters 3 and 4, and presents the conclusion of this dissertation.

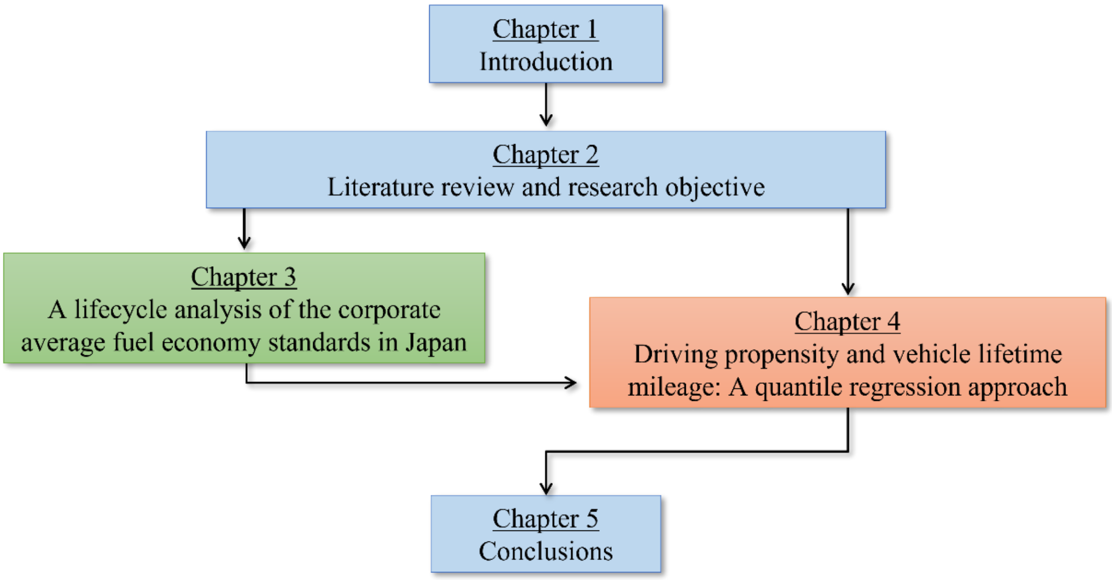


Figure 1-2. Structure of the thesis

Chapter 2. Literature Review

2.1. Corporate average fuel economy standard

Corporate Average Fuel Economy Standard (CAFE standard) was introduced in the United States in 1975 during the oil crisis. In an oligopolistic automobile market, the introduction of fuel economy standards is considered better from a social welfare perspective than the introduction of gasoline or environmental taxes (Greene, 1998).

Under the CAFE standards introduced in the United States, the CAFE value *C* (miles/Gallon: mpg) of a company is calculated as shown in Eq. (2-1),

$$C = \frac{\sum_{i=1}^{N} x_i}{\sum_{i=1}^{N} \frac{x_i}{z_i}} \tag{2-1}$$

where z_i (mpg) is the fuel economy value of vehicle model *i* of the automobile manufacturer, and x_i is the number of vehicle model *i* that the automobile manufacturer sold for the year. Furthermore, *N* is the number of different vehicle models sold by the relevant automobile manufacturer. The CAFE standard shown in Eq. (2-1) is a weighted average value of fuel economy by vehicle type using sales volume by vehicle type.

The CAFE standard value $\tilde{C}$ that is the standard value for the company is calculated as shown in Eq. (2-2),

$$\tilde{C} = \frac{\sum_{i=1}^{N} x_i}{\sum_{k=1}^{M} \frac{x_k}{\tilde{z}_k}} \tag{2-2}$$

where $\tilde{z}_k$ (km/L) is the target fuel economy value for vehicle category k, x_k is the total number of sales of vehicle models belonging to vehicle category k by a particular automobile manufacturer, and M is the number of vehicle categories. The vehicle category is divided between passenger vehicles and light-duty trucks.

Figure 2-1 shows changes in fuel economy standards by vehicle category. The red line indicates passenger vehicles, and the green line indicates light-duty trucks. In general, higher vehicle weight results in worser vehicle fuel economy. Therefore, the fuel economy standards for light-duty trucks, which have relatively heavy vehicle weights, are set lower than those for passenger vehicles, which have light vehicle weights. After the CAFE standard was introduced, the US CAFE standard remained unchanged from 1990 to 2009 (Figure 2-1). In the United States, the CLEAN Energy Act of 2007: H.R.6 was passed in 2007, and standard values have improved since 2010 (Figure 2-1). US CAFE standards continue to improve, so the fuel economy standards for passenger vehicles and light-duty trucks were set to 55.3 mpg and 39.3 mpg, respectively (Figure 2-1).

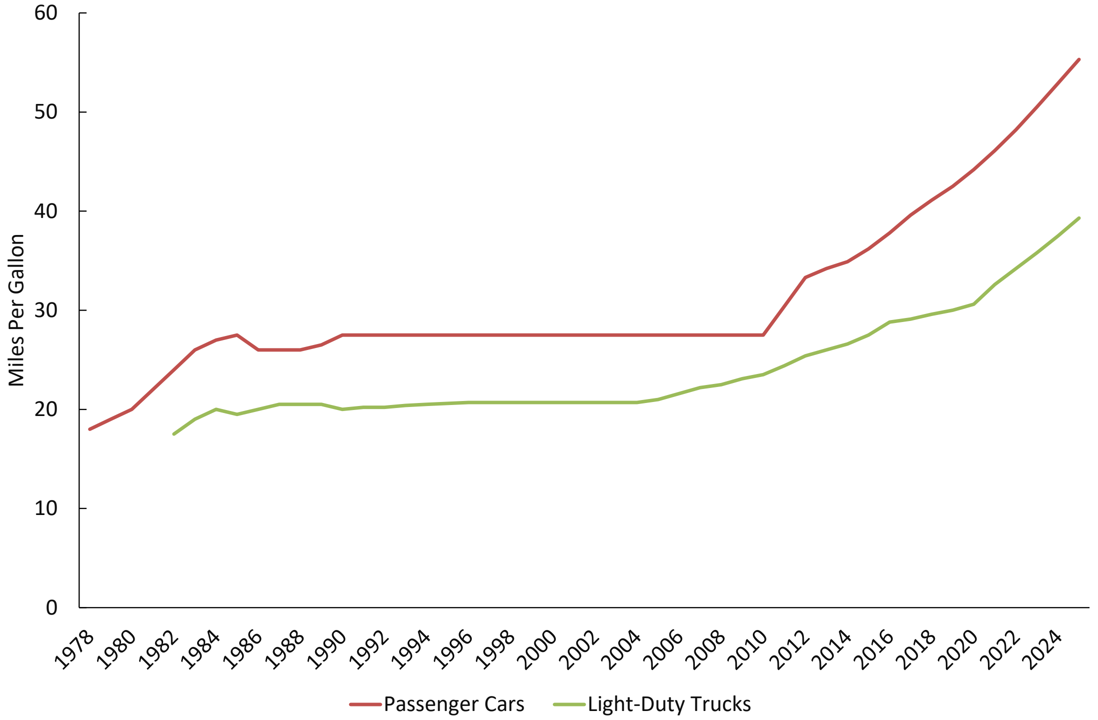


Figure 2-1. Vehicle Fuel Efficiency (CAFE) Requirements by Year

Source: Created by author from Office of Energy Efficiency and Renewable Energy (https://afdc.energy.gov/data/)

CAFE standards have not improved in the United States for about 20 years, so previous research on CAFE standards has focused on stricter fuel economy standards. The impact of a gasoline tax hike has also been analyzed. For example, Jacobsen, 2013 estimated social welfare scenarios with stronger CAFE standards and higher gasoline taxes, where they indicated that the social welfare of the latter was greater.

Previous research (e.g., Jacobsen, 2013) relies on the economic theory that increase in gasoline taxes also increase the economic burden on consumers, and subsequently cause reduction in gasoline consumption. However, there is still debate as to whether consumers properly value gasoline prices (Greene, 2010 (Allcott, 2011; Zirogiannis et al., 2019). For example, Zirogiannis et al., 2019 found that uncertainty about consumer valuations of gasoline prices changed vehicle sales. Specifically, Zirogiannis et al., 2019 indicated that the uncertainty of consumer gasoline price assessments causes variations in vehicle sales from -7% to +5%.

The United States sets CAFE standards by vehicle type (i.e., passenger vehicle and light-duty trucks), whereas Japan sets CAFE standards by vehicle weight. In Japan, changes in the sales volume of fuel-efficient vehicles that belong to a certain vehicle weight class affect the achievement of the CAFE standard for that company. In Japan, companies will be able to have credits that make up for shortfalls in CAFE standards. However, fuel-efficient vehicles, such as hybrid vehicles, require additional materials during manufacturing when compared to conventional internal combustion engine vehicles (Kagawa et al., 2013). CO_2 emissions from vehicle manufacturing are likely to increase as hybrid vehicle sales are promoted to achieve CAFE standards.

Table 2-1. CAFE standards in Japan and the United States

	Japan	U.S.A.
Introduced year	2020	1975
Base year	Every five years	Every year
Fuel economy credit	Credit between vehicle weight categories within an auto company	Credit between auto companies. Also possible for company to carry forward and carry back the achievement of the standard.

Table 2-1 shows the differences between CAFE standards in Japan and the United States. Japan sets the CAFE standard year every five years, whereas the United States sets it annually. Fuel economy credits in Japan are generated only between vehicle weight classes within a company; whereas fuel economy credits in the United States can be carried forward and backward from year to year, and can also be traded with other companies.

The basic concept of the CAFE standards introduced in Japan and the United States are the same, but the method of operation differs greatly. There is almost no previous research on fuel economy standards for Japan. Konishi & Managi (2020) identified the trade-off relationship between vehicle weight and fuel economy, and they indicated that making heavier vehicles makes it easier for companies to meet fuel economy standards. Konishi & Managi (2020) clarified loopholes in Japan's fuel economy standard regulations using vehicle data.

2.2. Life-cycle assessment

Life-cycle assessment (LCA) is a method for assessing the environmental impact of products and services throughout their life cycle. The International Organization for

Standardization (ISO) has started preparing international standards for environmental management since 1997 (Kliippel, 1998). According to (Guinee et al., 2011), the concept of LCA was established in the 1970s, and the number of studies on LCA has increased since the 2000s, after ISO standardization.

Figure 2-2 shows the changes in the number of articles published from 1990 to 2021 with the article search tag “Life Cycle Assessment (LCA)” obtained from the Scopus database (https://www.scopus.com/home.uri). It can be seen from Figure 2-2 that, in recent years, around 1,500 papers on LCA have been published per year. In particular, it should also be noted that there has been an increase in the number of studies on automobile LCA (Oda et al., 2022).

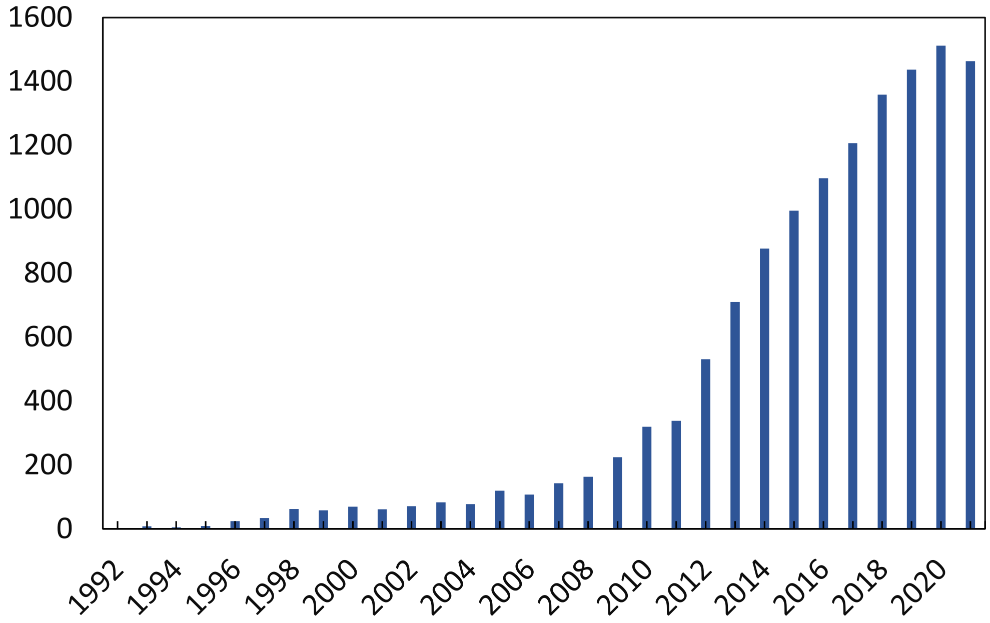


Figure 2-2. Changes in the number of articles published from 1990 to 2021 with the article search tag “Life Cycle Assessment (LCA)” obtained from the Scopus database

According to Oda et al., 2022, about 80% of automobile LCA studies focus on vehicle type comparisons (internal combustion engine vehicles vs. electric vehicles vs. fuel cell vehicles vs. hybrid vehicles) and vehicle weight reduction. The LCA of a single automobile has been conducted in many automobile studies. As shown above, conventional LCA has evolved into product level LCA (Hellweg & Milà Canals, 2014).

