Master's Thesis in Engineering

Analyzing the Effects of Car Sharing Services on GHG Emission Reduction

카셰어링 서비스의 온실가스 배출저감 효과 분석

August 2017

Graduate School of Seoul National University

Technology Management, Economics, and Policy Program

JiYeon Jung

Analyzing the Effects of Car Sharing Services on GHG Emission Reduction

지도교수 구윤모

이 논문을 공학석사학위 논문으로 제출함

2017 년 8 월

서울대학교 대학원

협동과정 기술경영경제정책 전공

정 지 연

정지연의 공학석사학위 논문을 인준함

2017 년 8 월

위 원 장 ___이 종 수___(인)

부위원장 ___구 윤 모___(인)

위 원 ___신 정 우___(인)

Abstract

Analyzing the Effects of Car Sharing Services on GHG Emission Reduction

JiYeon Jung
Technology Management, Economics, and Policy Program
The Graduate School
Seoul National University

The use of automobiles, which have long been considered private means of transportation, is now shifting toward car-sharing, which allows short-term rental of a vehicle on an as-needed basis. With the increasing concern for environmental issues, it is anticipated that car-sharing will contribute to the reduction of GHG emissions. However, there exist both positive and negative environmental effects from car-sharing. Carless individuals can drive instead of using public transit because car-sharing has enabled individuals to acquire personal auto-mobility at low cost, and individuals who had planned to purchase a vehicle may decide not to, and instead use car-sharing services. In this study, the environmental effects on greenhouse gas emissions (GHG) caused by this shift in mode of transportation were examined.

The analysis was based on the use of three types of models. A mixed logit model was used to analyze preferences for using car-sharing services. A binary logit model was used to analyze whether individuals were willing to dispose of owned vehicles or to forego vehicle purchases to use car-sharing services. A linear regression model was used to understand how much car-sharing would replace driving of owned vehicles or public transportation and how the mobility change by using car-sharing services. This also involved estimation of environmental impacts caused by car-sharing. To estimate the total effects of the introduction of car-sharing services on GHG emissions, three things were considered: mode-shift proportion, mobility change and reduction in vehicle ownership. In this study, scenario analysis was used to examine the effects of car-sharing services on GHG emission in various car-sharing-market situations. From the results, suggestions are made about operating car-sharing services so that they are more environmentally compatible.

Keywords: Sharing economy; Collaborative consumption; Shared-use vehicle; Discrete choice model; Greenhouse gas emissions; Sustainable traffic system; Eco-friendly transportation services

Student Number: 2015-21197

Contents

Abstract iii

Contents v

List of Tables viii

List of Figures x

Chapter 1. Introduction 1

1.1 Research Background 1

1.2 Research Objectives 2

1.3 Research Outline 6

Chapter 2. Literature Review 8

2.1 Preference Analysis Using the Discrete Choice Models 8

2.2 Demand Analysis on Car-Sharing Service 10

2.3 Effects of Car-Sharing on Travel Behavior and Car-sharing’s Impacts on GHG Emissions 11

2.4 Limitations of Previous Literatures and Research Motivation 14

Chapter 3. Data 17

3.1 Data Description 17

3.2 Survey Design (Discrete Choice Experiment) 23

Chapter 4. Methodology 28

4.1 Empirical Model 29

4.1.1 Mixed Logit Model 29

4.1.2 Binary Logit Model 32

4.1.3 Linear Regression Model 34

4.2 Framework for GHG Emission Impacts Analysis 36
4.2.1 Calculation of Effects of Car-Sharing Services 39
4.2.2 Simulation Analysis 55
Chapter 5. Results 58
5.1 Empirical Results 58
5.1.1 Preferences Analysis of Using the Car-sharing Services (Using the Mixed Logit Model) 58
5.1.1 Analysis of the Intention to Dispose of Owned Vehicles or to Forego Plans for Purchasing a Vehicle (Using Binary Logit Model) 61
5.1.1 Usage and Mobility Change of Transportation as an Introduction to Car-Sharing Services (Using Linear Regression Model) 66
5.2 Estimation of the Emission Effects from Car-Sharing 75
5.2.1 GHG Emissions in the Base Scenario: Most similar to the current car-sharing market 75
5.2.2 GHG Emissions from Increase in the EV Infrastructure 77
5.2.3 Scenario: Delivery service provided and one-way drive permitted 81
5.3 Discussion 82
Chapter 6. Conclusion 84
6.1 Concluding Remarks and Contributions 84
6.2 Limitations and Future Research Topics 86
Bibliography 88
Appendix: Example of Choice Experiment Survey (Korean version) 94

Abstract (Korean)..96

List of Tables

Table 1. GHG emissions by sectors in Seoul (Park, 2015) (Unit: 1000 tCO2e)............ 4
Table 2. Demographic characteristics of the respondents 17
Table 3. Attributes and levels of car-sharing services for discrete choice experiment 25
Table 4. Description of variables used for the estimation of environmental impacts 43
Table 5. Minimum and maximum values of GHG emission coefficient from electricity generation suggested by previous literatures (Edwards et al., 2004; Turconi, Boldrin, and Astrup, 2013).. 48
Table 6. Sales trends for passenger car in Korea (KEA, 2016b)..................................... 53
Table 7. Base scenario (Most similar to the current car-sharing market situation).......... 56
Table 8. Description of effect-coded variables (For mixed logit analysis) 58
Table 9. Estimation results for car-sharing service through a mixed logit choice model. 60
Table 10. Description of dummy-coded variables (For binary logit & linear regression analysis) 63
Table 11. Estimation results for disposing owned car or foregoing vehicle purchasing plan for car-sharing service through a binary logit choice model 64
Table 12. Estimation result for replacing ratio of driving hours with car-sharing (original) 66
Table 13. Estimation result for replacing ratio of driving hours with car-sharing (with individual characteristics) 67
Table 14. Estimation results for replacing ratio of public transit with car-sharing (original)... 69
Table 15. Estimation results for replacing ratio of public transit with car-sharing (with individual characteristics) 71
Table 16. Estimation results for mobility change with car-sharing (original)................. 72
Table 17. Estimation results for mobility change with car-sharing (with individual characteristics) 74
Table 18. Choice probability and forfeiting probability in the base scenario 76
Table 19. Emission in various car-sharing market scenario (unit: tCO2e)....................... 79
Table 20. Emission in various car-sharing market scenario using minimum and maximum

value of electricity emission (unit: tCO_2e) 80
Table 21. Scenario for the additional services (delivery service and one-way drive) 81

List of Figures

Figure 1. GHG Emission Trend in South Korea (OECD, 2016) 3
Figure 2. Proportion of direct GHG emission in Seoul in 2010 (Park, 2015) 5
Figure 3. Vehicle types of the vehicles owned 19
Figure 4. Fuel types of the vehicles owned 20
Figure 5. Usual time of using car-sharing services 22
Figure 6. Purpose of using car-sharing services 22
Figure 7. Framework for the analysis in this thesis 28
Figure 8. Visualization of how behavior changes effect GHG emission due to the introduction of car-sharing 38
Figure 9. Three main environmental effects from car-sharing due to behavioral change of each individual 40
Figure 10. Breakdown of Electricity Generation by Energy Source in Korea in 2014 (The World Bank, 2014) 49
Figure 11. Usage characteristics of public transit users (MOLIT, 2016) 51
Figure 12. Ratio of license holders among public transit users (MOLIT, 2016) 52
Figure 13. Sales trends for passenger cars in Korea (KEA, 2016b) 54
Figure 14. Trends in vehicles registered as non-business passenger cars 55
Figure 15. Change in the choice probability of car-sharing as EV charging station infrastructure (number of stations) increases 78
Figure 16. Reduction in daily GHG emissions with greater supply of EV charging 78
Figure 17. Response to the flowing station: “Car-sharing is an environment-friendly mode of transportation” 85

Chapter 1. Introduction

1.1 Research Background

Automobiles have long been considered private means of transportation. However, with the introduction of car-sharing services, a car could be rented in units of time, as short as ten minutes. Car-sharing services allow people to rent a car on a short-term as-needed basis, paying only for the time used and the distance driven (Lee, 2015). Not only a vehicle can be rented as-needed basis, car-sharing allow individuals to benefit from using a vehicle without the cost and responsibilities associated with ownership, as car-sharing service operators provide the car with maintenance, repairs, and insurance. Since it is providing a flexible alternative mode of transportation, the car-sharing market has grown rapidly, covering approximately 1,531 cities with 4.8 million members worldwide, in 33 countries on 5 continents as of October 2014 (Shaheen and Cohen, 2016).

With the growing popularity of car-sharing services worldwide, various studies analyzed the impacts of car-sharing extensively. Shared use allows the vehicle to be used as effectively as possible. As a solution to the societal problems of air pollution and heavy congestion, the city of Seoul suggested various policies to reduce traffic volume from private vehicles. In September 2012, the mayor of Seoul declared Seoul to be a sharing city, and supported various policies, assisting Nanum-car, Seoul's car-sharing service. As such, Seoul provided benefits to the service providers as follows. First, shared-vehicle providers were given a 50% discount for public parking lot spaces. As of October 1, 2013, discounts of KRW[1] 5.3M were given to 93 car-sharing vehicles. Second, electric vehicle sharing service providers were given a subsidy on the purchase of electric vehicles: KRW 15M from the city and KRW 15M from the national government. Additionally, free installation of normal-speed electricity chargers for electric vehicle was provided. Third, a policy for integrated transfer discounts on the public transit scheme is in use. Members using public transit to get to the car-sharing station within 30 minutes could receive an average discount of KRW 300–1,000 per use (Seoul Solution, 2016). Consequently, various assisting policies for the car-sharing service are being supported for fostering car-sharing.

Expected to reduce the number of privately owned vehicles and thus reducing congestion and air pollution on the road, car-sharing services are being highlighted as an innovative transport system for a sustainable society. According to a research car-sharing users are mostly in their 20s (39.9%) or 30s (37.8%) and 78% of the car-sharing users are carless (Kim et al., 2015). As most of car-sharing users do not own vehicle, it is necessarily to examine how individuals' decision for the mode of transportation changed with the introduction of car-sharing.

1.2 Research Objectives

[1] US dollar equivalent as of January 2017 is "USD1=KRW 1,185" (Bank of Korea; www.bok.or.kr).

Global warming is a seriously concerned global issue and as there is a strong relationship between consumer behavior and the environment, GHG emissions caused from the change in human activities are often used to examine the environmental impacts. Figure 1 shows the increasing trend of GHG emissions in South Korea. Total emissions excluding land use, land-use change and forestry are 693,533 t CO2e in 2013.

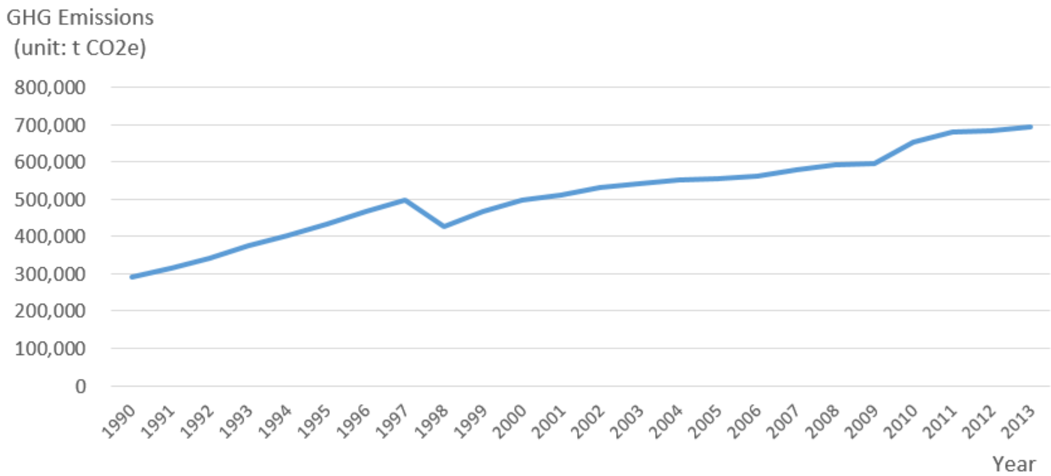


Figure 1. GHG Emission Trend in South Korea (OECD, 2016)

According to the report "Seoul in Statistics: Transportation," published from the Seoul Institute in 2015, the greenhouse gas (GHG) emissions in the transportation sector in Seoul are reported as 10,185,000t CO2e in 2010. Steadily increased annually, this measure accounts for the largest proportion of 37% in the total direct GHG emissions in 2010 as shown in Table 1 and Figure 2 (Park, 2015). Of the GHG emission in transportation sector, 94.4% of the emissions are emitted on the road in 2009 (KEEI, 2012). With increasing number of vehicles and rising GHG emission, advantages of the sharing economy in the transportation are getting attentions.

Table 1. GHG emissions by sectors in Seoul (Park, 2015) ·············(Unit: 1000 tCO2e)

		2005	2006	2007	2008	2009	2010
	Total	49,467	48,961	50,472	50,383	49,111	49,751
Direct emissions	Subtotal	29,719	28,699	29,028	28,157	26,273	26,102
	Energy industry	1,414	1,432	1,513	1,272	1,095	1,492
	Manufacturing & construction industries	1,491	1,453	1,401	1,368	431	386
	Transportation	10,673	10,634	10,826	10,785	10,636	10,185
	Household	8,306	7,777	7,142	6,987	6,764	7,016
	Commercial	4,538	4,283	4,558	4,250	4,056	4,464
	Public	382	200	363	351	352	169
	Agriculture, forestry & fishery	14	138	316	257	183	150
	Fugitive emissions	118	114	115	115	114	122
	Industrial processing & production	1,229	1,142	1,372	1,403	1,415	1,541
	Farmland, forest & other land uses	73	58	-7	57	-43	-658
	Waste	1,481	1,468	1,429	1,312	1,270	1,235
Indirect	Subtotal	19,748	20,263	21,442	22,224	22,837	23,648

emissions	Electric power	17,304	17,957	19,198	20,067	20,724	21,610
	Heat	263	257	294	307	364	377

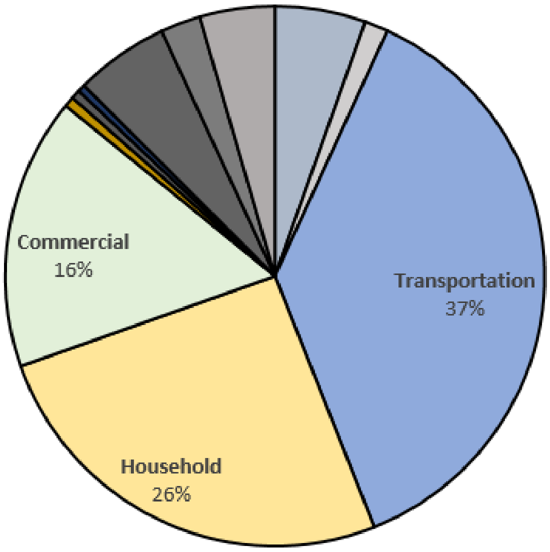


Figure 2. Proportion of direct GHG emission in Seoul in 2010 (Park, 2015)

Sharing economy in the transportation sector is emerging as a solution of urban problems of traffic congestion and excessive consumption. Especially with the increasing concerns of environmental issues, it is getting more attentions and support. In such situation, car-sharing is rising as an innovative solution, generating positive impact on the environment, while saving money and resources and increasing access to affordable transportation to the consumers. Sharing economy is alleged to be an environmental and economic activity as it reduces the waste by using resources effectively. Thus, sharing activities are prevalent around the world, wising to move toward sustainability.

However, as car-sharing service can affect the travel decisions of the individuals, behavior changes due to an alternative mode of transportation should be considered. People, who otherwise would have used the public transportation, might choose to drive car-sharing vehicle. The individual's travel activity and change in mode of transportation should be considered for the analysis. This study aims to examine environmental impacts of the car-sharing services by considering individual's transition in travel mode, mobility change and decision in vehicle ownership. This study examines the environmental impacts on greenhouse gas emissions (GHG) because of shift in mode of transportation.

1.3 Research Outline

This study consists of six chapters. Chapter 1 states the research objectives, contents, and range of the study. Among the sharing economy services, this study focuses on the transport sector. Considering cases in Korea, this study focuses on the car-sharing services only, and examines environmental impacts as people changes their usual mode of transportation to car-sharing services. Chapter 2 reviews previous literatures on discrete choice models, car-sharing services, and analysis on environmental impacts regarding the transportation sector in sharing economy. This chapter also deals with the motivation of the study and a discussion on the limitations of previous studies. Chapter 3 describes the data and samples used for the analysis in this study. Chapter4 explains methodology in analyzing the demand for a car-sharing services and the following environmental effects.

Chapter 5 delivers estimated results of environmental impacts of car-sharing on GHG emissions. Finally, Chapter 6 summarizes the content and presents contribution and limitations of this study.

Chapter 2. Literature Review

This chapter reviews previous literatures and research trend regarding the choice in mode of transportation, in specific to the car-sharing service. Furthermore, this chapter examines literatures that studied on the environmental effects of the car-sharing.

2.1 Preference Analysis Using the Discrete Choice Models

Discrete choice model is one of the most widely used method in analyzing consumer preferences. Understanding utility structure of the consumers in forecasting demand for new product or service is important for marketing, business management, policy evaluation and policy making. Thus, demand forecasting using the discrete choice models are used and applied in many areas of studies: transportation (Ben-Akiva et al., 1985), telecommunication (Batt and Katz, 1997), and business (Talluri and Van Ryzin, 2004).

Stated preference (SP) (or stated choice) data offer a significant benefit over revealed preference data, which represent observed choices on an actual market. Especially when the product or service is new or unfamiliar in the market, SP data can provide more information in hypothetical situations. Using the SP method, a discrete choice model allows to analyze the structure of consumers' preference. Specifically, SP is widely used to analyze travel choice behavior and identify behavioral response to chosen situations not revealed in the market (Hensher, 1994; Darren et al., 2008). Especially the choice analysis has long been applied in the studies of mode choices (Ben-Akiva et al., 1985; Train, 1978).

Train (1978) used the logit model in forecasting for a new transit system. In this study, the researcher predicted the share of the commuters' mode choices were compared with actual shares for each mode: auto alone, bus with walk access, bus with auto access, Bay Area Rapid Transit (BART) with bus access, auto access, and carpool. The model forecasted the share well and shown a prominent capability in predicting demands by using logit models. Ben-Akiva et al. (1985) deals with modelling demand and consumer behavior in specific to the transportation sector. They analyzed using discrete choice in the point of view of design of transit system, public policy, and systems management and planning in regards to the transport behavior.

Besides that, discrete choice models were used as a tool to analyze the preference and demands in various studies about mode of transportation. When an innovative alternative mode of transportation is introduced to the market, demand is analyzed using the SP method. Lee and Cho (2009) forecasted the demand of diesel passenger car using the discrete choice model. Beggs et al. (1981) analyzed the potential electric vehicle market using an ordered logit model. Brownstone et al. (1996) predicted the demand for electric vehicles in several situations in purchasing a vehicle. Train (1986) also estimated demand for various types of non-gasoline-powered automobiles in his studies using the scenario analysis.

Furthermore, Catalano et al. (2008) analyzed the shift in behavior toward the introduction of carpooling and car-sharing at a tourist site in Palermo, Italy by using the multinomial and nested logit models. This study analyzed the potential demand of carpooling and car-sharing in a congested traffic in the tour site area through the scenario analysis of imposing parking cost and limiting traffic area on private vehicles.

As shown in many previous studies in forecasting demands of transportation mode, discrete choice model is a credible method in analyzing demand for innovative mode of transportation. Thus, this study uses mixed logit model and binary logit model in understanding utility structure and specifying choice probability of the car-sharing service.

2.2 Demand Analysis on Car-Sharing Service

The Korea Transport Institute (KOTI, 2012) conducted a survey to analyze the travel behavior. The survey was conducted, targeted for the customers who joined the car-sharing service for over six months and used the car-sharing more than three times. It examined the preferences factors for car-sharing. Kim et al. (2014) similarly conducted a preference factors analysis of car-sharing in Suwon, South Korea. This study finds the potential demand for car-sharing was highest in the residential areas and around the stations, and the willingness to pay for the car-sharing service per hour was estimated to be KRW 7,967. According to the study results, car-sharing is more preferred than taxi and rental cars when the purpose of the trip is business, shopping and leisure.

Cevero (2003) used binomial logit model in predicting whether car-sharing users reduce vehicle ownership. The result examined that socio-economic influences on choices as such older and childless member who lived close to the station are more likely to forego vehicle ownership.

Katzev (2003) used a survey analysis to examine the behavior and factors influencing in use of car-sharing. The study states that majority (56.3%) of car-sharing users were motivated to use it to meet their periodic need of a vehicle or because they did not have or did not want to possess a vehicle. Also, this study found the relationship in-between the membership length distance to the station with the vehicle ownership. According to the results, car-sharing usage are not influenced by the ownership of a vehicle, but there has been moderate effect for the length of membership and distance to the station.

Duncan (2011) studied how much an individual can save by using car-sharing vehicle instead of purchasing the vehicle. In examining individual benefits of car-sharing, this study found that college students and households with low-income benefit from car-sharing.

As it can be seen in previous studies and surveys that discussed about the characteristics of car-sharing users, behavior changes in the use of transportation due to car-sharing differs by individual characteristics. Thus, individual characteristics must be considered in examining the modal change for car-sharing services.

2.3 Effects of Car-Sharing on Travel Behavior and Car-sharing's Impacts on GHG Emissions

Many researchers analyzed positive and negative effects of car-sharing in various aspects such as social, economic, and environmental effects (Chen and Kockelman, 2015; Katzev, 2003; Litman, 2000; Martin and Shaheen, 2011). The following previous literature shows positive and negative environmental impacts of car-sharing, including a reduction of emissions (Firnkorn and Muller, 2011; Haefeli et al., 2006), reduction in the number of private vehicles (Martin et al., 2010), reduction in distance travelled (Shaheen et al., 2009), and increase in mobility change (Cevero, 2003).

Litman (2000) compared benefits of car-sharing with alternative mode of transportations including private car, conventional rental, taxi and public transit. Providing an option in-between having no vehicle and owning a vehicle, car-sharing has positive impacts to the individuals in terms of urban mobility. By providing an alternative option in transportation mode, car-sharing could be cost effective than having a private vehicle to use between 10,000 and 16,093 kilometers (Duncan, 2011; Litman, 2000; Shaheen et al., 2009).

Katzev (2003) examined various possible impacts of car-sharing such as change in car ownership and mobility change using a survey. The result stated that reduced car ownership was not followed by a corresponding reduction in vehicle miles of travel, as vehicle miles of travel increases by non-car owners. Thus, this study implies the possibility of car-sharing’s negative impacts. Likewise, Cevero (2003) stated that two thirds of car-sharing users are carless and so the amount of car-use increase with the increase of carless individual’s use of vehicles on the road, which are shifted from non-auto mobility.

Martin and Shaheen (2011) estimated the net GHG emission impacts of car-sharing in North America as a result of changes in travel behavior among active car-sharing users and changes in the state of vehicle ownership and driving. In examining the change in annual household emission from the respondents that joined car-sharing, increased emission caused by gained access to automobiles and decreased emissions of shedding vehicles and less driving was taken into consideration. As a result, they observed the net impacts to be -0.84 t GHG per year per household and average vehicle kilometers traveled (VKT) per year was found to be reduced by 27%.

Chen and Kockelman (2015) examined the lifecycle effects on energy use and GHG emissions due to the travelers adopting car-sharing in the U.S. The result shows that current car-sharing members reduced their average individual transportation energy use and GHG emissions by roughly 51% since joining a car-sharing.

Note (2015) estimated the change in mobility as a result of car-sharing by examining the change in ownership and car use. In this study, researcher considered each mode of transport, including car, train, bus, and bicycle. By taking into two mobility effects, study found that there has been an average reduction of 1,600 car kilometers per year compared to before they started car-sharing, which is about the reduction of 250 kilograms of CO_2 among the car-sharing users.

Firnkorn and Muller (2011) analyzed the environmental effects of the car-sharing service called car2go in Ulm, Germany. The shift of driving car-sharing vehicle from using public transport or driving private car was taken into consideration and resulted in an average reduction of car-sharing users from -312 to -146 kg CO2 / year.

There are studies that suggested more sustainable way of operating car-sharing. Baptista et al. (2014) studied the energy, environmental and mobility impacts of car-sharing through empirical results of Lisbon, Portugal. This study demonstrated that CO2 emissions could be reduced about 35 and 65% if car-sharing vehicle is shifted to hybrid vehicle and electric vehicle respectively.

Various studies discuss about the numerous effects of car-sharing. However, the results are inconsistent between studies due to the difference in methodologies and data collection. As can be inferred from the existing literature, behavior changes in the use of transportation due to car-sharing differs by individual characteristics. Thus, it is essential to take individual preferences and characteristics into account in estimating the total net effect of car-sharing services.

2.4 Limitations of Previous Literatures and Research Motivation

Most of the studies were completed through surveys of the car-sharing users and have repeatedly demonstrated tendencies and behavior changes of the users. In regard to the studies that analyzed environmental impacts, previous studies estimated the impacts of car-sharing with overly optimistic assumptions. Car-sharing service is still a very new mode of transportation and studies based on the behavior of a limited group of early adopters could possibly result in a deviating behavior as car-sharing in those days was still in its infancy. Although the number of users is rapidly increasing, car-sharing as an innovative transportation mode, significant number of potential users are remaining in the market. Thus, using the discrete choice model in analyzing demand for innovative mode of transportation is necessary.

Moreover, when estimating the environmental impacts of car-sharing, both positive and negative effects should be considered. In the previous literatures that analyzed the car-sharing environmental impacts, these impacts were not considered comprehensively. This study, however, examines the environmental impacts on greenhouse gas emissions (GHG), considering thorough impacts including shifted travel time in mode of transportation, foregone vehicle ownerships, and mobility changes.

Furthermore, public transportation using behavior, willingness to use the car-sharing service, and rate of shifting their mode to car-sharing varies by individuals. However, in most studies, this effect was estimated as a group, meaning that only percentage of survey respondents were counted in when estimating the shift of mode of transportation. However, this way of estimating the shifting portion and hours could cause a bias result, because individual shifting rate could differ significantly. To fill this gap, this study employs the mixed logit modeling methodology to analyze behavior change in individual level. By doing so, this study could analyze the environmental impacts of car-sharing, incorporate the individual behavior changes and shifted amount of public transportation using hours into car-sharing.

In summary, this study makes three contributions to the previous literatures. Firstly, this study accommodates individual characteristics and preference heterogeneity at the individual level. Secondly, it examines the environmental effects when electric vehicle infrastructure expands through car-sharing services. Finally, it analyzes the effect of car-sharing on the willingness to own a vehicle if the newly introduced supplementary service such as vehicle delivery service, or one-way drive become available.

Chapter 3. Data

3.1 Data Description

An online survey was designed and conducted to investigate individual behavior in using means of transportation and to analyze preferences and intentions of using car-sharing services. The first section collects on the following socio-demographic characteristics of the respondents: gender, age, regions, occupation, household and individual income level, number of family members. The second section contains questions regarding travel time and respondents' use of transportation modes, as well as their background knowledge and understanding in the car-sharing services. The third section includes the discrete choice experiment. The online survey was conducted by Gallup Korea, a professional survey company in April 2017. The respondents include 1,022 adults aged 20-59 from urban area in Korea. This sample was using purposive quota-sampling based on the respondents' age, gender, and geographical area to ensure sample representativeness. Table 2 summarizes their demographic characteristics.

Table 2. Demographic characteristics of the respondents

	Category	Respondents	Percentage
	Total	1,022	-
Gender	Male	534	52.3%
	Female	488	47.7%
Age	20s	225	22.0%
	30s	337	33.0%

	40s	284	27.8%
	50s	176	17.2%
Occupation	Self-employed	72	7.0%
	Blue-collar	80	7.8%
	White-collar	636	62.2%
	House-maker/Student/Jobless	234	22.9%
Monthly household income (KRW 10,000)	Below 199	244	23.9%
	200-299	257	25.1%
	300-399	146	14.3%
	400-499	121	11.8%
	500-699	93	9.1%
	Above 700	54	5.3%
	No income	107	10.5%
Number of family members	1	98	9.6%
	2	127	12.4%
	3	285	27.9%
	4	402	39.3%
	Above five	110	10.8%

Driving ability is essential for operation (and use) of car-sharing services, so the potential users of car-sharing services are holders of driving licenses. Of 1,022 samples, 909 (89%) respondents possessed a driver's license, and to the question of whether they drive in daily life, only 772 of them responded that they do. The remaining 137 people (15%) had a driver's license, but did not drive on a daily basis. Among 1,022 samples, 879 (86%) of people owned a household car, and 211 (24%) of those people owned more than one car in their household. The types of vehicles owned are shown in Figure 3 and 4.

For those who owned more than one vehicle, only the mainly driven vehicle was used in the classification.

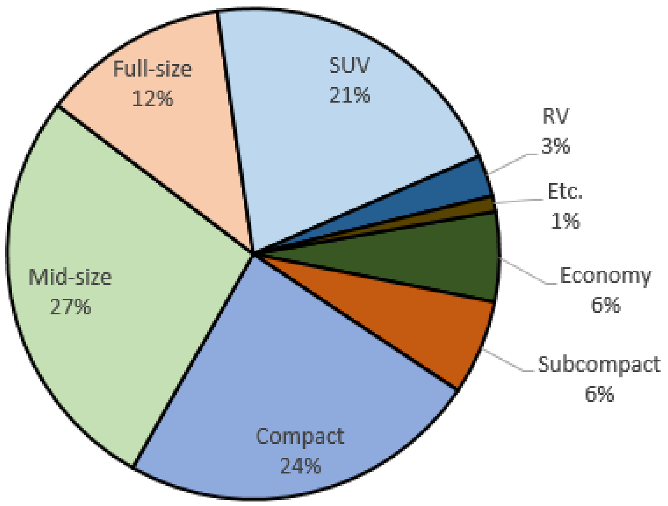


Figure 3. Vehicle types of the vehicles owned

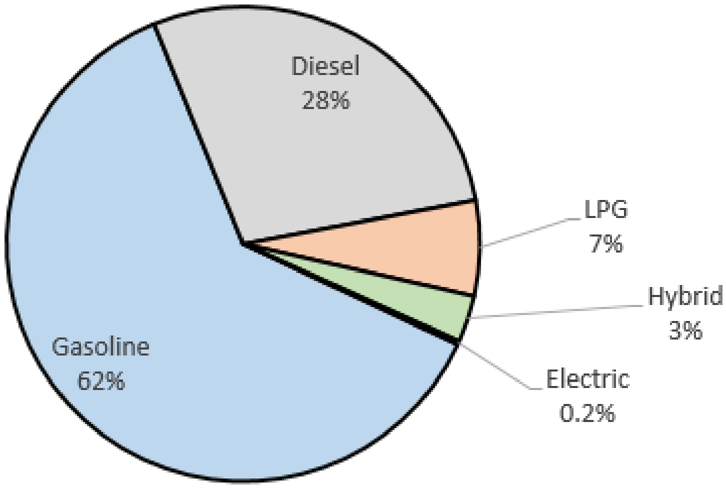


Figure 4. Fuel types of the vehicles owned

The automobiles owned were classified as follows: Economy (< 1000 cc), Subcompact (1000–1300 cc), Compact (1300–1600 cc), Mid-size (1600–2000 cc), Full-size (> 2000 cc), SUV, and RV as in Figure 3. Most of the vehicles owned used gasoline as fuel, followed by diesel, and LPG. Three percent were hybrids, and only two people owned fully electric vehicles.

To the question asking about their automobile purchasing plans, 245 people (23%) planned to purchase within one year, 288 people (28%) planned to purchase within three years, and 233 people (23%) planned to purchase a vehicle eventually, but realistically, did not feel that would occur within three years. The remaining 256 people (25%) responded that they had no plans to purchase a vehicle.

In asking about the awareness and use of car-sharing services, 846 people (83%) responded that they were aware of car-sharing services and 176 people (17%) reported they did not know about car-sharing. However, the number of actual users of car-sharing services was substantially smaller. Only 203 people (20%) reported that they had driven a car-sharing vehicle, while 819 people (80%) had no such experience.

For those who had experience using car-sharing services, questions were asked about the usual time of use and purposes for which the cars were used. Among the car-sharing users, 32 people (16%) used car-sharing services during commuting hours on weekdays, 63 people (31%) used them during non-commuting hours on weekdays, and 108 people (53%) used them on weekends, as shown in Figure 5. Also, the purposes for which car-sharing services were used are shown in Figure 6. The largest number of people (40%) use car-sharing services for short distance trips such as domestic or business trips in town, 52 people (26%) used them to transport for short distances such as to travel nearby, 35 people (17%) used them for business, and 20 people (10%) used them to commute to school or work. Few people (7%) used car-sharing services for long distance trips or to test drive a new automobile.