Meanwhile, fleet-based LCA is also being conducted for research on LCAs with automobiles other than technical assessment. Fleet-based LCA considers social background, such as the spread of electric vehicles, and analyzes the impact of car ownership on the environment. Analyzing the environmental impact of automobiles from a social perspective is important in assessing laws and regulations as well as for technical progress related to automobiles (Garcia & Freire, 2017). Dynamic fleet-based LCAs revealed that long-term vehicle ownership created additional environmental burdens. For example, Kim et al. (2003) found that, as the vehicle age increased, CO_2 emissions did not exhibit major changes, but that NO_x and SO_x emissions increased.

Previous research has shown that CO_2 emissions from vehicles other than fuel cell vehicles were greater during the usage stage (driving stage) than during the manufacturing stage (Oda et al., 2022). According to the Mazda Motor Corporation (2017), Mazda Sustainability Report, approximately 60% of the life-cycle emissions from an internal combustion engine vehicle are from the driving stage; whereas, this value was approximately 70% according to the Toyota Motor Corporation (2015)'s MIRAI LCA Report. The difference in emissions in the Mazda and Toyota reports was due to differences in the lifetime vehicle mileage assumptions that were used in the calculations.

Table 2-2 shows lifetime mileage values used in Japanese automobile LCA studies, and Table 2-3 shows lifetime mileage values used in automobile LCA studies in countries other than Japan. Tables 2-2 and 2-3 show that there is variation in the assumptions of mileage and vehicle life used in previous studies. It can be seen from Table 2-2 that, other than Kishita et al. (2016), studies used values close to the statistical value of the Automobile Inspection & Registration Information Association and the Ministry of Land, Infrastructure, Transport and Tourism Road Transport Bureau. Kishita et al. (2016) used the results of a questionnaire survey conducted in Suita City, Osaka Prefecture, and they assumed a value about half of the average annual mileage published by the Ministry of Land, Infrastructure, Transport and Tourism. In this way, when targeting a specific area, the mileage of a vehicle traveling in that area is significantly different from the mileage announced by public institutions. Meanwhile, not only does the mileage of automobile vary greatly by country, but even in studies targeting the United States, the assumed lifetime mileage varies by approximately 100,000 km (Table 2-3). In this way, previous research has not considered the uncertainty of mileage when calculating CO_2 emissions during driving, which accounts for the largest proportion in the automobile life-cycle.

Table 2-2. Mileage in automobile LCA studies targeting Japan

Author	Published year	Lifetime (years)	Total driving distance (km)	Annual driving distance (km)
Nakano et al.	2008		100,00- 213,333	
Nonaka & Nakano	2011	10	100,000	
Kishita et al.	2016	12		5,460
Sano et al.	2018		100,000	
Mazda Motor Corporation	2018	13	110,000	
Ishizaki & Nakano	2018	15	150,000	10,575
Kawamoto et al.	2019		200,000	
Kawajiri et al.	2021	12	150,000	
Automobile Inspection & Registration Information Association	2021	13.8		

Ministry of Land, Infrastructure, Transport and Tourism	2005		10,575

Table 2-3. Mileage in LCA studies targeting countries other than Japan

Author	Published year	Lifetime (years)	Total driving distance (km)	Annual driving distance (km)	Country
Lave & MacLean	2002	14	250,000		US
Granovskii et al.	2006	10	241,350		US
Samaras & Meisterling	2008		240,000		US
Gao & Winfield	2012		256,000		US
Hawkins et al.	2013		150,000		-
Nanaki & Koroneos	2013	10	250,000		Greece

Bickert et al.	2015	11		11,100	Germany
Bauer et al.	2015		240,000		Switzerland
Ellingsen et al.	2016		180,000		EU
Mayyas et al.	2017		320,000		US

Regarding this mileage uncertainty analysis, Weymar & Finkbeiner (2016) used data from 800,000 vehicles sold in Germany to analyze the relationship between vehicle age and mileage. Weymar & Finkbeiner (2016) estimated a single relationship with lifetime mileage (dependent variable) and vehicle life (independent variable) using regression analysis. However, Weymar & Finkbeiner (2016) did not consider the fact that lifetime mileage variability increases with vehicle age, so driving propensity has not yet been analyzed.

2.3. Contributions of the thesis

First, as mentioned in Section 2.1, an environmental analysis of the CAFE standards introduced in Japan has not been conducted. Therefore, in Chapter 3, assessments were conducted on the following aspects: how the spread of fuel-efficient hybrid vehicles, which generate fuel economy credits under Japan's CAFE standards, will affect the CAFE standards; and how CO_2 emissions during automobile manufacturing change under the optimal sales structure of companies satisfy the constraints of the CAFE standards. In Chapter 3, fuel economy standard analysis and LCA analysis, which have not been previously considered, are comprehensively conducted, and the sustainability of automobile companies is discussed.

An overview of automobile LCA studies is provided in Section 2.2, where it was indicated that automobile LCA studies have the following two problems. The first problem is that the uncertainty of lifetime mileage is not considered when estimating emissions during driving, which accounts for the largest proportion of CO_2 emissions in the automobile life-cycle. The second problem is that a single relational expression between vehicle age and mileage does not sufficiently capture driving propensity due to the increasing variation in lifetime mileage as the vehicle ages. Therefore, in Chapter 4, engine types are considered, and multiple relational expressions related to vehicle age and lifetime mileage are formulated. Furthermore, vehicle data are used to not only quantify a driver's driving propensity (i.e., relationship between vehicle age and lifetime mileage) by engine type, but also propose an uncertainty analysis framework for vehicle emissions based on the identified driving propensity.

Chapter 3. A Lifecycle Analysis of the Corporate Average Fuel Economy Standards in Japan

3.1. Introduction

The Paris Agreement, adopted in December 2015, attempts to tackle the growing problem of global warming by setting carbon dioxide (CO_2) emission reduction targets for each country in order to meet the goal of limiting the rise in the average global temperature to below 2 °C relative to the pre-industrial revolution level (United National Framework Convention Climate Change: UNFCC, 2015). To achieve this goal, limiting emissions from the transportation sector, which accounts for 29% of the CO_2 emissions of Organization for Economic Co-operation and Development (OECD) countries, is of paramount importance (IEA, 2016). In Japan, the transportation sector accounts for 20% of total CO_2 emissions, and 90% of these emissions are generated by the motor vehicle sector (Ministry of Land, Infrastructure, transport, and tourism, 2017). Accordingly, reducing tailpipe CO_2 emissions derived from motor vehicles is essential, especially by means of improving motor vehicle fuel economy.

In the United States, the Corporate Average Fuel Economy (CAFE) standard has been in effect since 1975(National Highway Traffic Safety Administration, 2016). This standard aims at improving the fuel economy of motor vehicles to ensure that the fuel economy of a relevant company does not drop below a fuel economy standard value (CAFE standard), a target which is a motor vehicle sales weighted average (National Highway Traffic Safety Administration(National Highway Traffic Safety Administration, 2016). In Japan, on the other hand, the fuel economy values of the most efficient vehicle models in specific vehicle weight categories (i.e., the best performing vehicles) are adopted as targets to drive improvements in the fuel economy of each vehicle model (Ministry of Land, Infrastructure, Transport and Tourism, 2011). This could be called the 'Top Runner Approach'. Japan plans to adopt CAFE standards in 2020, to use in addition to its current 'Top Runner Approach', with the dual objectives of reducing transportation sector CO_2 emissions and promoting more flexible motor vehicle sales by companies (Ministry of Land, Infrastructure, Transport and Tourism, 2011).

There are several problems with CAFE standards, however. The first is that even if the aggregated CAFE of a relevant company exceeds the CAFE target, the fuel economy of some of the company's vehicle models may still fall below the fuel economy standard value by vehicle weight category, and vehicle models with poor fuel economy will likely end up on the motor vehicle market. Increasing sales of hybrid vehicles is likely another factor that may drive up the CAFEs of companies. There is also a problem that hybrid vehicles (i.e., electric-petroleum hybrids) impose a heavier environmental burden in manufacturing than conventional gasoline vehicles because they require additional parts and materials (e.g., Kagawa et al., 2013).

Thus, CAFE standards may not well work toward reducing gasoline consumption and environmental burden through the fuel economy improvements over all the vehicle weight categories and vehicle types. Regarding this problem of CAFE standards, previous studies studied the optimal design of the CAFE standard and analyzed the welfare effects of tightening the CAFE standard in the U.S. (Kiso, 2017; Kleit, 2004; Levinson, 2017; Luk et al., 2016; Whitefoot & Skerlos, 2012)　Previous studies also compared reductions in fuel consumptions through increasing gasoline taxes and tightening the CAFE standards (Austin & Dinan, 2005; Bento et al., 2009; Jacobsen, 2013; Parry et al., 2007).

It is important to note that since the demand-side energy policy of a higher gasoline tax has already been imposed in many countries, the supply-side energy policy of improving the CAFE is needed to reduce the environmental burdens associated with the automobile. Studies estimated direct CO_2 emissions associated with fuel combustions of the transport sector, e.g., (Jenn et al., 2016; Woo et al., 2017), whereas an importance of the life cycle analysis has been increased (Guinee et al., 2011). To the best of our knowledge, there are very few studies evaluating how companies meeting the CAFE standards affects lifecycle CO_2 emissions through the automobile lifecycle.

It is essential to consider the lifecycle CO_2 emissions of motor vehicles rather than just fuel economy. In this study, CAFEs and CAFE targets of Japan's domestic automobile manufacturers were estimated and it was assessed how well the manufacturers met their targets. The impact that the introduction of the CAFE standards in Japan will have on motor vehicle-derived lifecycle CO_2 emissions was also analyzed.

Specifically, the 2015 sales performance figures of seven of Japan's automobile manufacturers (Toyota Motor Corporation, Nissan Motor Co., Ltd., Honda Motor Co., Ltd., Mitsubishi Motors Corporation, Mazda Motor Corporation, Suzuki Co., Ltd., and Subaru Co., Ltd.) and the published fuel economy values of the sold vehicle models were investigated, in order to estimate the CAFE of each company, as well as their CAFE target, and to assess how well the manufacturers met their targets in 2015.

The car sales of a specific company affect not only the CAFE based on the weighted-average fuel economies of the car sales but also the lifecycle CO_2 of motor vehicles sold by the company. To estimate the lifecycle CO_2 of motor vehicles, it is important to estimate the lifecycle CO_2 emission intensity of a specific vehicle model sold by the company expressed in ton-CO_2 per vehicle. This is because several studies treated a wide variety of vehicles as a specific homogeneous product and analyzed a life cycle assessment of the specific vehicle (e.g., aggregated conventional gasoline vehicle) with a comparison of the environmental burdens of conventional vehicles with vehicles equipping other engines, electric vehicles, hybrid vehicles, plug-in hybrid vehicles, and hydrogen fuel cell vehicles (Bauer et al., 2015; Hawkins et al., 2013; Samaras and Meisterling, 2008; Thomas, 2009).

Using the pooled observations of cars sold by the above seven manufactures in 2015, a statistically specified relationship was created between car prices and car weights as a regression equation. When the car price of an 'average vehicle' described in the Japanese commodity-by-commodity input-output table (Ministry of Internal Affairs and Communications, Japan, 2010) was inserted into the specified relationship between car prices and car weights, a car weight of the average vehicle could be obtained. Using the ratio between the embodied CO_2 emission intensity of the ‘average vehicle’ provided by the Embodied Energy and Emission Intensity Data for Japan using Input-Output Tables (Nansai & Moriguchi, 2012) and the car weight of the ‘average vehicle’ estimated in this study, the embodied CO_2 emission intensity of the specific vehicle model of the company was proportional to the weight of the car. Using the proposed methodology, a new database of disaggregated lifecycle emissions of motor vehicles sold by the Japanese auto manufactures was compiled.

Estimating the disaggregated lifecycle inventory database of motor vehicles, the impact that the introduction of the CAFE standards in Japan is likely to have on motor vehicle-derived lifecycle CO_2 emissions was evaluated, to assess the validity of the CAFE standards from an environmental perspective.