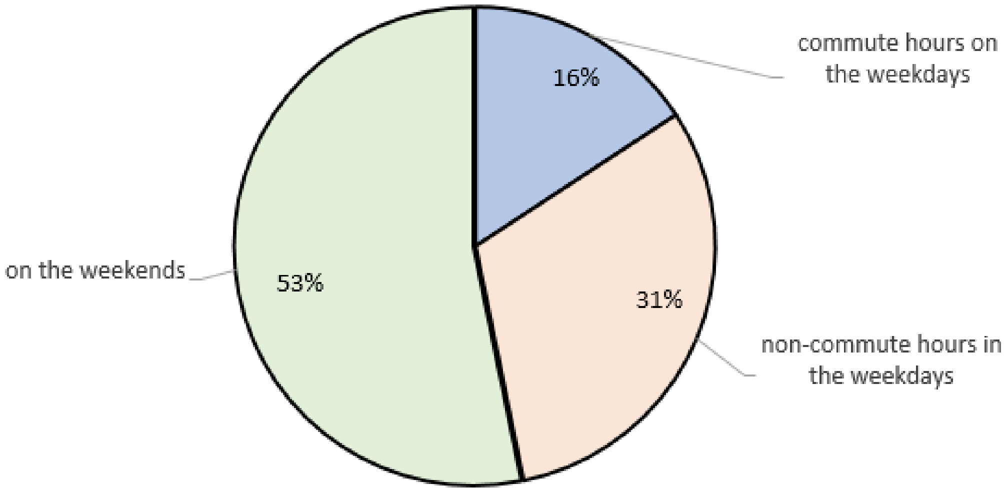


Figure 5. Usual time of using car-sharing services

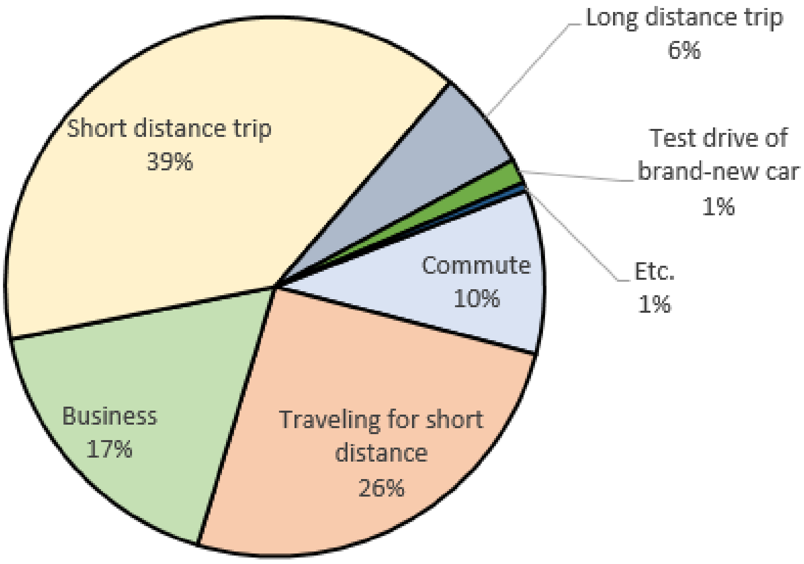


Figure 6. Purpose of using car-sharing services

3.2 Survey Design (Discrete Choice Experiment)

A discrete choice experiment was conducted to analyze consumer preferences on attributes that explain and affect car-sharing use. Because car-sharing services are only used by driving license holders, the choice experiment involved 909 of the 1,022 respondents who were holders of a driving license. Excluding missing data, the number of observations used in the empirical study of the car-sharing services was 807.

To design an appropriate choice experiment for car-sharing services, it was necessary to identify the core attributes and to assign levels accordingly. For this choice experiment, six attributes, namely the level of fueling and charging stations supplied, fuel type, vehicle type, pickup and delivery service, one-way drive, and cost of the car-sharing service were identified as affecting the mode of choice behavior for car-sharing services. The attributes and levels of car-sharing services for the discrete choice experiment are shown in Table 3.

Fuel charging station supplied level is an important attribute when it comes to driving an electric vehicle. Battery-powered electric vehicles emit zero emissions. Even considering emissions from power generation, carbon emissions from electric vehicles are still less than emissions from gasoline or diesel vehicles. In addition to being a more environmentally friendly choice, electric vehicles have lower vibration and noise compared with gasoline vehicles. Thus, one can drive more quietly with electric vehicles. However, driving electric vehicles may be inconvenient because there are still few electric charging stations compared to the number of gasoline filling stations. The total number of electric vehicle chargers in South Korea was 10,008 as of November 2016 (MOE, 2016). However, the Korean government plans on expanding the infrastructure for electric vehicle charging stations, and the number of chargers is increasing sharply (MOE, 2016). According to our survey, the reasons for reluctance to drive electric vehicles seemed to be the inconvenience from lack of charging infrastructure: 59.8% answered that inconvenience from lack of infrastructure was their reason for not considering the purchase of electric vehicles.

Fuel type, vehicle type, and cost of the service are commonly considered attributes when deciding on driving a vehicle. The pickup and delivery of car-sharing vehicles adds an extra level of convenience, because customers can request a specific vehicle to be delivered to their desired time and location. Driving the shared car only one way (hereafter ‘one-way drive’) is a key attribute that could reduce the advantage of having a privately owned vehicle. If ‘one-way drive’ were not allowed, the user would have to drive back to the location where the car was rented. Although it is limited to very specific areas, car-sharing operators in Korea are currently allowing one-way driving in Seoul, Gyeonggi, Incheon, and Busan (Greencar, 2017). As the number of car-sharing users grows, it is expected that one-way drive will be permitted in broader areas. As support services such as pickup and delivery or one-way drive become more freely available, there could be an increase in convenience that might increase the number of people who want to use car-sharing vehicles instead of purchasing a vehicle.

Table 3. Attributes and levels of car-sharing services for discrete choice experiment

Attribute	Attribute level	Description
Fuel charging station supplied level	15%	Given the number and supplied level of gas station of gasoline or diesel as 100%, station supplied rate refers to how much of LPG or EV fuel charging station is supplied.
	50%	
	80%	
	100%	
Fuel type	Gasoline or Diesel	For electricity vehicle can drive 200km with one time full charge, and vehicle can be charged at the renting station.
	LPG	
	Electricity	
Vehicle type	Economy, subcompact or compact vehicle	ex. Morning, Spark, Soul, Accent, Pride, Niro, Avante, K3, etc.
	Mid-size or full-size vehicle	ex. Sonata, K5, Grandeur, Genesis, K9, Chairman, etc.
	SUV (Sports Utility Vehicle)	ex. Tucson, Spotage, Tivoli, SantaFe, Trax, Orlando, etc.
Pickup & delivery service	Provided	If pickup and delivery services are provided, car-sharing vehicle will be delivered to door. If not provided, car-sharing vehicle can be picked up at the nearest station which is approximately 15 minutes of walking distance away.
	Not provided	
One-way drive	Allowed	If one-way drive is allowed, one can return the car-sharing vehicle at a different station from where it was rented.
	Not allowed	
Cost per hour	5,000	Refers to the total amount of cost to

(KRW)	10,000	rent for an hour. This includes gas price, time of renting, and insurance. This increases proportionally to time of renting.
	15,000	
	20,000	

The choice experiments were designed using these six attributes, and respondents were asked to choose their preferred alternative among hypothetical scenarios of car-sharing services. Subsequently, respondents were asked to answer whether they would be willing to use the service. Those who responded that they are not willing to use any of the car-sharing option are considered that they have chosen a no-choice option in later analysis, which is assumed to maintain transportation use behavior.

Based on the combinations of each attribute's level in Table 3, there are a total of 144 (= 3 * 3 * 2 * 2 * 4) possible car-sharing service alternatives, excluding the attribute of fuel charging station supplied rate based on the combinations of each attribute's level in Table 2. However, due to the difficulty for each respondent to evaluate all 144 alternatives, sixteen orthogonal alternatives were selected, using a fractional factorial design, to assure the orthogonality of each attribute within and between alternatives. These were further divided into eight choice sets, comprising two randomly arranged alternatives. As the attribute of the fuel charging station can be confusing if the level differs by each card, it was considered differently as other attributes. Additionally, in order to increase the randomness of the experiment and also take the attribute of fuel charring station supplied rate into consideration, the survey consisted of four different types, with different arrangement of the conjoint cards, and respondents were randomly chosen to answer different types.

Chapter 4. Methodology

This chapter describes the methods used to estimate the environmental effects of car-sharing services. As shown in Figure 7, for this study, the data about the mode of transportation used by each individual was collected first. This included the ownership of a car, fuel efficiency of the car owned, distance driven, hours using public transportation, etc. Second, then changes in transportation behavior, such as disposing of an owned vehicle, foregoing the purchase of a vehicle, increasing or decreasing mobility, and shifting to car-sharing services, were analyzed. In Section 4.1, the empirical models are introduced that were used in this thesis to examine the behavior change of individuals due to the introduction of car-sharing services. Last, the environmental effects from these changes in behavior were analyzed. Details about how these effects were calculated are discussed in Section 4.2.

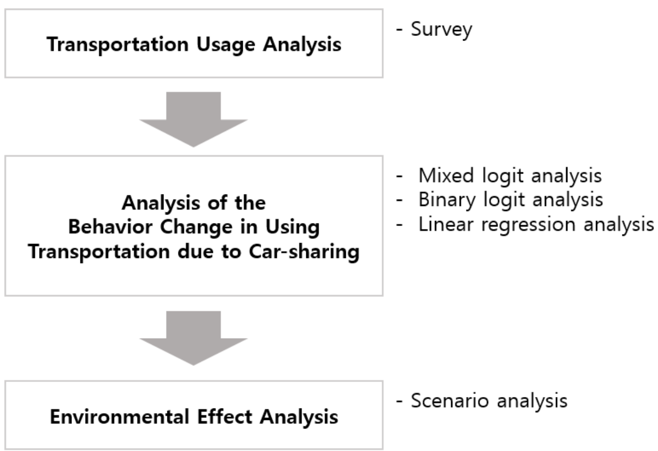


Figure 7. Framework for the analysis in this thesis

4.1 Empirical Model

4.1.1 Mixed Logit Model

A discrete choice model was used to examine the effect of car-sharing services and changes in consumer behavior. The one chosen in this case, the mixed logit model (McFadden and Train, 2000), is widely used to analyze consumer preferences, allowing the consideration of individual heterogeneity by assuming that a set of preference parameters follow a continuous distribution, such as a normal distribution.

Under the random utility maximization framework of discrete choice models (McFadden, 1974; Train, 2009), the utility of respondent n in choosing an alternative i can be written as equation (1):

$$U_{ni} = V_{ni} + \varepsilon_{ni} = \sum_{k=1}^{K} \beta_k X_{ik} + \varepsilon_{ni} \quad \text{Eq. (1)}$$

where the utility decomposed into the deterministic (V_{ni}) and stochastic part (ε_{ni}). Because the random utility maximization theory implies that a consumer chooses the alternative that provides the greatest utility, the choice-probability that consumer n chooses alternative i is derived as in equation (2).

$$\begin{aligned} P_{ni} &= P\left(U_{ni} > U_{nj}\right) \forall j \neq i \\ &= P\left(V_{ni} + \varepsilon_{ni} > V_{nj} + \varepsilon_{nj}\right) \forall j \neq i \\ &= P\left(\varepsilon_{nj} - \varepsilon_{ni} < V_{ni} - V_{nj}\right) \forall j \neq i \end{aligned} \quad \text{Eq. (2)}$$

In this model, the stochastic term ε_{ni} of the utility is assumed to follow an i.i.d. type I extreme value distribution. The density and cumulative distribution for each stochastic term ε_{ni} is defined as in equation (3) and (4).

$$f(\varepsilon_{ni}) = e^{-\varepsilon_{ni}} e^{-e^{-\varepsilon_{ni}}} \quad \text{Eq. (3)}$$

$$F(\varepsilon_{ni}) = e^{-e^{-\varepsilon_{ni}}} \quad \text{Eq. (4)}$$

Then, the choice probability can be calculated as in equation (5), integrated standard logit probabilities over a density of parameters.

$$P_{ni} = \int L_{ni}(\beta) g(\beta) d\beta \quad \text{Eq. (5)}$$

If the density of β is specified to be normal with mean b and covariance W, then the choice probability becomes equation (6).

$$P_{ni} = \int L_{ni}(\beta) g(\beta_n | b, W) d\beta \quad \text{Eq. (6)}$$

$$L_{ni}(\beta) = \frac{e^{V_{ni}}}{\sum_j e^{V_{nj}}} = \frac{e^{\beta' x_{ni}}}{\sum_j e^{\beta' x_{nj}}} \quad \text{Eq. (7)}$$

Then the likelihood function can be expressed as follows:

$$P_{ni} = \int \prod_{i} \left\{ L_{ni}(\beta) \right\}^{y_{ni}} g\left(\beta_n \middle| b, W\right) d\beta_n \quad \cdots\cdots \text{Eq. (8)}$$

$$Likelihood = \prod_{n=1}^{N} P_{ni} = \int \prod_{n=1}^{N} \prod_{i} \left\{ L_{ni}(\beta) \right\}^{y_{ni}} g\left(\beta_n \middle| b, W\right) d\beta_n \quad \cdots\cdots \text{Eq. (9)}$$

where $y_{ni} = 1$ if consumer n chooses alternative i and equals '0' otherwise. The mixed logit model allows representation of individual preference heterogeneity by assuming that a vector preference follows a continuous normal distribution. For estimation, simulated maximum-likelihood estimation or Bayesian estimation methods should be used instead of the traditional maximum-likelihood estimation method because the choice probability is not a closed form.

The utility that respondent n chooses as alternative i of the car-sharing service can be written as equation (10):

$$\begin{aligned} U_{ni\_carsharing} = {} & \beta_{stationrate} x_{stationrate} + \beta_{fueltype1} x_{fueltype1} + \beta_{fueltype2} x_{fueltype2} \\ & + \beta_{cartype1} x_{cartype1} + \beta_{cartype2} x_{cartype2} + \beta_{delivery} x_{delivery} \\ & + \beta_{oneway} x_{oneway} + \beta_{\text{cost}} x_{\text{cost}} + \beta_{nochoice} x_{nochoice} + \varepsilon_{ni} \\ & where\, \varepsilon_{ni} \sim i.i.d.\, type\, I\, extreme\, value\, distribution\, and\, \boldsymbol{\beta} \sim \mathrm{N}(b, W) \end{aligned} \quad \cdots\cdots \text{Eq. (10)}$$

The mixed logit model allows analysis of the individual heterogeneity by assuming that a set of preference parameters follow a continuous distribution. In this model, every parameter is assumed to follow a normal distribution.

4.1.2 Binary Logit Model

The binary logit model is used in the case where y_i is a binary response. Letting y_i be a binary response variable,

$$y_{ni} = \mathbf{\beta x} + \varepsilon_{ni} \quad \text{where} \quad y_i = \begin{cases} 1 & if\ yes \\ 0 & if\ no \end{cases} \quad \text{Eq. (11)}$$

In this study, a discrete choice model is used to estimate consumers' preferences for car-sharing alternatives. The discrete choice model assumes that consumers make choices that maximize their utility. According to the random utility theory, the utility U_{ni} of consumer n for the car-sharing i can be expressed as follows:

$$U_{ni} = V_{ni} + \varepsilon_{ni} = \sum_{k=1}^{K} \beta_k X_{ik} + \varepsilon_{ni} \quad \text{Eq. (12)}$$

In equation (12), V_{ni} refers to the deterministic part of utility and ε_{ni} indicates the stochastic part of the utility. The deterministic utility consists of a linear combination of K independent variables ($X_{ik}, k = 1,...,K$) and their coefficients (β_k). Moreover, the stochastic part is assumed to follow the type I extreme value distribution, and the probability density function and the cumulative density function are defined as $f(\varepsilon) = e^{-\varepsilon} / \left(1+e^{-\varepsilon}\right)^2$ and $F(\varepsilon) = 1/\left(1+e^{-\varepsilon}\right)$, respectively.

It was assumed that the consumer would dispose of an owned vehicle if the utility of disposing of the vehicle, and the use of the car-sharing service, were greater than zero. Similarly, it was assumed that a person who was planning to buy a vehicle would abandon the purchase of the vehicle if the utility of giving up the purchase of the vehicle and of using car-sharing were greater than zero. In short, the dependent variable can be defined as follows:

$$Y_{ni} = \begin{cases} 1, & if\, U_{ni} > 0 \;\; (\,foregone\, vehicle\, ownership\, or\;\, plan) \\ 0, & if\, U_{ni} \le 0 \;\; (maintain\, vehicle\, ownership\, or\;\, plan) \end{cases} \quad \cdots\cdots\cdots\cdots \text{Eq. (13)}$$

The model with binary dependent variable, and the stochastic part of utility that follows the type I extreme value distribution, is defined with the binary logit model. The choice probability of the binary logit model can be derived as follows (Train, 2009):

$$\begin{aligned} P_{ni} &= \Pr\left(U_{ni} > 0\right) \\ &= \int I\left(V_{ni} + \varepsilon_{ni} > 0\right) f\left(\varepsilon_{ni}\right) d\varepsilon_{ni} \\ &= \frac{e^{V_{ni}}}{1+e^{V_{ni}}} \\ &= \frac{e^{\beta' X_i}}{1+e^{\beta' X_i}} \end{aligned} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \text{Eq. (14)}$$

where $I(\bullet)$ is an indicator function, which is '1' if the value in the parenthesis is true, and '0' if it is false.