Companies would maximize profits from car sales under the CAFE standards. This study therefore formulated an optimization problem of maximizing profit, as the objective function, under constraints with respect to both car sales and the CAFE standards and examined how the optimized car sales of each company differed from the actual car sales and what effect achieving the CAFE standards would have toward reducing lifecycle CO_2 emissions under the optimized car sales.

The remainder of this chapter is organized as follows: Section 2 describes the methodology, Section 3 explains the data used in this study, Section 4 provides the results and discussion, and Section 5 concludes this paper.

3.2. Methodology

3.2.1. CAFEs and CAFE Targets for Automobile Manufacturers

The CAFE of each automobile manufacturer, C (km/L), was estimated based on the number of new vehicle sales and the published fuel economy values using the following equation:

$$C = \frac{X}{\sum_{i=1}^{N} \frac{x_i}{z_i}} \tag{3-1}$$

where X is the number of new vehicle sales of a particular automobile manufacturer j, z_i (km/L) is the fuel economy value of vehicle model i of the automobile manufacturer, and x_i is the number of vehicle model i that the automobile manufacturer sold for the year. Furthermore, N is the number of different vehicle models sold by the relevant automobile manufacturer. As the CAFE obtained from Equation (3-1) increases, the fuel economy of the 'average vehicle' sold by the relevant automobile manufacturer improves. The CAFE target, $\tilde{C}$ (km/L), is calculated as follows (National Highway Traffic Safety Administration (National Highway Traffic Safety Administration, 2016):

$$\tilde{C} = \frac{X}{\sum_{k=1}^{M} \frac{x_k}{\tilde{z}_k}} \tag{3-2}$$

where $\tilde{z}_k$ (km/L) is the target fuel economy value for a predefined passenger vehicle weight category k, x_k is the total number of sales of vehicle models belonging to vehicle weight category k by a particular automobile manufacturer, and M is the number of vehicle weight categories.

3.2.2. Sales Maximization

In this section, the optimal number of unit sales for each vehicle model for automobile manufacturers to maximize sales while satisfying the CAFE standards given by Equation (3-2) is estimated. This is done so by solving the linear programming problem illustrated in Equations (3-3) through (3-6) below.

$$\text{Max. } \sum_{i=1}^{N} p_i x_i \tag{3-3}$$

such that

$$\frac{\sum_{i=1}^{N} x_i}{\sum_{i=1}^{N} \frac{x_i}{(1+\varepsilon) z_i}} \geq \frac{\sum_{i=1}^{N} x_i}{\sum_{k=1}^{M} \sum_{i_k=1}^{N_j} \frac{x_i}{\tilde{z}_k}} \tag{3-4}$$

$$x_i \leq \alpha x_i^* \tag{3-5}$$

$$\sum_{i=1}^{N} x_i \leq \beta \sum_{i=1}^{N} x_i^* \tag{3-6}$$

where p_i is the price for each vehicle model, x_i^* is the actual number of units sold, α is a parameter for determining the upper limit of vehicle models i, β is a parameter determining the upper limit of total units sold, and ε represents the rate of fuel economy improvement. Equation (3-4) is a constraint for the linear programming problems in which the relevant company must meet the CAFE standards. In this study, four scenarios are considered: Scenario I, fuel economy for the vehicle models is the baseline value (ε = 1.0); and Scenarios II, III, and IV, in which fuel economy for the vehicle models is uniformly improved from the baseline fuel economy by 10%, 15%, and 20%, respectively (ε = 1.1, ε = 1.15, and ε = 1.2). Next, Equation (3-5) is the constraint for sales patterns in which the relevant company's current number of units sold for vehicle model i grows by a factor α, which is set as α = 2 for this study. Finally, Equation (3-6) is the constraint for the total number of units sold, which is set as β = 1 for this study. This study solves the sales maximization problem within the four fuel economy improvement scenarios given above (Scenarios I–IV) to estimate the optimal sales pattern for the vehicle models of the relevant automobile manufacturers.

3.2.3. Lifecycle CO_2 Emissions of the Automobile Manufacturers

For gasoline-engine and hybrid vehicle models i, the average lifecycle emission intensity per vehicle is found as f_m by taking the weighted average by number of units sold for the lifecycle emission intensity ($f_{m,i}^{g}$ and $f_{m,i}^{h}$) derived from the manufacturing, transportation, and sales origin for a single vehicle. Here, one can estimate the lifecycle

CO_2 emissions (t-CO_2) derived from the automobiles as sold by the relevant companies in Japan for 2015 as follows:

$$Q = \sum_{i \in N_g} x_i f_{m,i}^{g} + \sum_{i \in N_h} x_i f_{m,i}^{h} + \sum_{i=1}^{N} x_i f_{g,i} + \sum_{i=1}^{N} f_{h,i} \tag{3-7}$$

where N_g is the set of gasoline-engine vehicles models, N_h is the set of hybrid vehicle models, $f_{g,i}$ is the CO_2 emission intensity during travel for vehicle model i and $f_{h,i}$ is the CO_2 emission intensity during disposal of vehicle model i.

For a relevant automobile manufacturer, the weighted average fuel economy for a passenger vehicle i is defined as as e_i (km/L) and the lifetime travel distance of passenger vehicles as d (km). Thus, g_i (L), the lifetime gasoline consumption of a passenger vehicle i, is obtained as follows:

$$g_i = \frac{d}{e_i} \tag{3-8}$$

The CO_2 emissions due to gasoline consumption during travel per vehicle can then be estimated by multiplying the CO_2 emission intensity generated per liter of gasoline burned r_g by the quantity of gasoline consumed g_i from Equation (3-8):

$$f_g^{direct} = g_i r_g = \frac{dr_g}{e_i} \tag{3-9}$$

In addition, the CO_2 emissions associated with refining the gasoline necessary for travel per vehicle can be estimated by multiplying the CO_2 emission intensity generated per liter of gasoline refined r_c by the quantity of gasoline consumed g_i from Equation (3-8):

$$f_{g,i}^{indirect} = g_i r_c = \frac{dr_c}{e_i} \tag{3-10}$$

Thus, the embodied CO_2 emission intensity during travel per vehicle $f_{g,i}$ in Equation (3-7) is the sum of $f_{g,i}^{direct}$, the direct emissions generated by gasoline consumption during travel, and $f_{g,i}^{indirect}$, the indirect emissions generated in refining the gasoline:

$$f_{g,i} = f_{g,i}^{direct} + f_{g,i}^{indirect} \tag{3-11}$$

3.3. Data

In this study, the vehicle models of each company sold in 2015 were as follows: Toyota, 42; Nissan, 21; Honda, 17; Mitsubishi, 10; Mazda, 9; Subaru, 9; and Suzuki, 8. The number of vehicles of each model sold by each company, which is necessary for calculating the CAFE and CAFE target, can be obtained from data on the number of vehicles sold by brand (Japan Automobile Dealers Association, 2016). For the fuel economy of each vehicle model the fuel economy figures for each vehicle model in JC08 mode cycle was used, as published in the Automobile Fuel Economy List(Ministry of Land, Infrastructure, transport, and tourism, 2016). The vehicle weight categories for the CAFE standards due to be introduced in MY2020 are shown in Table A1.

The CO_2 emission intensities per passenger vehicle in manufacturing, during travel, and in disposal were estimated using the Embodied Energy and Emission Intensity Data for Japan Using Input-Output Tables (Nansai & Moriguchi, 2012). The passenger vehicle lifetime travel distance d was assumed to be 100,000 km and therefore estimated the emission intensity during travel r_g to be 0.00231 t-CO_2 and r_c to be 0.00063 t-CO_2. In addition, in accordance with a previous study (Kagawa et al., 2013), the emission intensity in disposal $f_{h,i}$ was set to be 0.0574 t-CO_2.

In order to estimate the life cycle CO_2 emission intensity of vehicles, the life cycle CO_2 emission intensity derived from both manufacturing and driving must be estimated for each vehicle model. While by no means a simple task, in this study, the lifecycle CO_2 emission intensity for each vehicle model was estimated by specifying a relationship for model sales prices and new vehicle weight. First, the sales price information was obtained for 82 gasoline-engine vehicle models sold by the automakers (Toyota, Nissan, Honda, Mitsubishi, Mazda, Subaru, and Suzuki) in 2015 from Autoc One(Autoc one, 2018), an informational site that releases comprehensive vehicle sales information. Vehicle weight information was also obtained for the same 82 models from the MLIT automotive information site (Ministry of Land, Infrastructure, Transport and Tourism, 2016). From the sales price and vehicle weight data for the 82 models, a regression analysis was run and the following results were obtained.

$$p_i^g = 0.35w_i^g - 222 \tag{3-12}$$

(7.46) (-3.09)

Adjusted R^2: 0.38

where w_i^g (kg) is the vehicle weight for vehicle model i and p_i^g (10,000s of Japanese yen) is the sales price for vehicle model i. The numbers in parentheses below the parameters are the t-values, and each of the estimated parameters is statistically significant at the 1% level in a two-sided test. The relationship given in Equation (3-12) shows us that an increase of 100 kg in vehicle weight corresponds to an increase of 350,000 yen in sales price.

From the 2005 Input-Output Tables, the average vehicle sales price in 2005 was 2.2 million yen. Given this, the relationship specified in Equation (3-12) can be used to estimate the average vehicle weight as $w^g = (220 + 222) / 0.35 = 1264$ kg. Meanwhile, from the Embodied Energy and Emission Intensity Databook (3EID) (Nansai & Moriguchi, 2012) as based on the 2005 Input-Output Table as released by the National Institute for Environmental Studies, the average lifecycle emission intensity for vehicle production is 1.93 t-CO_2 per 1 million yen, and the lifecycle emission intensity for transportation and sales services incidental to sales price for one vehicle unit is 1.2 t-CO_2

per 1 million yen. Accordingly, one can estimate a lifecycle CO_2 emission intensity of $1.93 \times 2.2 = 4.2$ t-CO_2 as derived from manufacturing one average vehicle in 2005 with a sales price of 2.2 million yen and vehicle weight of 1,264 kg. Next, the lifecycle CO_2 emission intensity was estimated, as derived from manufacturing a relevant vehicle model by taking the ratio of the vehicle weight of that model to the average vehicle weight (1,264 kg) and multiplying by the unit intensity derived from manufacturing. To estimate the lifecycle CO_2 emission intensity incidental to transportation and sales services for one unit of a relevant vehicle model, the lifecycle emission intensity for transportation and sales services was taken as 1.2 t-CO_2 per 1 million yen and multiplied this quantity by the sales price of the relevant vehicle model. The lifecycle CO_2 emission intensity $f_{m,i}^{g}$ for a single gasoline vehicle model i was then solved for by adding up the lifecycle CO_2 emission intensities derived from manufacturing and from transportation and sales for the relevant model. It is important to note that although we can estimate the lifecycle CO_2 emissions by multiplying the average lifecycle emission intensity for vehicle production (1.93 t-CO_2 per 1 million yen) by each vehicle price, and that the estimated emissions are not consistent with the vehicle weight important for the CAFEs.

Similarly, a separate regression analysis for 42 hybrid vehicle models was run and the following relationship for sales price and vehicle weight was obtained:

$$p_i^h = \underset{(8.12)}{0.41} w_i^h \underset{(-3.54)}{- 282} \tag{3-13}$$

Adjusted R^2: 0.62

where w_i^h (kg) is the vehicle weight for hybrid vehicle model i and p_i^h (10,000s of yen) is the sales price for hybrid vehicle model i. Again, the numbers in parentheses below the parameters are the t-values, and each of the estimated parameters is statistically significant at the 1% level in a two-sided test. The relationship given in Equation (3-13) shows us that an increase of 100 kg in vehicle weight for hybrid vehicles corresponds to an increase of 410,000 yen in sales price. The lifecycle CO_2 emission intensity $f_{m,i}^h$ derived from manufacturing and from transportation and sales for a single hybrid vehicle model i was solved for with the same methods described above for calculating unit intensity for a gasoline vehicle model. The detailed lifecycle CO_2 emission intensity data by vehicle model as estimated in this study are described in Table S3 of the Supporting Information.