To analyze which attributes of the car-sharing services are affected by giving up owning a personal vehicle, a binary logit model was used. A binary model was needed because there were only two outcomes—dispose of the owned vehicle for car-sharing or not, and forfeiting the plan for vehicle purchase or not. The equation for a binary logit model is as follows:

$$Y_{ni\_forfeitvehicleownership} = \begin{cases} 1,\ if\ U_{ni} > 0\ (foregone\ vehicle\ ownership\ or\ plan) \\ 0,\ if\ U_{ni} \leq 0\ (maintain\ vehicle\ ownership\ or\ plan) \end{cases} \quad \text{Eq. (15)}$$

where the utility from forfeiting vehicle ownership or forgo vehicle purchasing is as in equation (16):

$$\begin{aligned} U_{ni\_forfeit\,vehicle\,ownership} &= \alpha + \beta_{stataionrate} x_{stationrate} + \beta_{fueltype1} x_{fueltype1} \\ &+ \beta_{fueltype2} x_{fueltype2} + \beta_{cartype1} x_{cartype1} + \beta_{cartype2} x_{cartype2} \quad \cdots \text{Eq. (16)} \\ &+ \beta_{delivery} x_{delivery} + \beta_{oneway} x_{oneway} + \beta_{\cos t} x_{\cos t} + \varepsilon_{ni} \end{aligned}$$

$$\begin{aligned} where\ \ \alpha = \alpha_0 &+ \alpha_{age} x_{age} + \alpha_{education} x_{education} + \alpha_{eco-friendly} x_{eco-friendly} \\ &+ \alpha_{income\_indiv} x_{income\_indiv} \end{aligned}$$

4.1.3 Linear Regression Model

The linear regression model is used to examine the relationships between variables. Let Y denote the dependent variable and x_i the explanatory variable; then the relationship can be written as follows:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + ... + \beta_K x_K + \varepsilon \quad \cdots\cdots \text{Eq. (17)}$$

The linear regression model was used to analyze which attributes of car-sharing services, social demographic characteristics of individuals, and their attitudes towards the environment, affected to what extent they would replace their mode of transportation with car-sharing services or how much their total amount of mileage changed due to car-sharing services.

Equation (18) indicates how much an individual who owned a car would replace driving the owned car with driving car-sharing vehicles.

$$\begin{aligned} Y_{own\ car\_replacing\,rate} = & \beta_0 + \beta_{stationrate} x_{stationrate} + \beta_{delivery} x_{delivery} \\ & + \beta_{\text{cost}} x_{\text{cost}} + \alpha_{age} x_{age} + \alpha_{education} x_{education} \\ & + \alpha_{eco-friendly} x_{eco-friendly} \\ & + \alpha_{income\_indiv} x_{income\_indiv} + \varepsilon_{ni} \end{aligned} \quad \cdots\cdots \text{Eq. (18)}$$

Similarly, the linear regression model was designed to examine how much an individual who used public transportation would replace its use with car-sharing as follows:

$$
\begin{aligned}
Y_{\text{publictransit\_}replacing\,rate} = {} & \beta_0 + \beta_{stationrate} x_{stationrate} + \beta_{delivery} x_{delivery} \\
& + \beta_{\text{cost}} x_{\text{cost}} + \alpha_{age} x_{age} + \alpha_{education} x_{education} \\
& + \alpha_{eco-friendly} x_{eco-friendly} + \alpha_{income\_indiv} x_{income\_indiv} \\
& + \varepsilon_{ni}
\end{aligned}
\quad \cdots\cdots \text{ Eq. (19)}
$$

Last, the total amount of mileage change indicates how an individual changes his or her mobility as a result of adopting car-sharing services. Travel needs might increase because car-sharing vehicles provide more convenience for travel than public transportation does. On the other hand, mobility may be reduced with adoption of car-sharing, making a reservation in advance or having to go to the car-sharing station to rent a vehicle may be inconvenient for some individuals. This kind of positive or negative change in mobility from adopting car-sharing was examined using the linear regression model in equation (20).

$$
\begin{aligned}
Y_{mobilitychange} = {} & \beta_0 + \beta_{stationrate} x_{stationrate} + \beta_{delivery} x_{delivery} + \beta_{\text{cost}} x_{\text{cost}} \\
& + \alpha_{age} x_{age} + \alpha_{education} x_{education} + \alpha_{eco-friendly} x_{eco-friendly} \\
& + \alpha_{income\_indiv} x_{income\_indiv} + \varepsilon_{ni}
\end{aligned}
\quad \cdots\cdots\cdots \text{ Eq. (20)}
$$

4.2 Framework for GHG Emission Impacts Analysis

This study estimates and compares the effects of car-sharing in various market situations. In analyzing the GHG emission impacts of car-sharing services, it is important to understand changes in individual behavior regarding transportation mode with the introduction of a car-sharing alternative. The introduction of car-sharing services has led to three possible changes in behavior when using transportation: 1) individual with a private car replaces driving it with car-sharing vehicle, 2) individual using public transit replaces it with car-sharing vehicles, and 3) the desire for ownership of a vehicle changes, such as a vehicle owner disposes of a vehicle or a prospective buyer abandons a plan for purchasing a vehicle. These behavioral changes affect in GHG emissions.

Figure 8 shows individual behavioral changes because the introduction of car-sharing services has effects on GHG emissions. First effect comes from the difference in the fuel efficiency of the private vehicle and that of a car-sharing vehicle. Car-sharing vehicles may or may not have higher fuel efficiency compared to vehicles owned by individuals. The change in GHG emission was estimated by taking into consideration of how much an individual replaces driving the private vehicle with the car-sharing vehicle. For those who dispose of an owned vehicle, 100% of private driving would be replaced with car-sharing. A second effect results from change in GHG emission caused by use of car-sharing vehicles by a carless individual. A third effect relates to the emission reduction from reduced production of vehicles in terms of life cycle assessment.

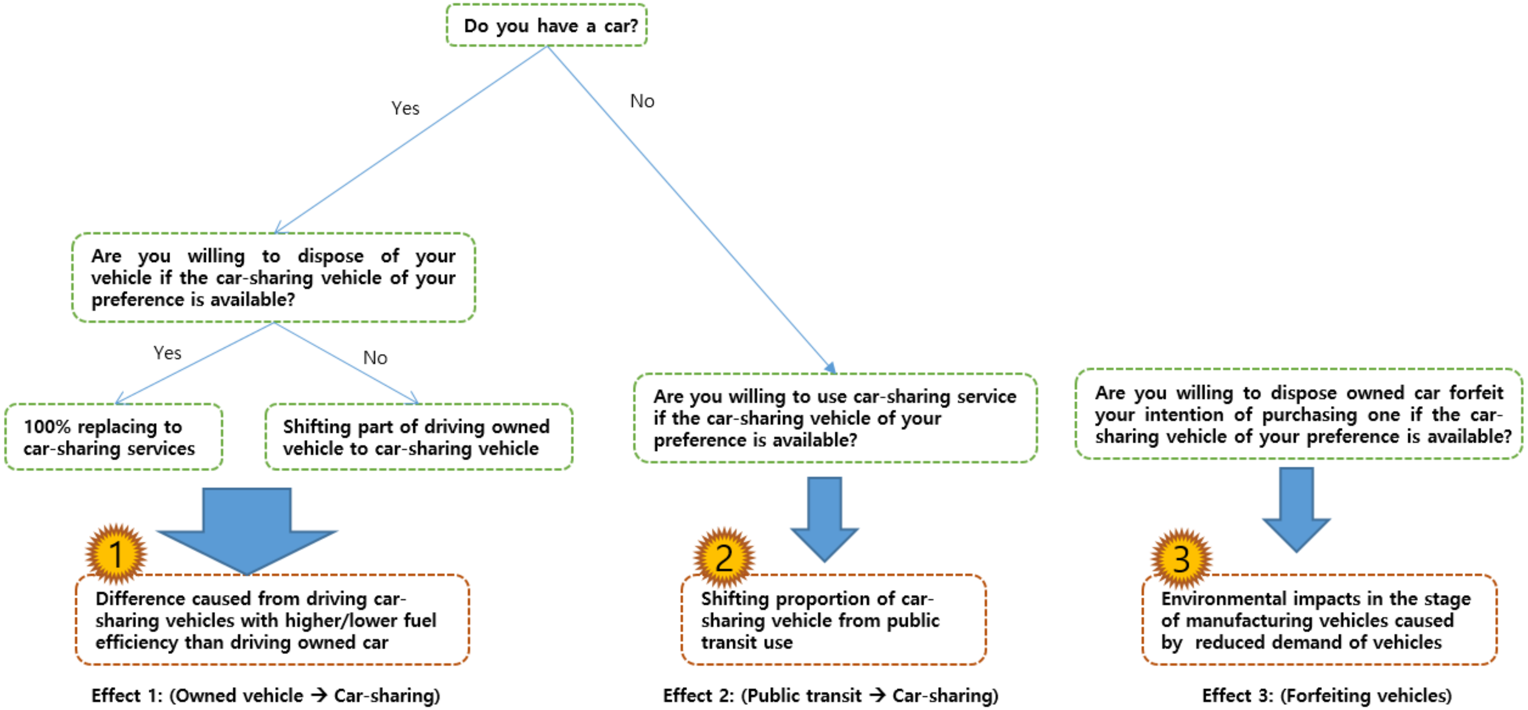
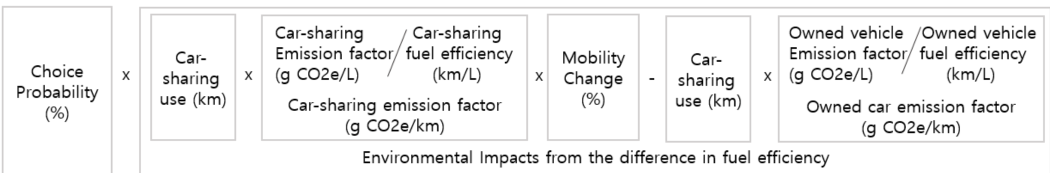


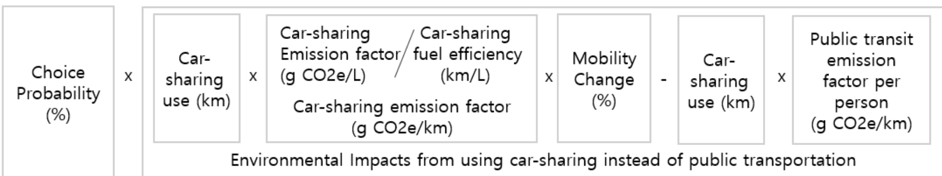
Figure 8. Visualization of how behavior changes effect GHG emission due to the introduction of car-sharing

4.2.1 Calculation of Effects of Car-Sharing Services

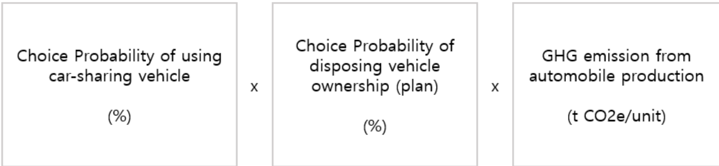
Three main environmental effects from car-sharing were analyzed. The first effect was the behavioral change of people driving owned vehicles to driving car-sharing vehicles. Because car-sharing vehicles are likely to be more fuel efficient than privately owned ones, car-sharing services usually reduce the environmental impacts caused by driving private vehicles. The second effect regards the behavioral change of using car-sharing vehicles by people who otherwise would have used public transportation. The third effect regards the change in desire to own a vehicle. With a reduced number of vehicles demanded, environmental impacts such as the amount of CO2e emission during the production of vehicles would be reduced. Figure 9 shows the processes used to calculate the three main environmental effects from using car-sharing services caused by behavioral change of individuals.



(a) Effect 1: Shifting owned car driving to car-sharing



(b) Effect 2: Shifting use of public transit to car-sharing



(c) Effect 3: Reduction in number of vehicle sales

Figure 9. Three main environmental effects from car-sharing due to behavioral change of each individual

Figure 9 describes the environment effects that an individual induces by adopting the car-sharing services. An individual can produce more than one effect. For example, one who uses an owned car and public transportation may decide to dispose of his or her vehicle and use car-sharing services. In such cases, all three effects are taken into consideration. However, some individuals who own a car and only use it and nothing else (such as public transportation), and who decide to keep ownership of a vehicle disregarding the introduction of car-sharing vehicles, might still use car-sharing vehicles on occasion. This person would be replacing his or her use of an owned car with car-sharing vehicles. Thus, only Effect 1 would be calculated for this individual. Each effect was calculated at an individual level to reflect individual heterogeneity.

The explanations for each effect are discussed below. Re-writing these equations at a population level, each effect can be written as follows, and descriptions of the variables used for the estimation are given in Table 4:

Effect1: Shifting of driving from an owned car to car-sharing vehicles

$$\frac{\left[\sum_{n=1}\sum_{i=1} CP_{ni} \times \left(CSV_{ni} \times CSE_{ni} \times MC_{ni} - CSV_{ni} \times OCE_{n}\right)\right]}{n_1} \times N_1 \quad \cdots\cdots\cdots\cdots\cdots\cdots \text{Eq. (21)}$$

$i = carsharing\ index$

$n = individual\ index$

$CP_{ni} = choice\ probability\,(\%)\ of\ \ individual\ \ n\ chooses\ a\ carsharing\ alternative\ i$

$CSV_{ni} = carsharing\ use\,(km)\ shifted\ \ from\ owned\ vehicle\ driving$

$CSE_{ni} = carsharing\ emission(gCO2e\,/\,km)$

$MC_{ni} = mobility\ change\,(\%)$

$OCE_{i} = owned\ car\ emission(gCO2e\,/\,km)$

$n_1 = number\ of\ \ carowners\,(\text{sample})$

$N_1 = number\ of\ \ carowners\,(\,population)$

The following variables were calculated as follows:

$CSE_{ni} = carsharing\ emission\ \ factor_{ni}\left(g\,CO2e\,/\,L\right)\cdot\ fuel\ efficiency_{i}\left(km/L\right)^{-1}$

$OCE_{n} = owned\ car\ emission\ \ factor_{n}\left(g\,CO2e\,/\,L\right)\cdot\ fuel\ efficiency_{n}\left(km/L\right)^{-1}$

$CSV_{ni} = drive_{n}(km)\cdot replace\ rate_{ni}(\%)$

Effect2-1: Shifting use of buses to car-sharing vehicles

$$\frac{\left[\sum_{n=1}\sum_{i=1} CP_{ni} \times \left(CSB_{ni} \times CSE_{ni} \times MC_{ni} - CSB_{ni} \times BE_{n}\right)\right]}{n_2} \times N_2 \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots \text{Eq. (22)}$$

$CSB_{ni} = carsharing\ use\,(km)\ shifted\ \ from\ bus\ use$

$BE_{n} = bus\ emission(gCO2e\,/\,km)$

$n_2 = number\ of\ bus\ users\ who\ have\ driving\ license\,(\text{sample})$

$N_2 = number\ of\ bus\ users\ who\ have\ driving\ license\,(population)$

The following variables were calculated as follows:

$CSB_{ni} = bus\ use(hr) \cdot conversion\ \ factor(km\,/\,hr) \cdot replace\ rate_{ni}\,(\%)$

$N_2 = number\ of\ bus\ users \cdot driving\ license\ holding\ rate$

Effect2-2: Shifting use of subways to car-sharing vehicles

$$\frac{\left[\sum_{n=1}\sum_{i=1} CP_{ni} \times \left(CSS_{ni} \times CSE_{ni} \times MC_{ni} - CSS_{ni} \times SE_{n}\right)\right]}{n_3} \times N_3 \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \text{Eq. (23)}$$

$CSS_{ni} = carsharing\ use\,(km)\ shifted\ \ from\ subway\ use$

$SE_i = subway\ emission$

$n_3 = number\ of\ subway\ users\ who\ have\ driving\ license$ (sample)

$N_3 = number\ of\ subway\ users\ who\ have\ driving\ license\ (population)$

The following variables are calculated as follows:

$CSS_{ni} = subway\ use(hr) \cdot conversion\ factor(km/hr) \cdot replace\ rate_{ni}(\%)$

$N_3 = number\ of\ subway\ users \cdot driving\ license\ holding\ rate$

Effect3: Disposing of an ownership of a vehicle

$$\frac{\sum_{n=1}\sum_{i=1} CP_{ni} \times CPD_{ni}}{n_4} \times N_4 \times EPC \quad \text{Eq. (24)}$$

$CPD_{ni} = choice\ probability\ of\ disposing\ a\ car\ ownership$

$EPC = emission\ from\ producing\ a\ car$

$n_4 = number\ of\ individuals\ with\ changed\ car\ ownership$ (sample)

$N_4 = number\ of\ vehicles\ sold\ per\ day$

Table 4. Description of variables used for the estimation of environmental impacts

Variable	Description	Source

Estimated variables used in calculation		
CP_{ni} , CPD_{ni}	Choice probability of the car-sharing services and choice probability of disposing a car-ownership varies by car-sharing attributes and individual characteristics.	Estimated value from conjoint experiment of the survey
CSV_{ni} , CSB_{ni} , CSS_{ni}	Car-sharing use shifted from owned vehicle or public transit is calculated by multiplying travel distance and replace rate. Replacement rate is calculated based on car-sharing attributes and individual characteristics.	
MC_{ni}	Mobility change indicates increased or decreased travel distances due to convenience of the car-sharing services. This value varies by differing car-sharing attributes and each individual.	
Fixed variables used in calculation		
CSE_{ni} , OCE_i ,	CSE_{ni} (car-sharing emission factor) and OCE_i (owned car emission factor) are calculated by dividing emission factor (gCO2e/L) by fuel efficiency (km/L or km/kWh) of the vehicle. The emission factor varies depending on the fuel type of vehicle. [Gasoline=2778.2gCO2e/L, Diesel=3241.3gCO2e/L, LPG=2942.6gCO2e/L, Electricity=393.3~865.1gCO2e/kWh].	JEC, 2014
fuel efficiency	Fuel efficiency of the car-sharing vehicle differs as follows: gasoline/diesel vehicle (13.7km/L), LPG vehicle (9.6km/L), electric vehicle (5.4km/kWh).	KEA, 2016a; Socar, 2017; Greencar, 2017
conversion factor	It converts travel time on public transit to travel distance. [0.35km/min]	MOLIT, 2016
BE_i , SE_i	Bus emission factor [57.3 g per person·km], Subway emission factor [26.0 g per person·km]	Park and Ko, 2014
EPC	emission from producing a car [4.6709 t CO2e per unit]	KEITI, 2015
N_1	The number of passenger car registered vehicle is used	MOLIT, 2016

	to take consideration of the number of car-owners [20,989,885 units]	
N_2	Number of daily bus users who have driving license [9,620,591 people]	MOLIT, 2016
N_3	Number of daily subway users who have driving license [5,208,389 people]	MOLIT, 2016
N_4	Number of vehicle sold a day in South Korea [4,091 units]	KEA, 2016b

For explanation of each variable in detail, refer to the following subsections.

<CO2e Emission Factor>

The effect could be different depending on which vehicle is used for car-sharing. Currently, a variety of vehicles including different sizes to different fuel types are used for car-sharing. In order to compare the environmental impacts coming from different types of car-sharing vehicles, three types of vehicles were considered: gasoline or diesel, LPG, and electric vehicles. In this study, gasoline or diesel, LPG and electric vehicles are used for the analysis of car-sharing environmental impacts, and CO2e emission factors were used accordingly. Various types of vehicles, including different sizes and electric vehicles are allocated as car-sharing vehicles. Unlike privately owned vehicles, car-sharing vehicles are allocated by providers, which means that customers must choose a vehicle from the limited options provided. By allocating energy-efficient vehicles, car-sharing can be structurally more environmentally friendly. In this study, environmental effects were analyzed when compact cars and electric vehicles were used for car-sharing.

In order to calculate the CO2e emission factor for gasoline vehicles, equation (25) was used, for LPG vehicles, equation (26) was used, and for electric vehicle, equation (27) was used.

$$\begin{aligned} &CO_2e\,emission\ factor_{gasoline}\left(gCO_2e/km\right) = \\ &\quad gasoline\,emission\ factor\left(gCO_2e/L\right)\cdot\ fuel\,efficiency^{-1}(km/L) \end{aligned} \quad \cdots\cdots\cdots\ \text{Eq. (25)}$$

$$\begin{aligned} &CO_2e\,emission\ factor_{LPG}\left(gCO_2e/km\right) = \\ &\quad LPG\,emission\ factor\left(gCO_2e/L\right)\cdot\ fuel\,efficiency^{-1}(km/L) \end{aligned} \quad \cdots\cdots\cdots\cdots\ \text{Eq. (26)}$$

$$\begin{aligned} &CO_2e\,emission\ factor_{EV}\left(gCO_2e/km\right) = \\ &\quad EV\,emission\ factor\left(gCO_2e/kWh\right)\cdot\ fuel\,efficiency^{-1}(km/kWh) \end{aligned} \quad \cdots\cdots\cdots\ \text{Eq. (27)}$$

Regarding the fuel efficiency of car-sharing vehicles, those operated by the two largest car-sharing firms in Korea were used for estimation. For the CO2e emission factor, the displayed fuel efficiency (km/L or kWh/L) data from the Korea Energy Agency (KEA, 2016a) are used for each vehicle. The fuel efficiency of gasoline car-sharing vehicles is based on the most commonly used gasoline or diesel mid-size car-sharing vehicle: the Hyundai Avante (13.7 km/L). For the LPG car-sharing vehicle, the value for the K5 (9.6 km/L) was used. There are four types of electric vehicles available for car-sharing. For electric vehicles, BMW i3, SM3, Ray, Ionic are vehicles available as car-sharing vehicles in the market (Greencar, 2017; Socar, 2017). Therefore, the average of the displayed fuel efficiencies (km/L or kWh/L) of these four vehicles was used for estimation. The average fuel efficiency was 5.375 km/kWh for the electric car-sharing vehicle.

Compared to the fuel efficiency of non-business passenger cars, the fuel efficiency of car-sharing vehicles is similar or better. According to statistics on the registration of domestic vehicles, non-business passenger cars are 60.70% gasoline, 30.05% diesel, 9.20% LPG, and 0.05% electric vehicles. In addition, the average fuel efficiency of gasoline, diesel, LPG, and electric vehicles in non-business passenger cars is 13.22 km/L, 12.87 km/L, 18.03 km/L, and 4.8 km/kWh, respectively (KEA, 2016a).

The gasoline emission factor (gCO_2e/L), which is the total value of the well-to-wheel GHG emissions of gasoline, diesel, and LPG fuels are estimated to be 2,778.2 gCO2e/L (well-to-tank: 2,314.4, tank-to-wheel: 463.8), 3,241.3 g CO2e/L (well-to-tank: 2,676.9, tank-to-wheel: 564.4), and 2,942.6 g CO2e/L, respectively. These figures were sourced from JEC, the joint collaboration between JRC (the EU Commission's Joint Research Center), EUCAR (the European Council for Automotive R&D), and CONCAWE (the oil companies' European association for environment, health, and safety in refining and distribution) (Edwards et al., 2004; JRC, 2014). The total well-to-wheel analysis combines the results of well-to-tank (the life-cycle analysis of a petroleum-based fuel pathway including all steps from crude oil recovery to final finished fuel) and tank-to wheel (actual combustion of fuel in motor vehicles for motive power) analysis.

In calculating the electricity emission factors (gCO_2e/kWh) for electric vehicles, CO2e emissions from electricity generation were considered. Thus, the emission coefficient from the mix of power plants as in Table 5 should be considered, and the portfolio of power plants for electricity production in Korea is shown in Figure 10. The portfolio of power plant for electricity production in Korea is as follows: coal (42.4%), nuclear (28.8%), gas (23.0%), oil (3.9%), and others (0.9%) (World Bank, 2014). In many studies, GHG emissions from electricity generation are reported with minimum and maximum values, due to fluctuating value depending on the calculation method. Therefore, this study also reports the environmental impacts with minimum and maximum values (see Table 5) (Edwards et al., 2004; Turconi, Boldrin, and Astrup, 2013).

Table 5. Minimum and maximum values of GHG emission coefficient from electricity generation suggested by previous literatures (Edwards et al., 2004; Turconi, Boldrin, and Astrup, 2013)

kgCO2e/MWh	**Min**	**Max**
Coal	660	1370
Natural gas	380	1000
Oil	530	890
Nuclear	3.1	35
Hydroelectric	2	20
SolarPV	13	190
Wind	3	41
Biomass	1	130

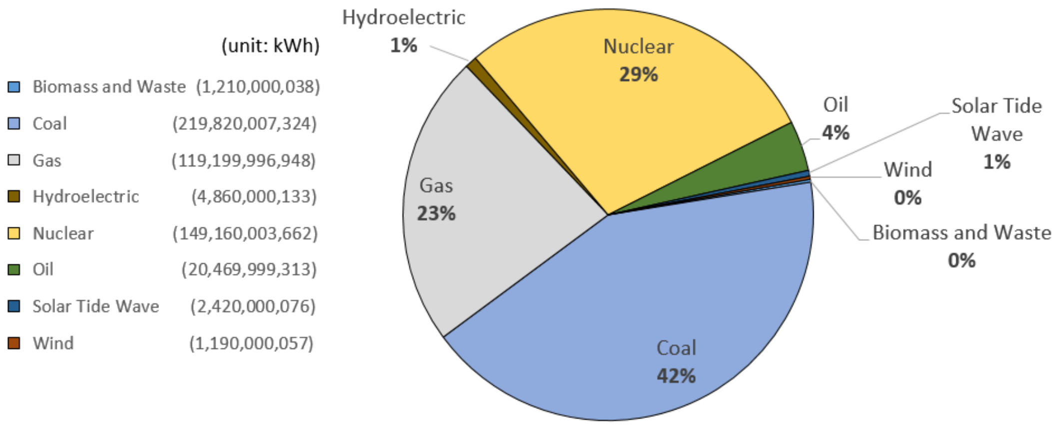


Figure 10. Breakdown of Electricity Generation by Energy Source in Korea in 2014 (The World Bank, 2014)

In calculation of shifted effect of using car-sharing from public transit, the following public transportation emission factors are used: bus emission factor 57.3 gCO2e per person·km and subway emission factor 26.0 gCO2e per person·km (Park and Ko, 2014).

<Conversion Factor>

For the survey, respondents were asked to answer questions regarding public transportation using behavior in travel time rather than distance, because individuals are more familiar with travel time than distances for public transportation. To convert hours into distances for the analysis, the average distance per trip for an individual that travels using public transportation was divided by the average time per trip. The average travel distance and time of one pass per person were 19.16 km and 54.57 min, respectively (MOLIT, 2016). Thus, the conversion factor is calculated as follows:

$$conversion\ factor = \frac{average\,travel\,distance}{average\,travel\,time} = 0.35 \text{ km/min} \quad \cdots\cdots\cdots\cdots\cdots \text{Eq. (28)}$$

This value was obtained from the survey results on the public transport survey conducted by the Korea Transportation Safety Authority (TS) and Ministry of Land, Infrastructure, and Transport (MOLIT). The survey was conducted from October 2015 to August 2016 for people who used public transit more than four times per week and were at least 15years old. A total of 83,600 individuals were sampled considering the ratio of the population composition in Korea for the statistics.

<Characteristics of the Public Transportation Users>

According to the public transport survey, the average daily number of public transportation users in Korea is 11,848,019 (MOLIT, 2016). According to the characteristics of public transportation users, 56.03% of those use only buses, 18.79% use only subway, and 25.17% use a combination (Figure 11). Therefore, it was estimated that daily number of bus users was $9,620,591\ (=11,848,019 \times 81.2\%)$, and that the daily number of subway users was $5,208,389(=11,848,019 \times 43.96\%)$ (MOLIT, 2016).

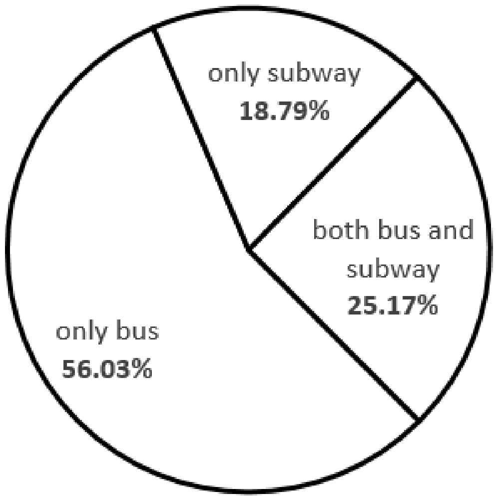


Figure 11. Usage characteristics of public transit users (MOLIT, 2016)

Among public transportation users, 29.4% did not hold driving licenses, as shown in Figure 12. The potential individuals who might shift their transportation use to car-sharing from public transit are those with driving licenses. Thus, 70.6% was used as the proportion of public transit users who held driving licenses.

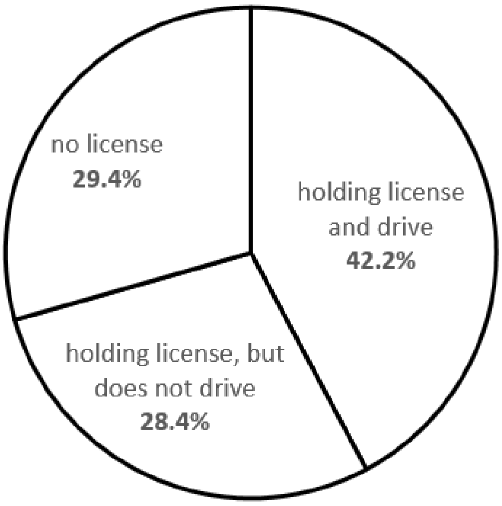


Figure 12. Ratio of license holders among public transit users (MOLIT, 2016)

<Number of Vehicles Sold per Day>

The third environmental effect from car-sharing considered in this study is the effect from forfeited vehicles. Car-sharing provides the benefits of personal mobility without the costs of owning a private vehicle. Such benefits motivate an individual to forego the intention of purchasing a vehicle. Reduced demand in vehicles would be reflected in vehicles sales, and hence, would reduce vehicle production. Therefore, in this study, foregone vehicles are taken into consideration to estimate the reduced GHG emissions from vehicles that did not have to be manufactured.

The number of passenger cars sold in Korea in 2015 was 1,493,207, of which 124,213 (85.3%) were domestic vehicles (KEA, 2016b). Table 6 and Figure 13 describe the average number of vehicles sold each day in Korea, including the vehicles produced in Korea and in other countries. For more accurate calculation of the CO2e emission caused by the reduced number of vehicles sold, the ratio of vehicles produced in Korea should be taken into consideration. However, this study refers to number of vehicle units sold in Korea in 2015 (4,091 units) instead of considering only the number of vehicles produced in Korea (3,403 units). This is because the related environmental problem is not limited to Korea, but is an issue for all nations. Thus, in this study, the number of vehicles sold in Korea was used so that GHG emissions from both domestic and imported vehicles could be discussed at a global level.

Table 6. Sales trends for passenger car in Korea (KEA, 2016b)

	2010	2011	2012	2013	2014	2015
domestic	3,237	3,264	3,083	2,954	3,174	3,403
import	247	283	358	432	590	688
Total	3,484	3,547	3,441	3,386	3,764	4,091

※Average sales per day (in vehicle units)

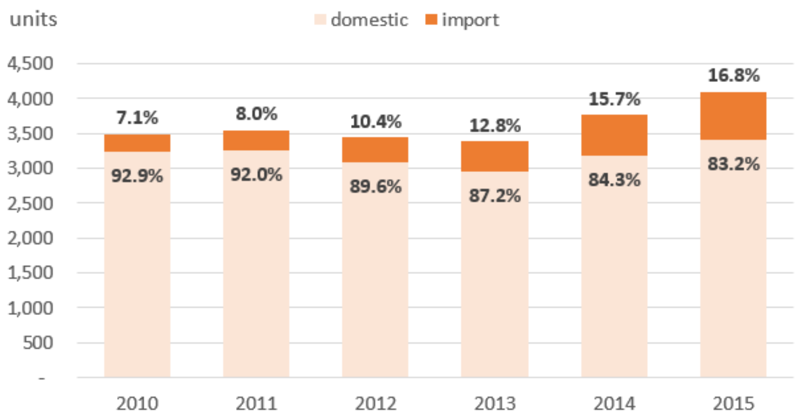


Figure 13. Sales trends for passenger cars in Korea (KEA, 2016b)

<CO2e Emission per Vehicle Production>

The carbon footprint value of manufacturing vehicles was used in estimating the impacts of forgone vehicles. The carbon footprint is considered the total GHG emissions caused by a product from the manufacturing stage to the termination stage. In this study, the carbon footprints of eleven vehicles reported by the Korea Environmental Industry and Technology Institute (KEITI) were used. The average total CO2e emissions from the carbon footprint (from the report), excluding the emissions during the use stage is 4.6709 t CO2e per vehicle (KEITI, 2015).

The first effect regards the behavioral change of people using car-sharing vehicles who otherwise would have used public transportation. With the introduction of car-sharing services, some portion of travel time by public transport has shifted to car-sharing for individuals who chose to adopt car-sharing. To estimate the average travel time that has been shifted from public transport to car-sharing, choice probability, travel time using public transport, and the proportion shifting to car-sharing were considered.