3.4. Results

3.4.1. Life-Cycle CO_2 Emission Intensities of Vehicle Models

Table 1 shows the data showing mean, standard deviation, maximum value and minimum value of the life cycle CO_2 emission intensities of vehicle models of seven automobile manufactures in Japan estimated by Equations (3-12) and (3-13). According to Table 3-1, the maximum value of the life cycle CO_2 intensity in seven firms is 60.74 t-CO_2/car Toyota CENTURY (gasoline vehicle) and the minimum value is 14.8 t-CO_2/car Toyota AQUA (Hybrid vehicle). Thus, there is a large difference in life cycle CO_2 intensities within a firm as well as between firms. The mean of the intensities of each firm is caused by the number attributes (e.g., body weight, fuel economy, etc.) of cars sold by the firm and it means that firms with a higher standard deviation of the intensities like Toyota have more varieties of cars.

Table 3-1. Lifecycle CO_2 intensities and life cycle CO_2 emissions in 2015

	The number of vehicle models	Estimated life cycle emission intensity					Baseline (2015) Life cycle CO_2
		Mean (t-	Weighted mean of	Standard deviation	Maximum value	Minimum value	

		CO_2/car)	the number of sold vehicles	(t-CO_2/car)	(t-CO_2/car)	(t-CO_2/car)	emissions (million t-CO_2)
Toyota	42	28.5	23.7	47.3	60.7	14.8	28.4
Nissan	21	32.7	24.9	39.3	54.4	18.3	8.0
Honda	17	22.8	21.2	13.8	32.6	15.9	8.0
Mitsubishi	10	28.0	27.7	32.6	45.3	18.0	0.7
Mazda	9	28.0	24.9	17.7	37.7	20.2	3.9
Suzuki	8	31.3	25.7	20.5	43.1	23.8	1.9
Subaru	9	28.1	27.7	9.0	35.7	20.9	3.4

The last column of Table 3-1 shows the life cycle CO_2 emissions of each firm in 2015 that is the benchmark emissions in this analysis. Importantly, Toyota has the largest number of vehicle models sold (see first column of Table 1) and it has the largest life cycle CO_2 emissions, amounting to 28.4 million t-CO_2 in 2015. This is because the life cycle CO_2 emissions depend on the number of sold cars as well as the number of sold vehicle models. The total of CO_2 emissions of Japan in 2015 was 1325 million t-CO_2 (Ministry of Environment., 2017) and the sum of the life cycle CO_2 emissions of seven automobile manufactures in 2015 was 54.2 million t-CO_2 that accounts for 4% of the total CO_2 emissions of Japan. Therefore, it is essential to management the life cycle CO_2

emissions in automobile industry.

3.4.2. CAFEs and CAFE Targets of Seven Automobile Manufacturers in Japan

Table 3-2 shows the CAFEs and CAFE targets of Japan's seven major automobile manufacturers (Toyota, Nissan, Honda, Mitsubishi, Mazda, Subaru, and Suzuki), as estimated using Equations (3-1) and (3-2).

Table 3-2. CAFEs and CAFE targets of seven automobile manufacturers

(unit: km/L)

Company name	CAFE target	CAFE
Toyota	17.6	19.0
Nissan	18.0	17.9
Honda	19.1	21.6
Mitsubishi	16.4	13.3
Mazda	20.6	18.2
Suzuki	23.2	21.2
Subaru	17.4	15.1

Table 3-2 shows that the CAFEs of Toyota and Honda exceeded their CAFE targets, while those of Nissan, Mitsubishi, Mazda, Subaru, and Suzuki fell below their CAFE targets. When the CAFE standards are introduced in 2020, Nissan, Mitsubishi, Mazda, Subaru, and Suzuki which cannot currently meet their targets, will need to step up their efforts to improve fuel economy. The relationships between fuel economy by vehicle model, vehicle weight, and the number of vehicle sales by model for the two automobile manufacturers that met their CAFE targets, Toyota and Honda, are plotted in Figures 3-1 and 3-2 of the Supporting Information, respectively. Figure 3-1 shows that Toyota sells a large number of vehicle models that have exceptionally good fuel economies. The fact that Toyota sells a much larger number of hybrid vehicles than the other six automobile manufacturers appears to be a factor in Toyota’s success in meeting the CAFE standards. On the whole, Honda sells fewer vehicle models with poor fuel economies than does Toyota, and for that reason, it too managed to meet the CAFE standards (Figure 3-2). Thus, differences in sales patterns and fuel economy technology between companies account for the gaps in their ability to achieve their targets.

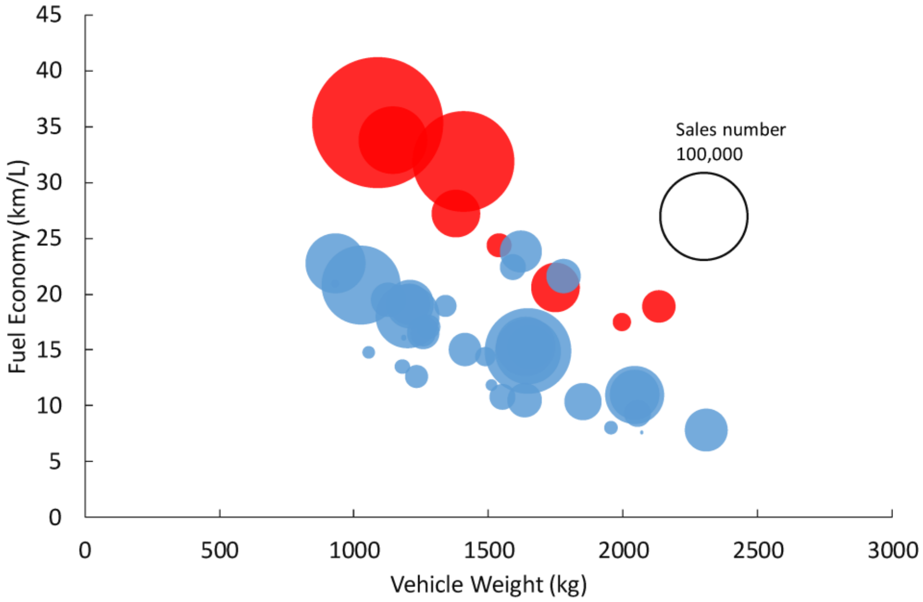


Figure 3-1. The relationships between fuel efficiency by vehicle model, vehicle weight, and the number of vehicle sales by model for Toyota

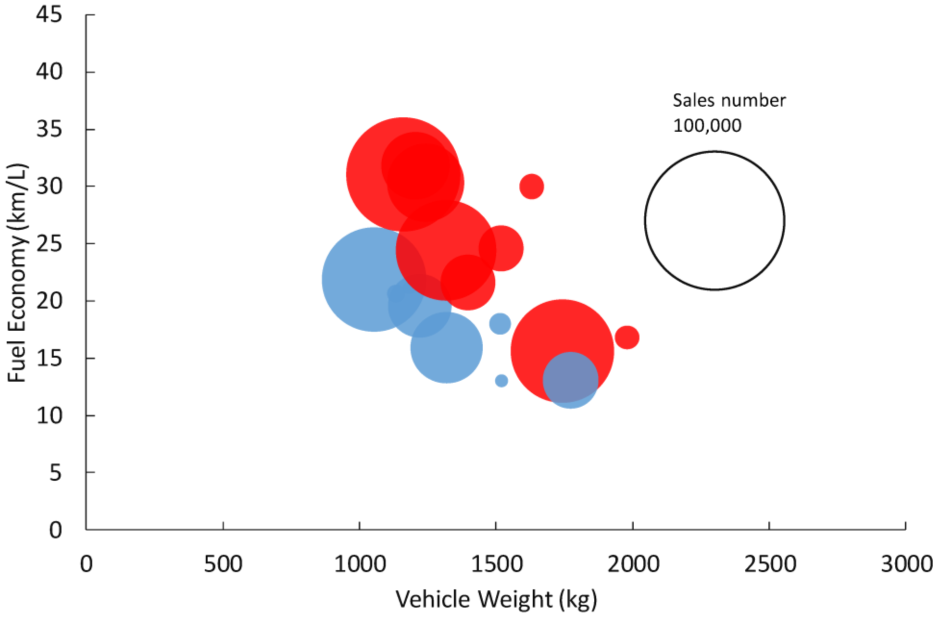
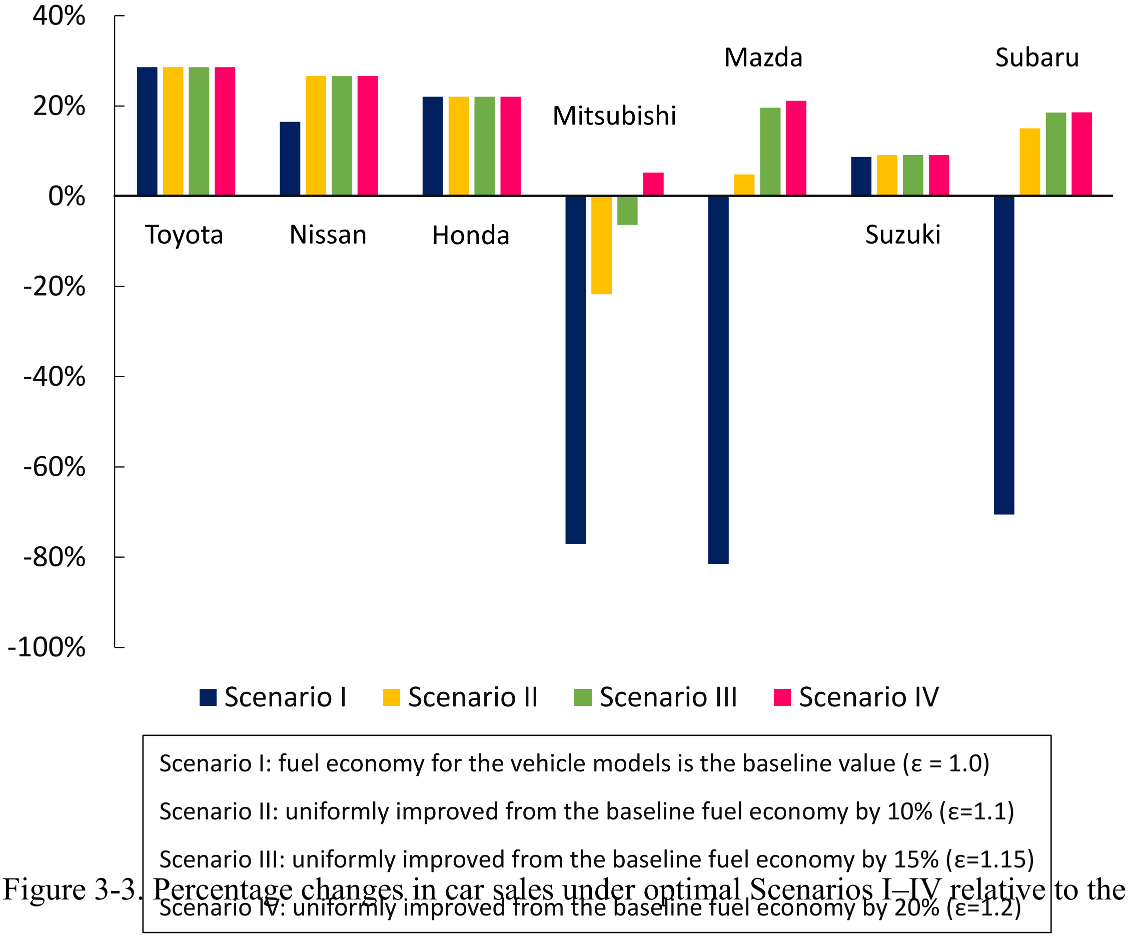


Figure 3-2. The relationships between fuel efficiency by vehicle model, vehicle weight, and the number of vehicle sales by model for Honda

3.4.3. Sales Maximization Under the CAFE Standards

Before delving into the results for sales maximization, let us first review the state of Japan's seven major automobile manufacturers as of 2015. According to the Japan Automobile Dealers Association, approximately 2.7 million passenger vehicles (standard-sized vehicles (white plate vehicles) and Kei passenger cars (yellow plate vehicles)) were sold in 2015. It should be noted that Kei passenger car has an engine of 660 cc or smaller, whereas standard-sized vehicles has a larger internal-combustion engine than 660 cc. Sales shares by company were led by Toyota at 46% (1.25 million vehicles), followed by Honda at 14% (380,000), Nissan at 11% (290,000), Mazda at 7% (180,000), Subaru at 5%, (120,000), Suzuki at 3% (70,000), and Mitsubishi at 1% (30,000). Japan's automotive-related industries combined for a market scale of 64 trillion yen (Ministry of Finance, 2016).