<Passenger Car Registered Status >

Figure 14 refers to the number of vehicles registered as passenger cars. Individuals who own vehicles are potential users of car-sharing services after disposing of their vehicle. Therefore, the 20,989,885 vehicles registered as passenger cars belong to individuals who have the potential to dispose of their vehicles to join car-sharing services (MOLIT, 2016).

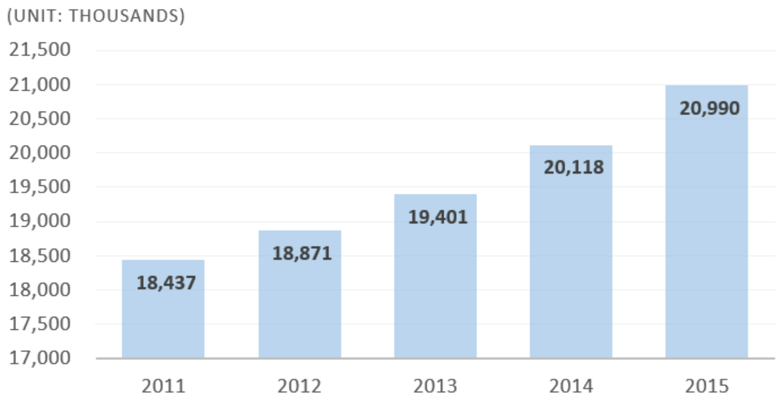


Figure 14. Trends in vehicles registered as non-business passenger cars

4.2.2 Simulation Analysis

As previously mentioned, this study involved estimation of the environmental effects of car-sharing services in different scenarios to suggest environmentally friendly ways of operating car-sharing. In this section, the scenarios designed for the estimation are explained: the base scenario and a scenario in which the EV charging infrastructure is enhanced by increasing the number of charging stations.

Table 7. Base scenario (Most similar to the current car-sharing market situation)

Attributes \ Choice alternative	Car-sharing vehicle A	Car-sharing Vehicle B	Car-sharing Vehicle C	-
Fuel charging station supplied level	100%	15%	5%	No choice
Fuel type	Gasoline or Diesel	LPG	Electricity	
Vehicle type	Mid-size or full-size vehicle	Mid-size or full-size vehicle	Mid-size or full-size vehicle	
Pickup & delivery service	Not provided	Not provided	Not provided	
One-way drive	Not allowed	Not allowed	Not allowed	
Cost (KRW /1hr)	10,000	10,000	10,000	

The base scenario was designed to reproduce a hypothetical scenario that was most like the car-sharing market situation at the time of the study. As shown in Table 7, there were three types of car-sharing vehicles in base scenario. The car-sharing Vehicle A was a gasoline or diesel type, mid- or full-size car-sharing vehicle. For these, pickup and delivery service was not provided and one-way drive was not permitted. The number of charging stations was equal to the current number of gas stations. Using such car-sharing vehicles cost KRW 10,000 per hour. The car-sharing Vehicle B was a LPG type car-sharing vehicle. Thus, the number of LPG fuel filling stations was about 15% of the number of current gasoline filling stations. The car-sharing Vehicle C was an electric vehicle, and so the number of charging stations was about 5% of the number of gasoline filling stations due to the limited EV infrastructure.

Based on this scenario, the choice probability of using car-sharing services, the choice probability of disposing of owned cars, and the environmental impacts were estimated in the following scenarios: 1) scenario in which infrastructure for electric vehicles increases, and 2) scenario where delivery service is provided and one-way drive is permitted.

Chapter 5. Results

5.1 Empirical Results

5.1.1 Preferences Analysis of Using the Car-sharing Services (Using the Mixed Logit Model)

For these choice experiments, six attributes, fuel charging station supplied level, fuel type, vehicle type, pickup and delivery, one-way drive, and cost of cost-sharing, were identified as affecting the mode of choice behavior for car-sharing services. All variables were coded to take the no-choice option into consideration, as suggested by Vermeulen et al. (2008). The no-choice option indicates that the respondent has no intention to use car-sharing, but to continue current travel behavior regardless of car-sharing options. The attributes and levels of car-sharing services for the discrete choice experiment are shown in Table 8.

Table 8. Description of effect-coded variables (For mixed logit analysis)

	Variables (Effect coding)
Fuel charging station supplied rate	15% (0.15)
	50% (0.5)
	80% (0.8)
	100% (1)
Fuel type	Gasoline or Diesel (-1, -1)
	LPG (1, 0)
	Electricity (0, 1)

Vehicle type	Economy, subcompact or compact vehicle (1, 0)
	Mid-size or full-size vehicle (0, 1)
	SUV (Sports Utility Vehicle) (-1, -1)
Pickup & delivery service	Provided (1)
	Not provided (-1)
One-way drive	Allowed (1)
	Not allowed (-1)
Cost per hour (KRW)	5,000 (5)
	10,000 (10)
	15,000 (15)
	20,000 (20)
No choice	other attribute levels (0)
	no choice (1)

In this study, the heterogeneous preferences in car-sharing services were estimated using the mixed logit model. The result from estimation of the utility function equation (29) is shown in Table 9.

$$
\begin{aligned}
U_{ni\_carsharing} = {} & \beta_{stationrate} x_{stationrate} + \beta_{fueltype1} x_{fueltype1} + \beta_{fueltype2} x_{fueltype2} \\
& + \beta_{cartype1} x_{cartype1} + \beta_{cartype2} x_{cartype2} + \beta_{delivery} x_{delivery} \\
& + \beta_{oneway} x_{oneway} + \beta_{\text{cost}} x_{\text{cost}} + \beta_{nochoice} x_{nochoice} + \varepsilon_{ni}
\end{aligned}
\qquad \cdots\cdots \text{Eq. (29)}
$$

$$
where\ \varepsilon_{ni} \sim i.i.d.\ type\ I\ extreme\ value\ distribution\ \ and\ \ \boldsymbol{\beta} \sim \mathrm{N}(b, W)
$$

Table 9. Estimation results for car-sharing service through a mixed logit choice model

Parameter	Mean estimate of β	Std. Err	P>|z|
$\beta_{stationrate}$	**0.481**	0.156	0.002
$\beta_{fueltype\_LPG}$	**-0.281**	0.076	0.000
$\beta_{fueltype\_Electricity}$	**0.132**	0.035	0.000
$\beta_{cartype\_economy}$	**-0.181**	0.037	0.000
$\beta_{cartype\_midsize}$	**-0.136**	0.041	0.001
$\beta_{delivery}$	**0.433**	0.026	0.000
β_{oneway}	**0.350**	0.029	0.000
β_{cost}	**-0.210**	0.007	0.000
$\beta_{nochoice}$	**-3.779**	0.182	0.000

※Bolded estimate value indicates $p<0.1$

The mean of each attribute represents the marginal utility of individuals for a unit change of an attribute level. The estimated results show that the mean value of each attribute-coefficient was statistically significant at the 99% confidence level.

When interpreting these results, the estimated parameter should be interpreted with care. Under the effects coding system, estimate of the parameter cannot be interpreted as it is. Rather, the reference level is inferred from the estimate of corresponding attribute parameters. That is, the parameter of the current level of car-sharing services for each attribute is equal to the negative sum of the coefficient estimated for that attribute. For example, the coefficient of the SUV type vehicle (reference level) in the car-sharing model is $-(\beta_{cartype1} + \beta_{cartype2}) = -(-0.181 - 0.136) = 0.317$.

Interpreting these results, the utility level increases with increase in the number of fueling and charging stations. The fuel type preference is reflected in the order electric, gasoline or diesel, and LPG for the car-sharing vehicles. The SUV is the most preferred among the various types of cars. This seems to reflect the growing trend of interest in SUVs in South Korea. Moreover, people prefer to use car-sharing services that provide pickup-and-delivery options and prefer to be able to drive one-way. Less expensive cost is preferred.

5.1.1 Analysis of the Intention to Dispose of Owned Vehicles or to Forego Plans for Purchasing a Vehicle (Using Binary Logit Model)

Changes in individual behavior caused by car-sharing can result in a change in the choice to possess a car. Because car-sharing provides the benefits of personal mobility at a low price, an individual could be motivated to release an owned vehicle. Using a binary logit model, changes in an individual’s intention to dispose of an owned vehicle in various car-sharing market situations were examined.

Because car-sharing provides the benefits of personal mobility without most of the costs of owning a private vehicle, an individual might also be motivated to forego the intention to purchase a vehicle. Therefore, foregone vehicles were taken into consideration to estimate the GHG emissions reduced by not manufacturing some vehicles. In estimating the effects of forfeited ownership of vehicles, CO2e emission per vehicle produced, number of vehicles sold in a day, and the forfeited vehicle ratio were used.

Thus, in this part of the study the intention of individuals to dispose of private vehicles or to forego purchasing a vehicle was explored in various car-sharing market situations. For this a binary logit model was used, as in equation (30), and results are given in Table 10.

$$Y_{ni} = \begin{cases} 1, & if\ U_{ni} > 0 \ \ (foregone\ vehicle\ ownership\ or\ plan) \\ 0, & if\ U_{ni} \leq 0 \ \ (maintain\ vehicle\ ownership\ or\ plan) \end{cases} \quad \cdots\cdots\cdots \text{Eq. (30)}$$

where the utility function of forfeiting vehicle ownership or foregoing vehicle purchases are as follows:

$$U_{ni\_forfeit\,vehicle\,ownership} = \alpha + \beta_{stataionrate} x_{stationrate} + \beta_{fueltype1} x_{fueltype1}$$
$$+ \beta_{fueltype2} x_{fueltype2} + \beta_{cartype1} x_{cartype1}$$
$$+ \beta_{cartype2} x_{cartype2} + \beta_{delivery} x_{delivery}$$
$$+ \beta_{oneway} x_{oneway} + \beta_{\cos t} x_{\cos t} + \varepsilon_{ni}$$
$$where\, \alpha = \alpha_0 + \alpha_{age} x_{age} + \alpha_{education} x_{education}$$
$$+ \alpha_{eco-friendly} x_{eco-friendly}$$
$$+ \alpha_{income\_indiv} x_{income\_indiv}$$

Table 10. Description of dummy-coded variables (For binary logit & linear regression analysis)

	Variables (Dummy coding)
Fuel charging station supplied rate	15% (0.15)
	50% (0.5)
	80% (0.8)
	100% (1)
Fuel type	Gasoline or Diesel (0, 0)
	LPG (1, 0)
	Electricity (0, 1)
Vehicle type	Economy, subcompact or compact vehicle (1, 0)
	Mid-size or full-size vehicle (0, 1)
	SUV (Sports Utility Vehicle) (0, 0)
Pickup & delivery service	Provided (1)
	Not provided (0)
One-way drive	Allowed (1)
	Not allowed (0)
Cost per hour (KRW)	5,000 (5)
	10,000 (10)
	15,000 (15)

20,000 (20)

Table 11. Estimation results for disposing owned car or foregoing vehicle purchasing plan for car-sharing service through a binary logit choice model

	Estimates	Std. Err	z	P>|z|
Car-sharing services attribute variable				
$\beta_{stataionrate}$	**0.578**	0.268	2.150	0.031
$\beta_{fueltype\_LPG}$	**0.517**	0.250	2.070	0.039
$\beta_{fueltype\_Electricity}$	**0.347**	0.144	2.410	0.016
$\beta_{cartype\_economy}$	-0.109	0.108	-1.010	0.314
$\beta_{cartype\_midsize}$	0.006	0.117	0.050	0.961
$\beta_{delivery}$	-0.009	0.090	-0.100	0.922
β_{oneway}	0.062	0.088	0.700	0.482
β_{cost}	**-0.024**	0.008	-2.930	0.003
Individual characteristic variables				
α_0	**-3.587**	0.549	-6.540	0.000

α_{age}	-0.004	0.005	-0.780	0.436
$\alpha_{education}$	**0.040**	0.023	1.770	0.076
$\alpha_{eco-friendly}$	**0.377**	0.053	7.160	0.000
α_{income_indiv}	**0.077**	0.018	4.220	0.000

※Bolded estimate value indicates $p<0.1$

The car-sharing attributes that matter in deciding whether to dispose of an owned vehicle or to forego buying a vehicle are station rate, fuel type, and cost of the car-sharing service.

From interpretation of these results, the utility level increased with increase in the number of fueling and charging stations. The fuel type preferred for car-sharing vehicles were, in the following order: electricity, gasoline or diesel, and LPG. Among the types of cars available, SUVs were the most preferred. This seems to reflect the growing trend of interest in SUVs in South Korea. Also, people preferred to use car-sharing vehicle services that offer pickup and delivery options and they preferred to be able to drive one-way with car-sharing vehicle. Users preferred lower cost. The individual characteristic variables that significantly affect decisions about forgoing car ownership were level of education, level of concern about the environment, and level of individual income. The higher the education level and the more the person cared about and practiced eco-friendly behavior daily, the more likely that an individual would change from possessing a car to using car-sharing services. Also, the higher the level of individual income, the more likely that an individual would use car-sharing services and forego vehicle ownership.

5.1.1 Usage and Mobility Change of Transportation as an Introduction to Car-Sharing Services (Using Linear Regression Model)

<Ratio of driving hours replaced with car-sharing hours>

The ratio of hours of driving private vehicles that were replaced (shifted) to car-sharing hours was estimated using linear regression analysis. The results of the regression analysis are presented in Table 12. The ratio of private vehicle hours replaced with car-sharing services is affected by four attribute variables: station rate, fuel type, one-way option, and cost.

Table 12. Estimation result for replacing ratio of driving hours with car-sharing (original)

	Estimates	Std. Err.	t	P>|t|
$\beta_{stataionrate}$	**0.045**	0.022	2.010	0.045
$\beta_{fueltype\_\mathrm{LPG}}$	**0.046**	0.021	2.210	0.027
$\beta_{fueltype\_Electricity}$	**0.031**	0.012	2.530	0.011
$\beta_{cartype\_economy}$	-0.002	0.009	-0.270	0.788

$\beta_{cartype\_midsize}$	-0.007	0.010	-0.720	0.471
$\beta_{delivery}$	0.010	0.007	1.340	0.180
β_{oneway}	**0.032**	0.007	4.370	0.000
β_{cost}	**-0.004**	0.001	-5.840	0.000
β_0	**0.154**	0.025	6.070	0.000

※Bolded estimate value indicates p<0.1

Using the variables that significantly impacted the shifting ratio, regression analysis was conducted once more, but this time including the respondents' social demographic information (e.g., age, education level, individual income level) and attitudes towards the environment, as in equation (31).

$$\begin{aligned} Y_{own\ car\_replacing\,rate} = \beta_0 + \beta_{stationrate}x_{stationrate} + \beta_{delivery}x_{delivery} \\ + \beta_{\text{cost}}x_{\text{cost}} + \beta_{age}x_{age} + \beta_{education}x_{education} \\ + \beta_{practice\_ecofriendly}x_{practice\_ecofriendly} \\ + \beta_{income\_indiv}x_{income\_indiv} + \varepsilon_{ni} \end{aligned} \quad \cdots\cdots\cdots\cdots\cdots\cdots \text{Eq. (31)}$$

Table 13. Estimation result for replacing ratio of driving hours with car-sharing (with individual characteristics)

	Estimates	Std. Err.	t	P>|t|

Car-sharing services attribute variable				
$\beta_{stataionrate}$	**0.045**	0.022	2.030	0.042
$\beta_{fueltype\_LPG}$	**0.047**	0.020	2.310	0.021
$\beta_{fueltype\_\mathrm{Electricity}}$	**0.033**	0.012	2.740	0.006
β_{oneway}	**0.031**	0.007	4.320	0.000
β_{cost}	**-0.004**	0.001	-5.800	0.000
β_0	**0.146**	0.044	3.340	0.001
Individual characteristic variables				
α_{age}	0.001	0.000	1.610	0.108
$\alpha_{education}$	**-0.007**	0.002	-3.810	0.000
$\alpha_{eco-friendly}$	**0.026**	0.004	6.180	0.000
α_{income_indiv}	0.002	0.001	1.230	0.219

※Bolded estimate value indicates p<0.1

Table 13 indicates the estimation result from the linear regression analysis with the individual characteristic variables. Interpreting this result, it was found that the greater the number of fueling and charging stations, the greater the portion of private vehicle driving replaced with driving of car-sharing vehicles. The power supply preferred was in the order electricity, gasoline or diesel, and LPG for the car-sharing vehicle. The driving one-way option positively influenced the rate of switching to car-sharing vehicles. The lower the cost for car-sharing, the more people would shift to car-sharing services from private transportation mode. The estimates for the age and individual monthly income variables did not significantly influence to replacement ratio. Individuals with lower education levels were more likely to replace car ownership with car-sharing. Last, the eco-friendliness variable, which indicates how much an individual believes that he or she practices green actions, positively affects the replacement ratio.