While these 2015 sales figures do not account for CAFE standards, as given in the previous section, fuel economy and sales patterns for each vehicle model are two necessary elements for achieving the CAFE standards. Thus, the sales for each scenario will now be given with regards to the CAFE standards by performing sales maximization as specified in Equation (3-3)



Scenario I: fuel economy for the vehicle models is the baseline value (ε = 1.0)

Scenario II: uniformly improved from the baseline fuel economy by 10% (ε=1.1)

Scenario III: uniformly improved from the baseline fuel economy by 15% (ε=1.15)

Scenario IV: uniformly improved from the baseline fuel economy by 20% (ε=1.2)

Figure 3-3. Percentage changes in car sales under optimal Scenarios I–IV relative to the actual sales.

Figure 3-3 shows the rate of change in current sales for Scenarios I through IV compared to 2015 sales. Sales tend to increase with the rate of fuel economy improvements but are still decreasing for some companies; this likely depends on the sales patterns of the different companies. The slumping sales of certain companies can be explained by the poor fuel economy of each vehicle model and limited vehicle models that can be sold to satisfy the CAFE standard constraint. In contrast, sales for Nissan and

Suzuki, two manufacturers who have not met their CAFE targets, increased in Scenario I, illustrating the vital importance of sales patterns (Figure 3-3). In Scenario IV (fuel economy improved 20%), total sales across all seven manufacturers increased by 13.7 trillion yen, with each manufacturer increasing as follows: 10 trillion yen at Toyota, 2 trillion at Nissan, 700 billion yen at Mazda, 600 billion yen at Subaru, 200 billion yen at Honda, 100 billion yen at Mitsubishi, and 100 billion yen at Suzuki. Overall, the automotive market would increase 20% (Figure 3-3).

Currently, five of the seven manufacturers—Nissan, Mitsubishi, Mazda, Suzuki, and Subaru—have not achieved their CAFE targets (Table 3-2). As shown in Table 3-3, however, all seven can implement sales plans for maximizing sales and still achieve the CAFE standards in all of the fuel economy scenarios. Even though the sales optimization has the CAFE standards imposed as an inequality constraint, note that the CAFEs, which are based on the endogenously determined optimal vehicle model sales figures, are the same as the CAFE target. One important point is that Toyota's CAFE target based on its actual units sold for 2015 is 17.0, whereas its CAFE target based on optimized units sold would have been 15.6. This illustrates that sales activity aimed at sales maximization will bring down the CAFE target and consequently lead to a lack of discipline.

Table 3-3. CAFEs and CAFE targets of seven automobile manufacturers for the actual and optimal cases.

Actual case				Optimal case under Scenario I		
Company name	CAFE target	CAFE	Achievement status (Yes/No)	CAFE target	CAFE	Achievement status (Yes/No)
Toyota	17.6	19.0	Yes	15.6	15.6	Yes
Nissan	18.0	17.9	No	16.6	16.6	Yes
Honda	19.1	21.6	Yes	17.3	20.0	Yes
Mitsubishi	16.4	13.3	No	22.6	22.6	Yes
Mazda	20.6	18.2	No	20.1	20.1	Yes
Suzuki	23.2	21.2	No	23.2	23.2	Yes
Subaru	17.4	15.1	No	16.9	16.9	Yes
Mean	18.9	18.0		18.9	19.3	
S.D	2.3	3.0		3.1	3.0	

If the above CAFE standards are instated, each company can fashion their sales activity to maximize sales by shifting their sales patterns. In the next section, the environmental loads brought about by the sales activity of each company if this happens are analyzed.

3.4.4. Lifecycle CO_2 Emissions Under the Optimized Sales Pattern

The original purpose of the CAFE system was to restrict CO_2 and air pollutant emissions by making fuel economy standards more flexible. Thus, a simple analysis of

CAFE standard achievement rates would be insufficient; one needs to analyze how the CAFE standards relate to the lifecycle CO_2 emissions associated with vehicles. Therefore, this section analyzes the lifecycle CO_2 emissions derived from vehicles with the CAFE standards introduced.

As estimated with Equation (3-7), the lifecycle CO_2 emissions associated with vehicles manufactured by their relevant automobile manufacturer (the carbon footprint of that automobile manufacturer) in 2015 were as follows: 20 million tons for Toyota, 8 million tons for Honda, 7 million tons for Nissan, 3.6 million tons for Mazda, 3 million tons for Subaru, 1.4 million tons for Suzuki, and 730,000 tons for Mitsubishi. These constitute a footprint of approximately 40 million tons for all seven manufacturers. Thus, the Japanese automotive industry's carbon footprint accounts for roughly 30% of CO_2 emissions attributed to Japan's transportation sector (Ministry of Land, Infrastructure, Transport and Tourism 2017).

Next, Figure 3-4 shows the rate of change in carbon footprint for each company from their baseline carbon footprints, based on the optimal units sold for each company in fuel economy improvement Scenarios I through IV if they maximize their sales while meeting the CAFE standards. From Figure 3-4, one can see that as the fuel economy improvement rates increase and gasoline consumption decreases, a company's carbon footprint will also tend to decrease.

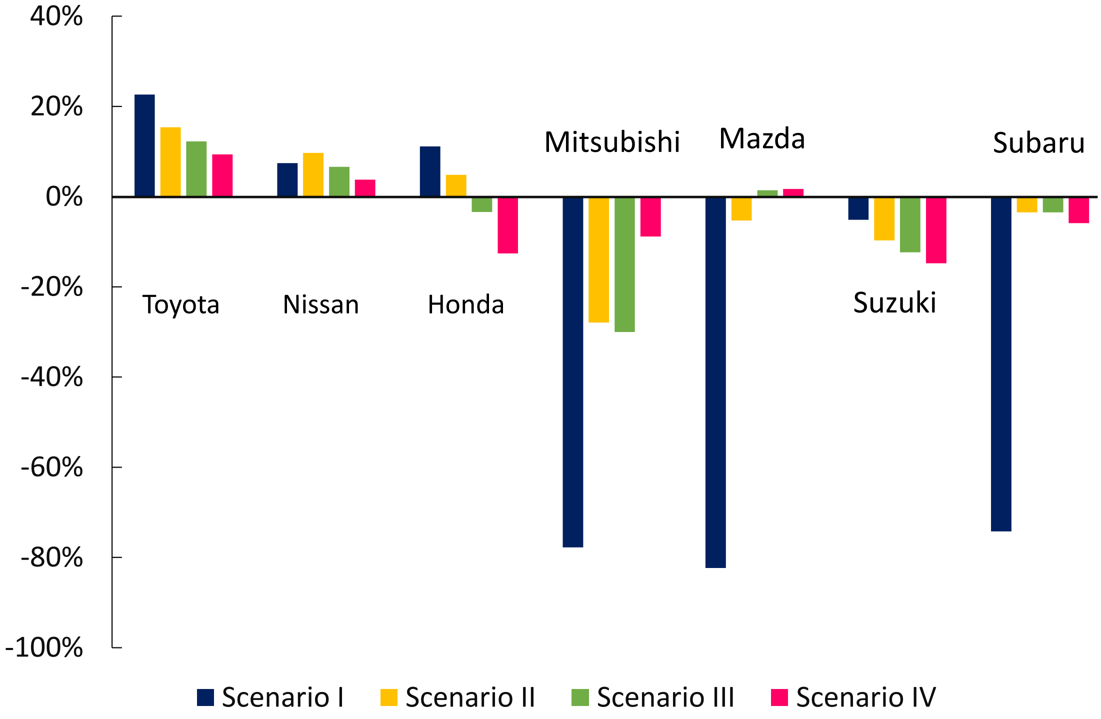


Figure 3-4. Percentage changes in lifecycle CO_2 emissions under optimal scenarios I–IV relative to the actual emissions.

In addition, from Figures 3-3 and 3-5, although optimal vehicle sales patterns under the CAFE standard constraint would help to increase sales, they would also increase carbon footprints and thus be bad for the environment (see the Toyota and Nissan values in Figures 3-3 and 3-4). Based on the estimated optimal sales patterns for each company in Scenario IV, where fuel economy for the vehicle models sold is improved 20%, the overall carbon footprint for all seven companies would be approximately 53 million tons, a 1.2-fold increase over their 2015 carbon footprint. In looking to maximize sales, manufacturers have tended to sell heavier vehicles, given the correlation between weight and price. Thus, their carbon footprint based on the optimal sales patterns has not decreased compared to the 2015 baseline value. One important finding in this study is that automobile manufacturer behavior—striving to achieve CAFE standards with the goal of maximizing car sales—will increase their carbon footprint and actually worsen the environment. Is is therefore concluded that it is necessary for automobile manufacturers to mitigate the carbon footprint associated with vehicle lifecycle under the CAFE standards.

3.5. Conclusion and Policy Implications

This study estimated the CAFEs and CAFE targets of seven Japanese automobile manufacturers, and identified the manufacturers that met their CAFE targets and those that did not. It was clearly observed that the manufacturers that met their CAFE targets were of two distinct types: a company that offered a wide range of vehicle models with good fuel economy (Honda) and a company that focused on selling vehicle models with exceptionally good fuel economy (Toyota).

This study further proposed an optimization problem with an objective function of maximizing the profit under constraints with respect to both car sales and CAFE standards, and addressed the question of how the optimized car sales of each company differ from the actual car sales and what the effect of meeting the CAFE standards would have on reduction in lifecycle CO_2 emissions under the optimized car sales. Our main findings were as follows:

(1) Automobile manufacturers can maximize their sales under the constraints of the CAFE standards, but vehicle sales plans based on sales maximization will lower their CAFE standard scores and could cause a moral hazard among automobile manufacturers.

(2) Economically optimal automobile manufacturer behavior—striving to achieve CAFE standards while maximizing sales—will increase the manufacturers' overall carbon footprint and actually worsen the environment.

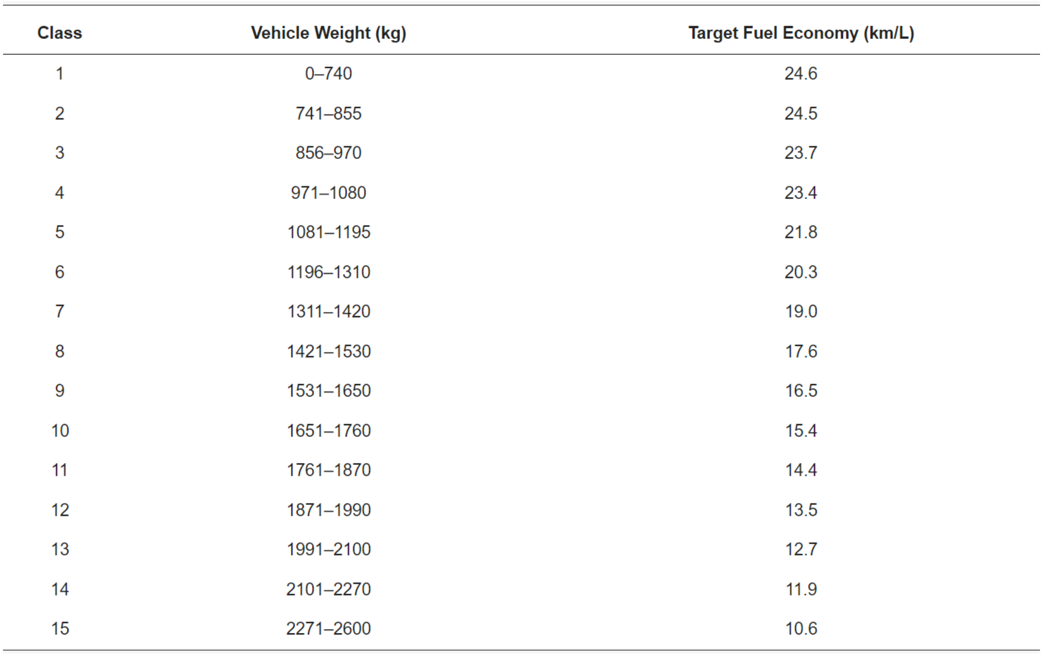
Toyota published an environmental report (Toyota Motor Corporation, 2013) concluding that "In the United States, Toyota's model year 2013 fleet achieved the required U.S. Corporate Average Fuel Economy (CAFE) standards and Toyota met the required GHG standards in both the United States and Canada". Although it is important to communicate environmental outcomes to the public, it seems that the relationship between CAFE and GHG emissions is still unclear, because the GHG emissions reported by Toyota took into consideration only CO_2 emissions generated by fuel consumption in a defined distance; the 2013 report did not assess how a strategy to achieve the CAFE standards would affect the overall CO_2 emissions through the automobile lifecycle.

Although one of the objectives of the Japanese CAFE standards is to promote more flexible motor vehicle sales by companies(Ministry of Land, Infrastructure, Transport and Tourism, 2011), the standard ignores an important aspect of life cycle CO_2 emissions. This paper suggests that automakers should pay more attention to the corporate life cycle CO_2 emissions and publish a more comprehensive sustainability report including answers to the questions of how meeting the CAFE standards would affect the corporate lifecycle CO_2 emissions, and what strategy can be effective for reducing the corporate lifecycle CO_2 emissions under the CAFE standards. This study demonstrates that the CAFE analysis framework proposed in this paper is powerful for addressing the above questions. In addition, the results reveal that Japanese automakers can significantly reduce CO_2 emissions under the CAFE standards.

It is also important to note that automobile manufactures that violate the CAFE standards in Japan will be fined one million Japanese yen after implementation of the CAFE standards, thus the fine under the Japanese CAFE standards will be much less than those in the U.S.A. and European countries (Ministry of Land, Infrastructure, Transport and Tourism, 2011). To strengthen these currently weak regulations, the Japanese government should monitor the achievement status of all automobile manufactures and obligate the Japanese automobile manufactures to submit comprehensive sustainability reports as described above to the government. Such sustainability reports including the results estimated using the analysis framework proposed in this study can be practically useful for policy makers in arguing how the CAFE standards can contribute to reducing societal CO_2 emissions, and what might be a more effective policy centered around automobile lifecycle management under the CAFE standards.

Appendix.

Table A1. Weight categories



Class	Vehicle Weight (kg)	Target Fuel Economy (km/L)
1	0–740	24.6
2	741–855	24.5
3	856–970	23.7
4	971–1080	23.4
5	1081–1195	21.8
6	1196–1310	20.3
7	1311–1420	19.0
8	1421–1530	17.6
9	1531–1650	16.5
10	1651–1760	15.4
11	1761–1870	14.4
12	1871–1990	13.5
13	1991–2100	12.7
14	2101–2270	11.9
15	2271–2600	10.6

Chapter 4. Driving Propensity and Vehicle Lifetime Mileage: A Quantile Regression Approach

4.1. Introduction

The Organization for Economic Co-operation and Development (OECD) Environmental Outlook shows that "greenhouse gas emissions from the transportation sector are projected to double by 2050 due to a strong increase in demand for cars in developing countries, and OECD economies have been responsible for most of the emissions." (OECD, 2011, p.15). In particular, it is extremely important to reduce the emissions of motor vehicles by improving their fuel efficiency (OECD, 2011).

The Corporate Average Fuel Economy (CAFE) standard is one example of policies aimed at improving fuel efficiency. This standard was adopted by the United States in 1975 (National Highway Traffic Safety Administration, 2016) and it is aimed at improving vehicle fuel efficiency, whereby the average vehicle fuel efficiency (miles per gallon) calculated from the weighted average of sold vehicles must not fall below the "fuel efficiency target standard (miles per gallon) established by the government" (National Highway Traffic Safety Administration, 2016).

Meanwhile, Japan has adopted the “top-runner” model, which aims for the fuel efficiency (km per liter) of all models manufactured by specific automotive companies to approach that of the most fuel-efficient model in the relevant vehicle weight category (Ministry of Land, Infrastructure, transport, and tourism, 2011). In addition to the top-runner model, Japan plans to adopt company-specific fuel efficiency standards from 2020, in line with its twofold goal of reducing the CO_2 emissions of the transport sector and realizing more flexible promotion of vehicle sales (MLIT, 2011). Important forerunners of the CAFE standard include the tightening of fuel efficiency standards and increases in gasoline taxes to reduce gasoline consumption. The impacts of these environmental regulations have been estimated and well documented in previous literature (e.g., Austin & Dinan, 2005; Bento et al., 2009; Goldberg, 1998; Jacobsen, 2013; Whitefoot & Skerlos, 2012).

Kaneko (2019) measured the effects of the CAFE standard on vehicle lifecycle CO_2 emissions (i.e., the CO_2 emissions produced during vehicle manufacture, driving, and disposal) from vehicles sold by relevant automotive companies. However, when calculating CO_2 emissions during driving (i.e., emissions from fuel consumption), Kaneko (2019) is limited by the assumption that drivers have fixed propensities to drive and that all drivers travel the same distance in a year. Other previous studies have also ignored the question of how often drivers use their cars. Kaneko (2019) assumes an average annual mileage of 10,000 km (or a lifetime mileage of 100,000 km over a vehicle's 10-year lifespan)—based on a 2015 report by the Toyota Motor Corporation—when calculating vehicle lifecycle CO_2 emissions. There have been many studies on vehicle lifecycle, in which vehicle lifetime mileages range from 150,000 to 300,000 km among these lifecycle assessment studies (e.g., Hawkins et al., 2013).

An important study by Weymar & Finkbeiner (2016) analyzed the relationship between vehicle lifetime and lifetime mileages using data of 800,000 vehicles sold in Germany. They divided cars into eight segments, from urban small cars (A000) to midsized cars (A00, A0, A, B, C, D) and ultra-luxury cars (E); they also differentiated between gasoline and diesel engines and found that varying lifetimes and mileages of passenger cars depend upon the engine type and the vehicle's segment. Based on their study, Weymar & Finkbeiner (2016) recommended differentiating between three different groups of segments,A00/A0, A/B, and C, with mileages of 170,000, 200,000, and 230,000 km, respectively.

A limitation of Weymar & Finkbeiner (2016) study is that it ignores the differences in heterogeneous drivers' propensity to drive and estimates “one relational expression” between lifetime mileage (the dependent variable) and vehicle lifetime (the independent variable) using regression analysis.

In this study, we seek to extend upon the work of Weymar & Finkbeiner (2016). First, we focus on one gasoline and one hybrid vehicle of similar function to analyze the relationship between lifetime mileage (the dependent variable) and vehicle lifetime (the independent variable) for both types of vehicle. Second, we employ a quantile regression approach to estimate the effect of the driver's propensity to drive on lifetime mileage, an indicator of how actively drivers use their vehicles. Third, by estimating the CO_2 emissions produced by driving based on driver's propensity to drive, we analyze the effect of propensity to drive on vehicle lifecycle CO_2 emissions.

The remainder of this chapter is structured as follows: Section 2 describes our methods, Section 3 describes the data used in the research, Section 4 presents the results, and Section 5 describes the limitations of the present study. Finally, some concluding remarks are made in Section 6.

4.2. Methodology

In response to the aforementioned gaps in previous research, this study employs a quantile regression approach to analyze consumers' propensities to drive (Koenker & Bassett, (1978). We use the ordinary least squares (OLS) method to determine the properties of the average of the distribution of observed data (in the case of this study, vehicle age and mileage data; Koenker & Bassett (1978)). However, it is not always possible to analyze the averages of observed data; furthermore, in the case of insurance risks or social disparities, the upper and lower extremes of a range of observed data distributions are extremely important to the analysis. Accordingly, a regression analysis of observed data quantiles (i.e., quantile regression analysis) is used to focus on the distribution of the observed data (Koenker & Bassett, 1978).

The quantile regression analysis model is described below. Random samples—including individual n data points—are shown as $\{(Y_1, X_1), \dots, (Y_n, X_n)\}$. Here, X_i denotes the independent variable vector for i numbered observed data, while Y_i denotes the dependent variable for i numbered observed data. Considering the conditional quantile Y_i when independent variable vector X_i is applied, we may express the Y_i conditional τ

quantile as follows:

$$Q_\tau(Y|X) = \inf\{y: F_{y|X}(y|x) \geq \tau\} \tag{4-1}$$

Here, $F_{Y|X}(y|x)$ denotes the Y_i conditional distribution function. Accordingly,

$$Q_\tau(Y|X) = F_{Y|X}^{-1}(\tau|x) \tag{4-2}$$

holds true. When estimating Y quantiles under condition X, Q_τ is defined as a function related to x. We then formulate the quantile regression analysis model as follows:

$$\log Y_i^k = \beta_{0\tau}^k + \beta_{1\tau}^k X_i^k \tag{4-3}$$

Here, Y_i^k denotes the average annual mileage (km) of vehicle number *i* of model *k*, while X_i^k indicates the age of vehicle number *i* of model *k*. Note that this study focuses on hybrid (k = 1) and gasoline vehicles (k = 2). $\beta_{0\tau}^k$ and $\beta_{1\tau}^k$ in equation (4-3) are endogenously determined parameters. In particular, $\beta_{1\tau}^k$ denotes the rate of change in average annual mileage (Y_i^k) when vehicle age (X_i^k) changes by one unit (for example, one year). In general, increases in vehicle age should be accompanied by a gradual decrease in average annual mileage; therefore, $\beta_{1\tau}^{k}$ should be negative. $\beta_{0\tau}^{k}$ expresses the effect of other factors on the average annual mileage.

Using Koenker & Bassett (1978) check function ρ_τ, the two parameters in equation (4-3) can be estimated as follows:

$$\left(\hat{\beta}_{0\tau}^{k}, \hat{\beta}_{1\tau}^{k}\right) = \arg\min_{\beta_{0\tau}^{k}, \beta_{1\tau}^{k}} \sum_{i=1}^{n} \rho_\tau\left\{\log Y_i^k - \left(\beta_{0\tau}^{k} + \beta_{1\tau}^{k} X_i^k\right)\right\} \tag{4-4}$$

Defining $\log Y_i^k - \left(\beta_{0\tau}^{k} + \beta_{1\tau}^{k} X_i^k\right)$, which indicates the error as u_i^k, check function ρ_τ is formulated as

$$\rho_\tau = u_i^k \times \left(\tau - 1\left\{u_i^k < 0\right\}\right), \tag{4-5}$$

wherein $1\left\{u_i^k < 0\right\}$ is an indicator function, taking a value of 1 when $u_i^k < 0$ and 0 otherwise.

4.3. Data

We used data on vehicles advertised for sale on the used car sales website Goonet Exchange (https://www.goo-net.com/). These included 3,618 Prius models from 2002 to 2017 (1800cc displacement, new retail price JP¥2.5 million, Toyota Motor Corporation) and 239 Premio models from 2000 to 2017 (1500 to 2000cc displacement, new retail price JP¥2 million, Toyota Motor Corporation). The Toyota Prius is a hybrid vehicle, while the Premio is a gasoline vehicle. By focusing on these two Toyota models with similar engine displacement and internal space profiles, we analyze variations in the propensity to drive of drivers owning a typical hybrid or a typical gasoline vehicle.

We used regression analysis of quartile points with average annual mileage as the dependent variable (km) and vehicle age (years) as the independent variable. Table 4-1 shows descriptive statistics for the Prius and Premio average annual mileages. The Prius had an average annual mileage of around 10,000 km and the Premio about 6,280 km, suggesting that owners of hybrid vehicles tend to drive more frequently and/or longer. Using the vehicle database, we solved a linear programming problem (Eq. (4-4)) for each vehicle type by the MATLAB software and estimated two parameters of $\hat{\beta}_{0\tau}^{k}$ and $\hat{\beta}_{1\tau}^{k}$, respectively.

We used the “catalog-based worldwide harmonized light vehicles test cycle -” average fuel efficiencies (km/l) of 32.1 km/L (City-mode: 29.9 km/l and Highway-mode: 31.2 km/l) for Prius and 17.8 km/L (City-mode: 12.6 km/l and highway-mode: 20.5 km/l) for Premio and estimated their annual total gasoline combustions per vehicle (kl) by dividing the annual mileage (km) by the catalog-based fuel efficiency (km/l)(Toyota Motor Corporation, 2020a, 2020b). The World-Harmonized Light-Duty Vehicles Test Procedure, introduced in Japan in October, 2016, requires Japanese auto companies to provide information on catalog-based fuel efficiencies to consumers (Ministry of Land, Infrastructure, transport, and tourism, 2011). The annual CO_2 emissions at driving phase per vehicle are estimated by multiplying the annual total gasoline combustion by the CO_2 emissions intensity from gasoline combustion of 2.32 t-CO_2/kl (Ministry of the Environment, 2017).

Table 4-1. Descriptive statistics – Prius and Premio average annual mileages (10,000 km).

	Min.	SD	1st quantile	Median	Mean	3rd quantile	Max.	Number of observations

Prius	0.0003	0.768	0.575	0.9	1.074	1.344	8.0	3,618
Premio	0.0005	0.421	0.329	0.5	0.628	0.800	2.6	239

4.4. Results

4.4.1. Decreasing rate of average annual mileage

In a lifecycle assessment report of its hydrogen-powered car (Mirai), Toyota Motor Corporation (2015) compared the lifecycle CO_2 emissions of gasoline and hydrogen vehicles (premium saloon class). In their report, the lifecycle CO_2 emissions are estimated based on the assumption that the vehicles in question would travel an average of 10,000 km per year and a total of 100,000 km during their 10-year lifespan (Toyota Motor Corporation, 2015).