<Ratio of replacement of public transit use with car-sharing services>

The ratio of people replacing public transit use with car-sharing services is estimated using the regression analysis. The results of the regression analysis are presented in Table 14. The ratio of people replacing their use of public transit with car-sharing services is affected by four attribute variables: station rate, fuel type, one-way option, and cost.

Table 14. Estimation results for replacing ratio of public transit with car-sharing (original)

	Estimates	Std. Err.	t	P>|t|
$\beta_{stataionrate}$	**0.055**	0.024	2.340	0.020

$\beta_{fueltype\_\mathrm{LPG}}$	**0.062**	0.022	2.820	0.005
$\beta_{fueltype\_Electricity}$	**0.035**	0.013	2.680	0.007
$\beta_{cartype\_economy}$	0.001	0.009	0.060	0.953
$\beta_{cartype\_midsize}$	-0.011	0.010	-1.020	0.308
$\beta_{delivery}$	0.006	0.008	0.800	0.421
β_{oneway}	**0.035**	0.008	4.460	0.000
β_{cost}	**-0.004**	0.001	-5.440	0.000
β_0	**0.151**	0.027	5.540	0.000

※Bolded estimate value indicates p<0.1

Using the variables that significantly impacted the shift ratio, regression analysis was conducted once more, but this time including the respondents' social demographic information (e.g., age, level of education, level of individual income) and attitudes towards the environment.

$$\begin{aligned} Y_{\mathrm{publictransit}\_replacing\,rate} = {} & \beta_0 + \beta_{stationrate}x_{stationrate} + \beta_{delivery}x_{delivery} \\ & + \beta_{\mathrm{cost}}x_{\mathrm{cost}} + \beta_{age}x_{age} + \beta_{education}x_{education} \\ & + \beta_{practice\_ecofriendly}x_{practice\_ecofriendly} \\ & + \beta_{income\_indiv}x_{income\_indiv} + \varepsilon \end{aligned} \quad \cdots\cdots\cdots\cdots \text{Eq. (32)}$$

Table 15. Estimation results for replacing ratio of public transit with car-sharing (with individual characteristics)

	Estimates	Std. Err.	t	P>|t|
Car-sharing services attribute variable				
$\beta_{stataionrate}$	**0.056**	0.024	2.380	0.017
$\beta_{fueltype\_LPG}$	**0.063**	0.022	2.860	0.004
$\beta_{fueltype\_Electricity}$	**0.037**	0.013	2.890	0.004
β_{oneway}	**0.034**	0.008	4.470	0.000
β_{cost}	**-0.004**	0.001	-5.450	0.000
β_0	0.065	0.047	1.390	0.166
Individual characteristic variables				
α_{age}	0.000	0.000	-0.360	0.716
$\alpha_{education}$	-0.002	0.002	-0.920	0.360
$\alpha_{eco-friendly}$	**0.029**	0.005	6.470	0.000
α_{income_indiv}	**0.005**	0.002	2.980	0.003

※Bolded estimate value indicates p<0.1

Table 15 indicates the estimation results of the linear regression analysis with individual characteristic variables for the replacement ratio of public transit with car-sharing. Interpretation of this result indicated that the greater the number of fueling and charging stations, the greater the portion of public transportation replaced with car-sharing. The fuel type preferred was in the order electricity, gasoline or diesel, and LPG for the car-sharing vehicles. The driving one-way option positively influenced the rate of switching to car-sharing vehicles. The lower the cost of car-sharing, the greater the number of people who would shift to car-sharing services from public transport use. The estimates for age and education were not statistically significant influences on the replacement ratio. Individuals who cared more about the environment would be more likely to shift from private transportation mode to car-sharing. Last, higher income positively affected the replacement ratio.

<Mobility change with car-sharing services>

With the introduction of car-sharing services, some new travel demand has been induced due to the availability of another travel option (mode). Car-sharing also has reduced some travel demand due to the inconvenience of renting a vehicle.

Table 16. Estimation results for mobility change with car-sharing (original)

	Estimates	Std. Err.	t	P>|t|

$\beta_{stataionrate}$	0.012	0.009	1.370	0.172
$\beta_{fueltype\_LPG}$	0.013	0.008	1.610	0.108
$\beta_{fueltype\_Electricity}$	**0.011**	0.005	2.290	0.022
$\beta_{cartype\_\mathrm{economy}}$	-0.002	0.004	-0.490	0.624
$\beta_{cartype\_midsize}$	-0.005	0.004	-1.230	0.220
$\beta_{delivery}$	0.001	0.003	0.380	0.706
β_{oneway}	**0.006**	0.003	2.010	0.045
β_{cost}	**-0.001**	0.000	-3.220	0.001
β_0	**0.023**	0.010	2.230	0.026

※Bolded estimate value indicates p<0.1

The results of the regression analysis the mobility change from adopting car-sharing services are shown in Table 16. The mobility change was affected by two attribute variables: the one-way option, and cost. Using the variables that significantly impacted the shift ratio, regression analysis was conducted once more, but this time involving the respondents' social demographic information (e.g., age, level of education, level of individual income) and attitudes towards the environment.

$$\begin{aligned} Y_{mobilitychange} = \beta_0 + \beta_{stationrate} x_{stationrate} + \beta_{delivery} x_{delivery} \\ + \beta_{\text{cost}} x_{\text{cost}} + \beta_{age} x_{age} + \beta_{education} x_{education} \\ + \beta_{practice\_ecofriendly} x_{practice\_ecofriendly} \\ + \beta_{income\_indiv} x_{income\_indiv} + \varepsilon \end{aligned} \quad \cdots\cdots\cdots\cdots \text{Eq. (33)}$$

Table 17. Estimation results for mobility change with car-sharing (with individual characteristics)

	Estimates	Std. Err.	t	P>|t|
Car-sharing services attribute variable				
β_{oneway}	**0.006**	0.003	2.260	0.024
β_{cost}	**-0.001**	0.000	-3.380	0.001
β_0	**0.043**	0.015	2.850	0.004
Individual characteristic variables				
α_{age}	**-0.000**	0.000	-1.780	0.075
$\alpha_{education}$	**-0.002**	0.001	-2.670	0.008
$\alpha_{eco-friendly}$	**0.008**	0.002	4.930	0.000
α_{income_indiv}	**0.002**	0.001	2.910	0.004

※Bolded estimate value indicates p<0.1

Table 17 indicates the estimation results of the linear regression analysis. From interpretation of these results, it was determined that the one-way option positively increased mobility. The older, and lower the level of education of an individual was, the lower the chance of adopting the car-sharing services. As with the results above, individuals practicing more eco-friendly behavior were more likely to choose higher mobility by changing to car-sharing services. Such results seem to be due to the recognition that car-sharing service is an environmentally friendly mode of transportation. Last, higher individual income positively influenced the change in mobility.

5.2 Estimation of the Emission Effects from Car-Sharing

Refer to Section 4.2 for the framework of the GHG emission effects analysis and description of the variables used in the calculations. By setting the scenario analysis in this study, the different GHG emission effects caused by the car-sharing services were compared for different market situations.

5.2.1 GHG Emissions in the Base Scenario: Most similar to the current car-sharing market

The effects of car-sharing services were analyzed for different market situations. To be able to compare the results, a base scenario was set at the attribute levels, and thus creating a hypothetical scenario, most similar to the current car-sharing market (see Table 18).

Table 18. Choice probability and forfeiting probability in the base scenario

Choice alternative / Attributes	Car-sharing vehicle A	Car-sharing Vehicle B	Car-sharing Vehicle C	-
Fuel charging station supplied rate	100%	15%	5%	No choice
Fuel type	Gasoline or Diesel	LPG	Electricity	
Vehicle type	Mid-size or full-size vehicle	Mid-size or full-size vehicle	Mid-size or full-size vehicle	
Pickup & delivery service	Not provided	Not provided	Not provided	
One-way drive	Not allowed	Not allowed	Not allowed	
Cost per hour (KRW)	10,000	10,000	10,000	
Choice probability	34.90%	14.36%	21.17%	-
Forfeiting probability	16.20%			-

For the base scenario, three car-sharing types were used in the car-sharing market, and are described in Table 18. Given this scenario, the total amount of GHG emissions was calculated to be 2809.83 tCO2e. This indicates that with the car-sharing services, there was GHG emissions by 2809.83 tCO2e per day (Table 19). This means that due to the introduction of car-sharing services, there were four specific results [Effect 1 (−5928.90 tCO2e), Effect 2-1 (7069.30 tCO2e), Effect 2-2 (4763.77 tCO2e), and Effect 3 (−3094.33 tCO2e)]. This amount of GHG emissions equals to 1,025,589.36 t CO2e per year. In

South Korea, GHG emission attributed to passenger cars on the road in 2009 was 38,821,000 tCO2 (KEA, 2016b). Thus, calculating the total emissions due to the introduction of car-sharing services suggest a reduction of about 2.6% of the CO2 emissions from passenger cars.

5.2.2 GHG Emissions from Increase in the EV Infrastructure

Electric vehicles have the advantage of fuel efficiency and emit much less while on the road. However, people are not in favor of driving electric vehicles due to the inconvenience in charging the batteries. Thus, in the analysis of this scenario, the choice probability of each type of car-sharing vehicle was examined, along with how the GHG emission reduction changed with increase in the number of charging stations. Figure 15 describes the changes in the choice probability of each type of car-sharing vehicle as the supply of EV charging stations increases. Although the total number of car-sharing users remained fairly constant, the number of individuals who previously preferred to use gasoline, diesel, or LPG fuel types of car-sharing vehicles became more willing to use the EV type for car-sharing.

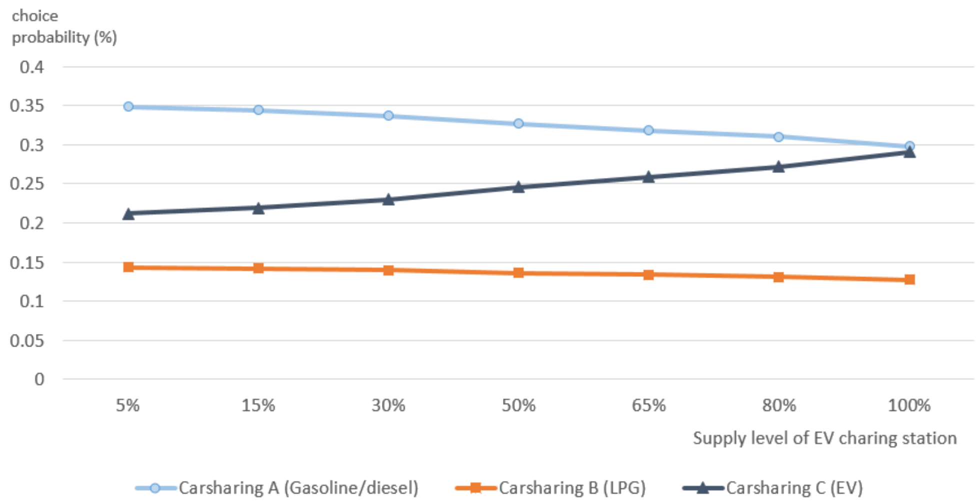


Figure 15. Change in the choice probability of car-sharing as EV charging station infrastructure (number of stations) increases

The effects of the change in the choice probability of electric vehicle car-sharing on the total reduction of GHG emissions can be seen in Figure 16.

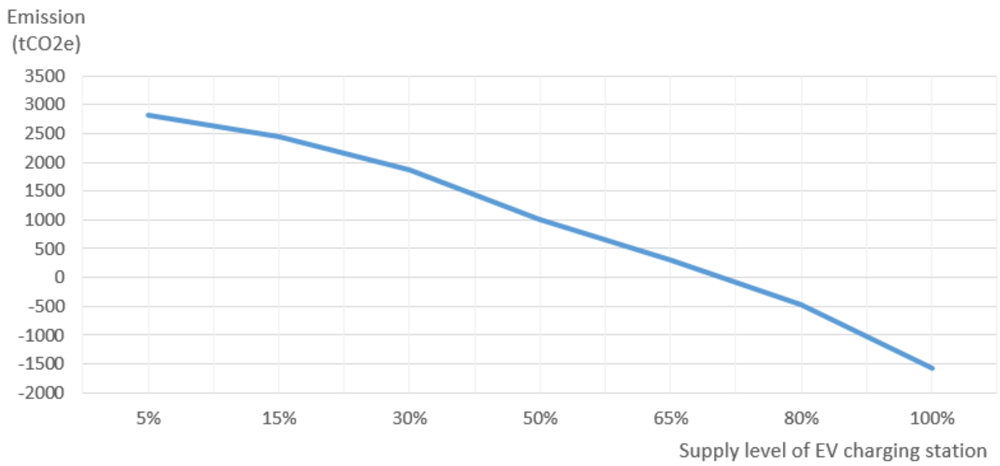


Figure 16. Reduction in daily GHG emissions with greater supply of EV charging

Table 19. Emission in various car-sharing market scenario (unit: tCO2e)

	Base scenario	EV 50% scenario	EV 100% scenario
Effect 1	-5928.90	-7058.19	-8617.48
Effect 2-1	7069.30	6770.51	6337.56
Effect 2-2	4763.77	4603.62	4353.00
Effect 3	-3094.33	-3302.74	-3652.28
Total Effect (day)	2809.83	1013.19	-1579.20
Total Effect (year)	1,025,589.36	369,815.97	-576,408.46

With increase of the EV infrastructure, more individuals were willing to drive electric car-sharing vehicles. If the number of EV charging stations increased to about 50% of the gasoline stations, the choice probability of using electric car-sharing vehicles increases. Thus, the GHG emissions on the roads could be reduced to 1013.19 t CO2e/day. Comparing this to the base scenario, there would be 1796.64 tCO2e less emission per day, which equals to 655,773.6 tCO2e for a year. If EV charging stations increased to 100% of the number of gasoline stations, the emission would be reduced to 1579.20 tCO2e/day. Comparing this to the base scenario, there would be 2877.57 tCO2e less emission per day (1,050,313.05 tCO2e less per year compared to the base scenario), which indicates there could be positive environmental effects from car-sharing services if there is also an increase in the number of EV charging stations and associated infrastructure.

The threshold point where emission reduction occurs through car-sharing services with increase in the infrastructure of EV charging station is when the number of charging stations reaches 71.1% of the gasoline/diesel stations. If this were to happen, the emission caused by the changed behavior of individuals switching to car-sharing would equal zero.

In calculating the effect of car-sharing services, the value of 629.19 gCO2e/kWh was used for the electric-emission factor instead of reporting the value as minimum and maximum (393.33–865.05 gCO2e/kWh) to eliminate any confusion. However, in reality the emission factor could vary depending on the mix of green power generation options in the country. Thus, it would be more accurate to report estimates of the impacts as in Table 20.

Table 20. Emission in various car-sharing market scenario using minimum and maximum value of electricity emission (unit: tCO2e)

	Base scenario		EV 50% scenario		EV 100% scenario	
	min	max	min	max	min	max
Effect 1	-7001.73	-4856.08	-8,486.26	-5,630.12	-10,537.07	-6,697.89
Effect 2-1	6460.21	7678.39	6,103.03	7,437.98	5,629.43	7,045.70
Effect 2-2	4420.12	5107.42	4,224.74	4,982.50	3,948.23	4,757.76
Effect 3	-3094.33	-3094.33	-3,302.74	-3,302.74	-3,652.28	-3,652.28
Total Effect (day)	784.27	4835.40	-1,461.24	3,487.63	-4,611.70	1,453.29
Total Effect (year)	286,257	1,764,921	-533,352	1,272,984	-1,683,269	530,452

5.2.3 Scenario: Delivery service provided and one-way drive permitted

Delivery of car-sharing vehicles is a newly introduced option in the car-sharing market. With this convenience, the number of individuals willing to give up ownership of a vehicle is expected to increase. However, the analysis results showed that the desire for car ownership is reduced, but does not seem to have a very large impact. As seen in Table 21, the choice probability and the forfeiting probability does not show a significant difference from those of the base scenario (16.20% →16.35%).

Table 21. Scenario for the additional services (delivery service and one-way drive)

Attributes \ Choice alternative	Car-sharing vehicle A	Car-sharing Vehicle B	Car-sharing Vehicle C	-
Fuel charging station supplied rate	100%	15%	5%	No choice
Fuel type	Gasoline or Diesel	LPG	Electricity	
Vehicle type	Mid-size or full-size vehicle	Mid-size or full-size vehicle	Mid-size or full-size vehicle	
Pickup & delivery service	Provided	Provided	Provided	
One-way drive	Allowed	Allowed	Allowed	
Cost per hour (KRW)	15,000	15,000	15,000	
Choice probability	37.09%	15.38%	22.70%	-
Forfeiting probability	16.35%			-

5.3 Discussion

Through the analysis of individual behavioral change in the transportation modes used in relation to car-sharing services, the GHG emissions were estimated under typical current and hypothetical car-sharing market situations. The results indicate that the current way of operating car-sharing services is not environmentally friendly.