However, according to estimates by Kagawa et al. (2011) and Oguchi & Fuse (2015), the lifespan of Japanese cars ranges from 11 to 13 years[1]. Moreover, Austin & Dinan (2005) estimate an exponential rate of decay in miles traveled and show that the

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[1] Kagawa et al. (2011) focused on ordinary passenger cars that were newly purchased from 1990 to 1995 in Japan and found that the average vehicle lifetime slightly increased from 11.4 years to 11.7 years. On the other hand, Oguchi & Fuse (2015) focused ordinary passenger cars that were newly purchased from 1990 to 2000 in Japan and estimated the average vehicle lifetime as 13.3 years.

average gasoline-fueled car in the United States shows a 4.5% reduction in mileage according to the vehicle's age. In other words, a one-year increase in vehicle age is associated with a 4.5% reduction in average annual mileage. It is important to note that the rate of reduction in mileage as a function of vehicle age differs greatly among vehicle types.

This study focused on the Toyota Prius (hybrid) and Premio (gasoline) to estimate the rate of change in mileage according to vehicle age using a quantile regression analysis with quantiles of τ = 0.25, 0.5, 0.75, and 0.9. Tables 2 and 3 present the results of the quantile regression analysis for the Prius and the Premio, respectively. The far-right columns in each table show the results of the estimated parameters using OLS regression.

One important finding shown in Tables 4-2 and 4-3 is that both the Prius and Premio vehicle age parameters $\hat{\beta}_{1\tau}^{1}$ and $\hat{\beta}_{1\tau}^{2}$ show negative values, and the absolute values of each parameter become larger with increases in the quantile. This indicates that, for drivers who drive longer distances, the rate of decrease in average mileage grows as the vehicle age increases.

The rate of decrease in average annual mileage for the Prius at quantile $\tau = 0.5$ (i.e., the median value) is $\beta_{1,0.5}^{1} = -7.7\%$ (Table 4-2), while for the Premio, it is $\beta_{1,0.5}^{2} = -3.1\%$ (Table 4-3). These figures differ noticeably from the 4.5% rate of decrease in average annual mileage estimated by Austin & Dinan (2005). Importantly, the rate of decrease for the Prius is more than twice that of the Premio. In the past, it has been conventionally assumed that—due to the higher cost of a hybrid compared with a gasoline-powered vehicle—Prius owners would keep their hybrid car for longer until an economically rational break-even point is reached. However, Prius owners may not purchase their cars with the expectation of driving long distances over extended periods; rather, they may drive long distances due to the relatively high fuel efficiency of younger vehicles. As the vehicle ages, its average annual mileage drops rapidly and fuel efficiency declines.

Table 4-2. Prius: estimates of relational expression for vehicle age and average annual mileage

	Quantile regression				OLS
τ	0.25	0.5	0.75	0.9	
$\beta_{0\tau}^{1}$	-0.304	0.259	0.738	1.105	0.159
	(***)	(***)	(***)	(***)	(***)

$\beta_{1\tau}^{1}$	-0.053	-0.077	-0.096	-0.112	-0.074
	(***)	(***)	(***)	(***)	(***)

Note: We performed the quantile regression for 1000 bootstrap samples. *, **, and *** denote the statistical significance at the 10% level, 5% level, and 1% level, respectively.

Table 4-3. Premio: estimates of relational expression for vehicle age and average annual mileage

	Quantile regression				OLS
τ	0.25	0.5	0.75	0.9	
$\beta_{0\tau}^{2}$	-0.819	-0.411	0.194	0.553	-0.531
	(***)	(***)	(***)	(***)	(***)
$\beta_{1\tau}^{2}$	-0.036	-0.031	-0.054	-0.059	-0.028
	(***)	(***)	(***)	(***)	(*)

Note: We performed the quantile regression for 1000 bootstrap samples. *, **, and *** denote the statistical significance at the 10% level, 5% level, and 1% level, respectively.

4.4.2. Effects of drivers' propensity to drive on CO_2 emissions

To accurately estimate vehicle emissions, we need a deeper understanding of how a driver uses a passenger car for the lifetime of the vehicle. As discussed, car owners with older cars tend to drive shorter distances. Figure 4-1 illustrates the annual mileage during the average vehicle lifetime of x_1 years. One can assume that car owners with older cars tend not to take long trips to avoid, for example, mechanical issues on the highway. Figure 1 shows that the "variable" annual mileage for long trips decreases during vehicle lifetime and the variable mileage calculated by $y_1 - y_0$ becomes zero at the end of vehicle lifetime, x_1, at which point car owners use a passenger car only for daily city driving. Thus, we can estimate the "constant" annual mileage for daily city driving as y_0 (Figure 4-1).

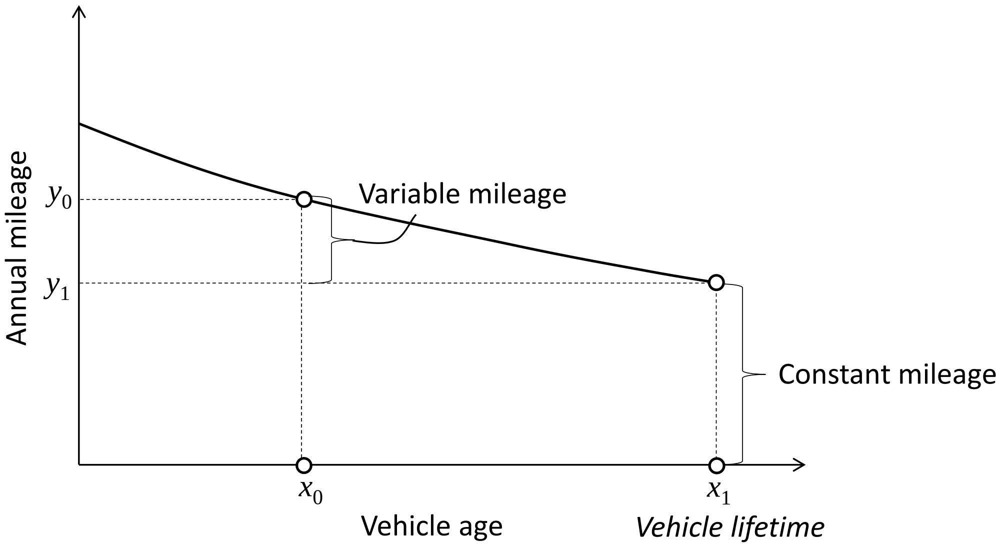

Figure 4-1. Constant and variable annual mileage during the vehicle lifetime

Based on the parameters in Tables 4-2 and 4-3 and equation (4-3), constant annual mileage can be easily estimated as $\exp\left(\hat{\beta}_{0\tau}^{k} + \hat{\beta}_{1\tau}^{k} \times 13\right)$ where we set the vehicle lifetime as 13 years following previous studies (Kagawa *et al.*, 2011; Oguchi and Fuse, 2015). The variable annual mileage is calculable as $\exp\left(\hat{\beta}_{0\tau}^{k} + \hat{\beta}_{1\tau}^{k} \times X^{k}\right) - \exp\left(\hat{\beta}_{0\tau}^{k} + \hat{\beta}_{1\tau}^{k} \times 13\right)$ (i.e., annual mileage minus constant annual mileage).

Table 4-4 shows the constant and variable annual mileage for the Prius during the average vehicle lifetime of 13 years. When we look at the result at quantile $\tau = 0.5$ (i.e., the median value), Prius owners drive 4,760 km for constant city driving at the end of vehicle lifetime (see the last row of Table 4-4). The variable annual mileage for highway driving rapidly decreases from 7,230 km to zero during the vehicle lifetime (Table 4-4). The constant annual mileage for the Premio at quantile $\tau = 0.5$ is 4,430 km (see the last row of Table 4-5). It is important to note that the constant annual mileages for the Prius and Premio are almost the same, whereas the variable annual mileages for highway driving differ significantly between the hybrid vehicle and the conventional gasoline vehicle (Tables 4-4 and 4-5).

Table 4-4. Prius: constant and variable annual mileage during the average vehicle lifetime (10,000 km)

	τ=0.25			τ=0.5			τ=0.75			τ=0.9		
Vehicle age	Constant driving	Variable driving	Total	Constant driving	Variable driving	Total	Constant driving	Variable driving	Total	Constant driving	Variable driving	Total
1	0.370	0.329	0.700	0.476	0.723	1.200	0.600	1.300	1.900	0.704	1.995	2.699
2	0.370	0.293	0.664	0.476	0.635	1.111	0.600	1.126	1.726	0.704	1.709	2.413
3	0.370	0.259	0.629	0.476	0.552	1.028	0.600	0.968	1.568	0.704	1.454	2.158
4	0.370	0.226	0.597	0.476	0.476	0.952	0.600	0.824	1.425	0.704	1.225	1.929
5	0.370	0.196	0.566	0.476	0.405	0.882	0.600	0.694	1.294	0.704	1.021	1.725
6	0.370	0.166	0.537	0.476	0.340	0.816	0.600	0.575	1.176	0.704	0.838	1.542
7	0.370	0.139	0.509	0.476	0.280	0.756	0.600	0.468	1.068	0.704	0.675	1.379
8	0.370	0.112	0.483	0.476	0.224	0.700	0.600	0.370	0.970	0.704	0.528	1.232
9	0.370	0.087	0.458	0.476	0.172	0.648	0.600	0.281	0.882	0.704	0.398	1.102
10	0.370	0.064	0.434	0.476	0.124	0.600	0.600	0.200	0.801	0.704	0.281	0.985
11	0.370	0.041	0.412	0.476	0.079	0.555	0.600	0.127	0.728	0.704	0.177	0.881
12	0.370	0.020	0.391	0.476	0.038	0.514	0.600	0.061	0.661	0.704	0.083	0.787
13	0.370	0.000	0.370	0.476	0.000	0.476	0.600	0.000	0.600	0.704	0.000	0.704

Table 4-5. Premio: constant and variable annual mileage during the average vehicle lifetime (10,000 km)

	τ=0.25			τ=0.5			τ=0.75			τ=0.9		
Vehicle age	Constant driving	Variable driving	Total	Constant driving	Variable driving	Total	Constant driving	Variable driving	Total	Constant driving	Variable driving	Total
1	0.276	0.149	0.425	0.443	0.200	0.643	0.602	0.549	1.150	0.807	0.832	1.639
2	0.276	0.134	0.410	0.443	0.180	0.623	0.602	0.488	1.090	0.807	0.738	1.545
3	0.276	0.120	0.396	0.443	0.161	0.604	0.602	0.431	1.033	0.807	0.649	1.456
4	0.276	0.106	0.382	0.443	0.143	0.586	0.602	0.377	0.978	0.807	0.566	1.373
5	0.276	0.092	0.368	0.443	0.125	0.568	0.602	0.325	0.927	0.807	0.487	1.294
6	0.276	0.079	0.355	0.443	0.107	0.550	0.602	0.276	0.878	0.807	0.413	1.220
7	0.276	0.067	0.343	0.443	0.091	0.534	0.602	0.230	0.832	0.807	0.343	1.150
8	0.276	0.054	0.331	0.443	0.074	0.517	0.602	0.187	0.788	0.807	0.277	1.084
9	0.276	0.043	0.319	0.443	0.058	0.502	0.602	0.145	0.747	0.807	0.215	1.022
10	0.276	0.031	0.308	0.443	0.043	0.486	0.602	0.106	0.708	0.807	0.156	0.964
11	0.276	0.021	0.297	0.443	0.028	0.471	0.602	0.069	0.670	0.807	0.101	0.908
12	0.276	0.010	0.286	0.443	0.014	0.457	0.602	0.033	0.635	0.807	0.049	0.856
13	0.276	0.000	0.276	0.443	0.000	0.443	0.602	0.000	0.602	0.807	0.000	0.807

Considering that fuel efficiency is sensitive to vehicle speed, we calculated the "constant" annual total gasoline combustions per vehicle (kl) by dividing the constant annual mileage (km) by the catalog-based fuel efficiency for city driving (km/l) and the "variable" annual total gasoline combustions per vehicle (kl) by dividing the variable annual mileage (km) by the catalog-based fuel efficiency for highway driving (km/l). Vehicle emissions at the driving phase are then calculated by multiplying the total of constant and variable gasoline consumptions by the CO_2 emission factor.

In the next step, we analyzed the effects of drivers' propensity to drive on CO_2 emissions during the driving period of the vehicle's lifecycle. Figure 4-2 shows the effects of propensity to drive among Prius owners on "annual CO_2 emissions during the driving phase" (Figure 4-2, left-hand axis) and "cumulative CO_2 emissions across an average 13-year vehicle lifetime" (Figure 4-2, right-hand axis). The right-hand axis of Figure 2 shows the difference arrived at by subtracting "cumulative emissions calculated using a -7.7% rate of decrease in average annual mileage within the $\tau = 0.5$ quantile, as estimated in the present study" from "cumulative emissions calculated over a 13-year lifespan under uniform average annual mileage of 10,000 km and 'average' fuel efficiency, as per Toyota modeling." A positive difference indicates that cumulative CO_2 emissions calculated with the assumption of uniform average annual mileage (i.e., as per Toyota modeling) have been overestimated.

Figure 4-2 shows that—based on Toyota's modeling—the annual CO_2 emissions from driving for the hybrid vehicle (Prius) remain stable across its lifetime at around 0.7 tons/year (the red line in Figure 4-2). Conversely, the results from our quantile regression analysis indicate that the annual CO_2 emissions from driving decline with increasing vehicle age for all quantiles (Figure 4-2). In particular, Prius owners at the $\tau = 0.9$ quantile, indicative of longer mileages, show a reduction in the roughly 0.5 tons of annual CO_2 emissions from driving across an average 13-year vehicle lifespan (Figure 4-2).

The bars in Figure 4-2 show that the cumulative CO_2 emissions—assuming uniform average annual mileages (as per Toyota's modeling)—tend to be higher than the cumulative CO_2 emissions when considering decreases in average annual mileages, as vehicles age (Figure 4-2). This overestimation of cumulative emissions is more pronounced for the Premio, a gasoline-powered vehicle with relatively poorer fuel efficiency, compared with the hybrid (Figure 4-3).

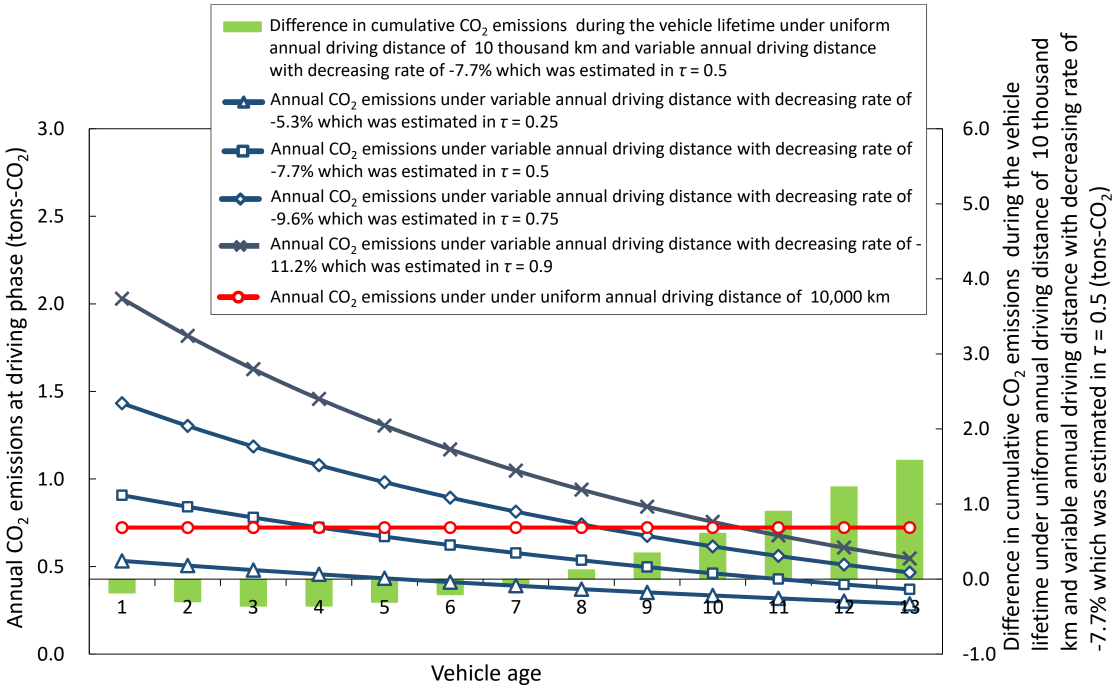

Figure 4-2. Prius CO_2 emissions at driving phase per vehicle

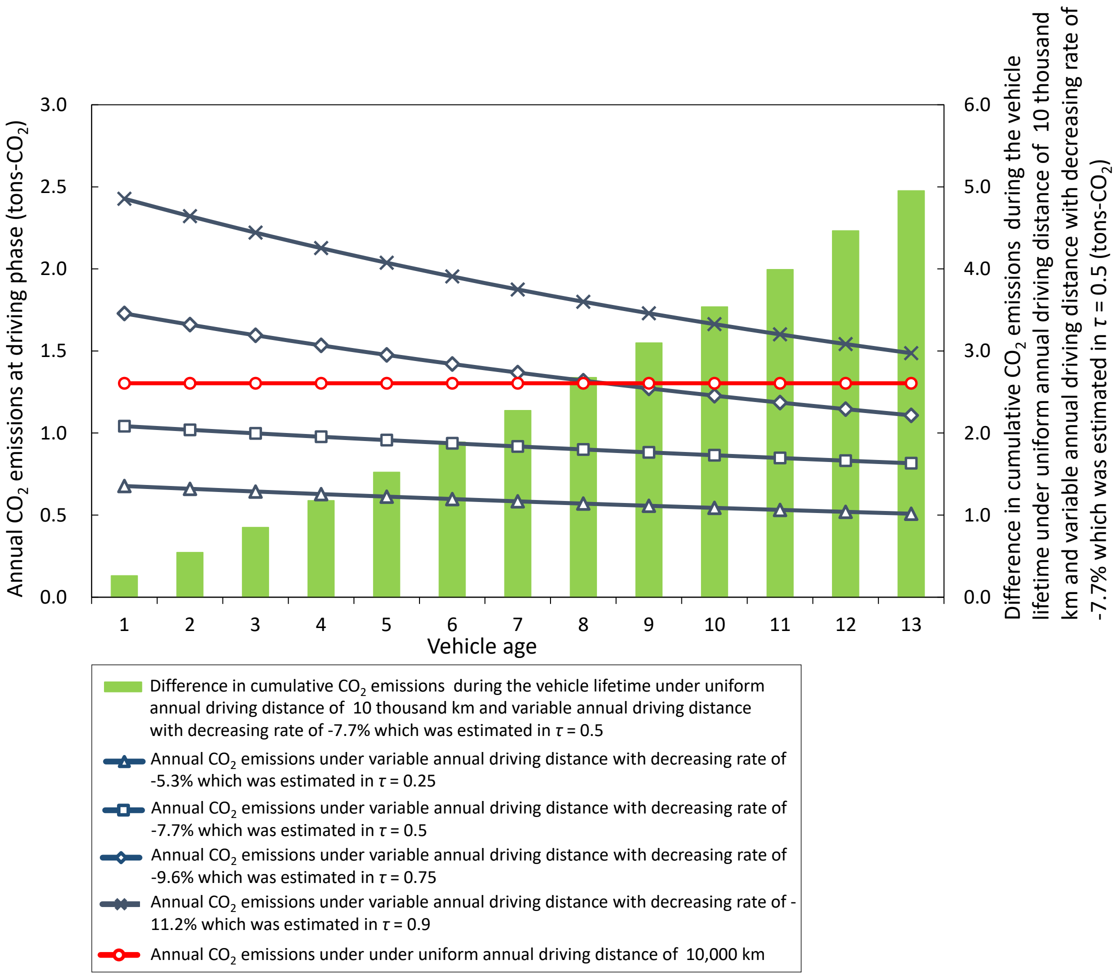

Figure 4-3. Premio CO$_2$ emissions at driving phase per vehicle

4.5. Limitations of the present study

Using data on used Prius and Premio cars, we estimated the rate of decline in annual mileage as a function of vehicle age. The vehicles' ages were calculated by subtracting the "year in which the vehicle was first registered as a new vehicle" from "the year in which the vehicle was sold as a used vehicle." Furthermore, if a Prius owner, for example, were to relinquish the vehicle after five years with a cumulative mileage of 60,000 kms, our observed data on vehicle age and average annual mileage would be $X_i^1 = 5$ (years) and $Y_i^1 = 1.2$ (10,000 km), respectively. The limitation of such data is the inability to analyze the extent to which the Prius owner has altered the annual average mileage during the five-year period. Our analysis involved estimating the effects of vehicle age on vehicle owners' "average" propensity to drive by comparing the "average annual mileage of people owning a Prius for shorter periods" with the "average annual mileage of people owning a Prius for longer periods."

4.6. Concluding remarks

In one of its publicly available lifecycle assessment reports, the Toyota Motor Corporation (2015) estimates vehicles' CO_2 emissions from driving based on the assumed average annual mileage of 10,000 km over the course of the vehicle's lifetime (a lifetime mileage of 100,000 km accrued over a 10-year vehicle lifespan). However, these results, which are based on the use of a fixed propensity to drive in the calculations, are misleading.

This study revealed that average annual mileages for Prius model vehicles decline from between 5.3% to 11.2% for each one-year increase in vehicle age. The cumulative CO_2 emissions reported by the Toyota Motor Corporation are considerably higher than those in this study, based on calculations that take into account the rates of decrease in average annual mileage. These results indicate that actual lifecycle CO_2 emissions for the Prius are smaller than those reported and, accordingly, we may conclude that the hybrid Prius is a more environmentally friendly vehicle.

However, an important finding was that the cumulative CO_2 emissions from driving the gasoline-powered Premio were estimated at more than twice those of the hybrid (see Figures 4-2 and 4-3). The estimated cumulative CO_2 emissions from driving a Premio during a 13-year lifespan, as estimated using Toyota modeling, overestimated around 50,000 at the quantile of 0.5 (Figure 4-2). Accordingly, in terms of conducting a lifecycle assessment, the impact of decreased average annual mileage as a function of vehicle age is highly significant when comparing the lifecycle CO_2 emissions of gasoline and hybrid vehicles.

Based on our results, we suggest the following guidelines for future lifecycle assessments. Uncertainty analyses should be performed, taking into account a rate of decrease in average annual mileages in the range of 5% to 11% for every one-year increase in vehicle age, when calculating CO_2 emissions during the driving of ‘hybrid’ vehicles. Further, uncertainty analyses should also be performed taking into account a rate of decrease in average annual mileages in the range of 4% to 6% for every one-year increase in vehicle age, when calculating CO_2 emissions during the driving of ‘gasoline’ vehicles. The results of such analyses that account for drivers’ propensity to drive should be included in the lifecycle assessment reports of relevant vehicles for the evaluation of their environmental profiles. Vehicle manufacturers and life cycle assessment practitioners should avoid communicating misleading environmental information to consumers.

Chapter 5. Conclusions

In Chapter 3, the achievement status of CAFE standards by Japanese automobile manufacturers was clarified, and the impact of CAFE standards on CO_2 emissions was estimated. The results suggested the possibility of CAFÉ-based moral hazards, which were not indicated in previous research. Furthermore, the results showed that introducing fuel economy standards alone is insufficient for reducing life-cycle CO_2 emissions in the automobile industry.

In Chapter 4, quantile regression analysis was used to estimate uncertainties in lifetime mileage that are important for life-cycle analysis. The results showed that the rate of decrease in average annual mileage varied between 4% to 6% for hybrid vehicles and between 5% to 11% for gasoline vehicles, depending on drivers' driving tendencies. As mentioned in Chapter 2, research on fleet-based LCA has been accumulated in automobile LCA research. However, using the mileage uncertainty analysis framework that was developed in Chapter 4, the reliability of social LCA studies regarding automobiles could be improved.

The United Kingdom has announced a ban on the sale of new internal combustion engine vehicles (Department for Transport, 2020), and in such ways, regulations on CO_2 emissions from the global transport sector are becoming increasingly strict. Under these circumstances, the EU has announced that, from 2024, it will gradually start emission regulations based on LCA for battery electric vehicles (BEV), the demand for which is rapidly increasing. However, there has been little progress in the construction of a data platform for more accurate LCAs, and efforts toward decarbonization of the automobile sector remain insufficient. The reliability of LCA analysis of automobile companies and vehicle models should be improved by using the automobile LCA analysis framework based on drivers' driving tendencies developed in the present research. Japan has set the goal of reducing CO_2 emissions to virtually zero by 2050, and the LCA analysis method developed in this thesis can greatly contribute to the proposal of emission reduction measures, particularly in the mobility sector.

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Mitsuki Kaneko

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