Car-sharing services provide an innovative urban mode of transportation, allowing individuals to be able to use a vehicle without many of the costs of maintaining a privately owned vehicle. However, the results show that the current way of operating the car-sharing services is not environmentally friendly. Therefore, it should be considered whether car-sharing services are truly a sustainable innovation in mobility for the transportation system. Although current car-sharing services are not eco-friendly in terms of GHG emissions due to the attendant induced travel demand, the result suggests that car-sharing services could be operated in a more environmentally friendly manner. The eco-friendlier way of operating the car-sharing services would be to encourage individuals to use more power-efficient vehicles. However, this can be only done by increasing the number of EV charging stations sufficiently that more individuals choose to ride on EVs instead of gasoline-fueled vehicles.

Furthermore, additional service options such as pickup and delivery of car-sharing vehicles or a one-way driving option would be expected to encourage individuals to forego a planned vehicle purchase or to dispose of a currently owned vehicle. However, the results also indicate that the probability of foregoing purchases would probably not significantly affect private ownership of a vehicle. Although the choice probability of using car-sharing vehicles increases, individuals are not willing to dispose of their vehicles or to forego a planned vehicle purchase.

Chapter 6. Conclusion

6.1 Concluding Remarks and Contributions

In this study, the GHG environmental effects from a shift in the mode of transportation was examined. Using a mixed logit model, consumer preferences and choice probability of using car-sharing services were analyzed. For the estimation of environmental impacts, the mode shifting proportion and reduction in vehicle ownership due to the introduction of car-sharing services were considered. The behavioral change in car ownership in relation to introduction of various car-sharing services was estimated using a binary logit model. Furthermore, individual characteristic variables were included when estimating the preferences, replacement rate, and change in mobility caused by adopting car-sharing services.

The results show that extra GHG emissions caused by the shift from use of public transport or privately owned vehicles to car-sharing outweigh the GHG reduction effect from the foregone (unpurchased/unproduced) vehicles. The findings of this study provide implications that car-sharing may not be as environmentally friendly as expected in terms of GHG emissions. Many people mistakenly assume that all sharing activities are environmentally friendly. Figure 17 shows how many people agrees to the environment-friendliness of the car-sharing services. 54.5% of individuals responded that they agree or strongly agree to the environmental-friendliness of car-sharing services.

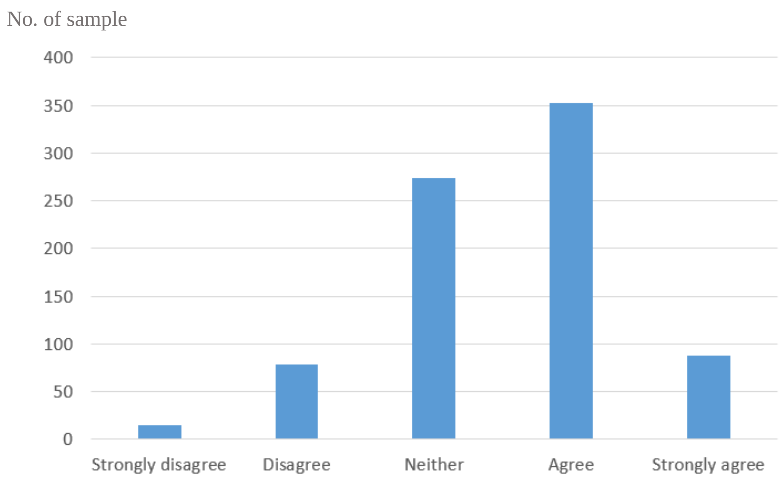


Figure 17. Response to the question of how much do you agree to the following statement: "Car-sharing is an environment-friendly mode of transportation"

Car-sharing service provides an alternative mode of transportation, allowing individuals to use a vehicle at relatively low cost. Yes, it is an innovative mobility that is more environment-friendly compared to the private vehicle. However, as car-sharing service is not a more environment-friendly alternative mode of transportation in comparison to the public transportation. Thus, in order to understand the true environmental effects from car-sharing, it was essential to examine individual behavior changes in adopting car-sharing. Understanding the true impacts of car-sharing would allow to construct more effective policy for creation of a sustainable society and transportation system.

Various types of vehicles, including different sizes of car and electric vehicles are allocated as car-sharing vehicles. Unlike privately owned vehicles, car-sharing vehicles are allocated by the providers. This means that customers choose the car-sharing vehicles from among the limited options available from the providers. Therefore, to reduce the negative environmental impacts caused by car-sharing, more efficient vehicles (e.g., higher fuel efficiency or longer life cycles) could be allocated as car-sharing vehicles. To reduce emissions in the transport sector through car-sharing services, creating an environment in which many people could choose more EV car-sharing vehicles is most important. Furthermore, in order to maximize this effect, having a greener mix of electricity generation options is important.

In summary, the proliferation of conventional car-sharing vehicles has not made a significant contribution to GHG reduction. However, if the infrastructure for electric vehicles were increased, this analysis shows that the total GHG emission could be reduced to zero percent, compared to the current car-sharing market situation. Thus, the proliferation of fuel-efficient EV car-sharing vehicles, rather than supporting car-sharing itself, is a more effective way to reduce GHG emissions through car-sharing services.

6.2 Limitations and Future Research Topics

The limitations of this study include the fact that environmental impacts were only considered in terms of GHG emissions, and social and economic impacts, such as individual benefits of using vehicles without owning them, were not considered in estimating the effects of car-sharing services. However, because the aim of this study was to analyze the environmental impacts from car-sharing, these topics were outside its scope. As previously mentioned, there are numerous positive effects in terms of other aspects of car-sharing, such as increased mobility of individuals at a cheaper cost than by owning vehicles. However, the three main effects that cause positive and negative environmental effects were analyzed and ways suggested to operate car-sharing services in a more environment-friendly manner.

Bibliography

Baptista, P., Melo, S., and Rolim, C. (2014). Energy, environmental and mobility impacts of car-sharing systems. Empirical results from Lisbon, Portugal. Procedia-Social and Behavioral Sciences 111, 28-37.

Batt, C. E. and Katz, J. E. (1997). A conjoint model of enhanced voice mail services. Implications for new service development and forecasting. *Telecommunications Policy*, *21*(8), 743-760.

Beggs, S., Cardell, S., and Hausman, J. (1981). Assessing the potential demand for electric cars. Journal of Econometrics 17(1), 1-19.

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

Brownstone, D., Bunch, D.S., Golob, T.F., and Ren, W. (1996). A transactions choice model for forecasting demand for alternative-fuel vehicles. Research in Transportation Economics 4, 87-129.

Catalano, M., Lo Casto, B., and Migliore, M. (2008). Car sharing demand estimation and urban transport demand modelling using stated preference techniques. European Transport 40, 33-50.

Cervero, R. (2003). City CarShare: First-year travel demand impacts. *Transportation Research Record: Journal of the Transportation Research Board*, (1839), 159-166.

Chen, T. D. and Kockelman, K. M. (2015). Carsharing's life-cycle impacts on energy use and greenhouse gas emissions'. Energy Policy.

Darren, B., Jill, H., and Nolan, J., (2008). Assessing producer stated preferences for identity preservation in the Canadian Grain Handling and Transportation System. Canadian Journal of Agricultural Economics 56, 243-256.

Duncan, M. (2011). The cost saving potential of carsharing in a US context. *Transportation*, *38*(2), 363-382.

Edwards, R., Mahieu, V., Griesemann, J. C., Larivé, J. F., and Rickeard, D. J. (2004). Well-to-wheels analysis of future automotive fuels and powertrains in the European context. SAE Technical Paper No. 2004-01-1924.

Firnkorn, J. and Müller, M. (2011). What will be the environmental effects of new free-floating car-sharing systems? The case of car2go in Ulm. *Ecological Economics*, *70*(8), 1519-1528.

Greencar. (2017). [online] Available at: https://www.greencar.kr/ [Accessed 12 Jan. 2017].

Hensher, D. A. (1994). Stated preference analysis of travel choices: the state of practice. Transportation 21(2), 107-133.

JRC (Joint Research Center). (2014). Well-to-Wheels Report Version 4.a: JEC Well-To-Wheels Analysis "Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context.". Joint Research Center (JRC) of European Commission.

Korea Environmental Industry and Technology Institute (KEITI) (2015). Carbon reduction label: Information report 2015. 204-205. (in Korean)

Katzev, R. (2003). Car sharing: A new approach to urban transportation problems. Analyses of Social Issues and Public Policy 3(1), 65-86.

Kim J.S, Park K.C, and Ko J. (2015). Social and economic effects of car-sharing services. *Issue & Diagnosis*, (183), 1-25.

Kim, S., Lee, K., and Choi, K. (2014). Preferences Factors Analysis for Car-sharing. Journal of The Korean Society of Civil Engineers, 34(4), 1241-1249.

Korea Energy Agency (KEA) (2016a). Vehicle energy efficiency labeling and standard and average fuel economy. Available at: http://www.energy.or.kr/renew_eng/energy/transport/vehicle.aspx [Accessed 1 November 2016].

Korea Energy Agency (KEA). (2016b). Vehicle Fuel Economy and CO2 Emission: Data and Analysis. Yongin: Korea Energy Agency. (In Korean)

Korea Energy Economics Institute (KEEI) (2012). Yearbook of Regional Energy Statistics 2011, Statistical Report , 1-319. (in Korean)

Korea Transport Institute (KOTI). (2012), Estimation of the Demand for Car-Sharing Service. KOTI Research Report, 1-149. (In Korean)

Lee, S. (2015). A review of car-sharing research: with a focus on domestic thesis and research papers. The Institute For Korean Regional Studies, 1-12. (in Korean)

Lee, J., and Cho, Y. (2009). Demand forecasting of diesel passenger car considering consumer preference and government regulation in South Korea. Transportation Research Part A: Policy and Practice, 43(4), 420-429.

Litman, T. (2000). Evaluating car-sharing benefits. Transportation Research Record, 1702, 11-20.

Martin, E.W. and Shaheen, S.A. (2011). Greenhouse gas emission impacts of carsharing in North America. IEEE Transactions on Intelligent Transportation Systems 12(4), 1074-1086.

McFadden, D. (1974). The measurement of urban travel demand. Journal of Public Economics, 3(4), 303-328.

McFadden, D., and Train, K. (2000). Mixed MNL models for discrete response. Journal of Applied Econometrics 15(5), 447-470.

Ministry of Environment (MOE). (2016). Electric vehicle charging station installation plan. Available at: http://www.me.go.kr/home/web/board/read.do?board MasterId=1&boardId=704440&menuId=286 [Accessed 28 June 2017].

MOLIT (2016). Statistical Yearbook of MOLIT. Gyeonggi: Ministry of Land, Infrastructure and transport. (in Korean)

Note, P. B. L. (2015). IMPACT OF CAR SHARING ON MOBILITY AND CO2 EMISSIONS.

OECD (2016). Greenhouse gas emissions by source, OECD Environment Statistics (database).

Park, H. S., (2015). Seoul Statistical Series: Population, Economy, Transportation, Housing. (The Seoul Institute Statistical Report). Seoul: The Seoul Institute. 1-124.. Retrieved November 22, 2016, from http://english.seoul.go.kr/get-to-know-us/statistics-of-seoul/.

Park, J. and Ko, J. (2014). Comparing Methods for Apportioning Transport CO2 Emissions to Sub-Regional Areas in Seoul. *The Seoul Institute*, 15(4), 65-78.

Seoul Solution, (2016). Seoul Solution Main Activity: Policy Sharing. Available at: https://seoulsolution.kr/content/shared-transport-car-sharing-seoul-nanum-car?language=en [Accessed 22 November 2016].

Shaheen, S., Cohen, A., and Chung, M. (2009). North American carsharing: 10-year retrospective. *Transportation Research Record: Journal of the Transportation Research Board*, (2110), 35-44.

Shaheen, S., and Cohen, A. (2016). Innovative mobility carsharing outlook: carsharing market overview, analysis and trends. *University of Berkeley, California*.

Socar. (2017). [online] Available at: https://www.socar.kr/ [Accessed 12 Jan. 2017].

Talluri, K. and Van Ryzin, G. (2004). Revenue management under a general discrete choice model of consumer behavior. *Management Science, 50*(1), 15-33.

The World Bank. (2014). World Development Indicators: Electricity production, sources, and access. Available at: from http://wdi.worldbank.org/table/3.7 [Accessed 27 November 2016].

Train, K. (1978). "A Validation Test of a Disaggregate Mode Choice Model". Transportation Research. 12: 167–174. doi:10.1016/0041-1647(78)90120-x.

Train, K. (1986). Qualitative Choice Analysis: Theory, Econometrics, and an Application to Automobile Demand (Vol. 10). MIT Press, Cambridge, Massachusetts.

Train, K.E. (2009). Discrete Choice Methods with Simulation. Cambridge University Press, Cambridge, Massachusetts.

Turconi, R., Boldrin, A., Astrup, T. (2013). Life cycle assessment (LCA) of electricity generation technologies: overview, comparability and limitations. Renewable and Sustainable Energy Reviews 28, 555-565.

Vermeulen, B., Goos, P., and Vandebroek, M. (2008). Models and optimal designs for conjoint choice experiments including a no-choice option. International Journal of Research in Marketing, 25(2), 94-103.

Appendix: Example of Choice Experiment Survey

■ For empirical study (Korean version)

카셰어링 서비스

1. 다음은 **카셰어링에 대한 선호도**를 묻는 질문입니다.
2. 응답하실 유형별 선호도 질문은
   1) **카셰어링 관련 설명문**과
   2) **카셰어링 유형별 선호도**를 묻는 질문 10개가 제시됩니다.
3. 귀하께서는 **1) 카셰어링 서비스 관련 설명문을 숙지하시고, 2) 카셰어링 유형별 선호도에 응답해 주시면 됩니다.**

카셰어링이란, 자동차를 빌려 쓰는 방법 중의 하나로, 차량을 예약하고 자신의 위치와 가까운 주차장에서 차를 빌린 후 반납하는 제도이며, 10분 단위로 대여가 가능하다는 점에서 렌터카 사업과 차이가 있음. (예 : 쏘카, 그린카, 나눔카, 씨티카)

다음의 속성 및 수준 설명문을 읽고 다음 장에서 제시되는 유형별 카셰어링의 선호에 대해 응답해 주십시오.

속성 (카셰어링)	유형
1. 연료종류 (일반 주유소 대비 보급률)	전기 (일반 주유소 대비 50% 수준)
2. 차량 종류	SUV
3. 차량 배송·픽업 서비스	제공 (차량 배달서비스가 제공됨)
4. 반납장소	같은 시·군내 다른 대여 장소에 반납가능 (제한범위 내 편도가능)
5. 사용금액	10,000원/1시간

예를 들어, 위와 같은 카풀 서비스는 아래와 같은 유형을 의미 합니다.

1) 대여할 차량이 **전기자동차로, 전기차 충전소가 현재 일반 주유소 대비 약 50% 수준**으로 보급되어 있는 상황이며,
2) 차종은 SUV입니다.
3) 차량 **배송 및 픽업 서비스가 제공**되어, 차량이 집 앞까지 배송되어 차량을 대여하기 위해 대여소까지 이동할 필요가 없으며,
4) 차량을 대여한 장소와 동일한 곳에 반납할 필요가 없어 **제한 범위 내에서 편도사용**이 가능하며,
5) 이러한 카셰어링 사용금액이 **1시간당 10,000원**입니다.

문 . 다음 제시한 **카셰어링 서비스** 유형 중, 귀하께서 **가장 선호하는 유형에** 응답해 주십시오.

카셰어링 서비스	유형 A	유형 B	유형 A,B 둘다 선호하지 않음
1. 연료 종류 (일반 주유소 대비 보급률)	휘발유·경유 (주유소 100%수준)	전기 (충전소 50% 수준)	
2. 차량 종류	준중형 이하	준중형 이하	
3. 차량 배송 · 픽업 서비스	제공 (차량이 집 앞으로 배송됨)	미제공 (차량대여를 위해 대여소까지 도보 15분 이동이 필요함)	
4. 편도운행 가능	가능 (차량을 다른 차고지에 반납 가능함)	불가능 (차량반납을 위해 빌린 곳으로 되돌아 가야함)	
5. 사용금액	5,000원/1시간	15,000원/1시간	
1위 선호 유형 (하나만 응답)			

카셰어링 서비스 이용계획

1. 다음은 카셰어링 서비스 도입 시 귀하의 **이용계획**에 대해 묻는 질문입니다. 2. 다음 제시한 카셰어링 서비스가 도입되었을 때 귀하의 **교통수단 이용행동에 변화를 고려하여 응답해 주시면 됩니다.**

문 . 다음 제시한 카셰어링 서비스가 도입되었을 때 귀하의 **교통수단 이용행동에 변화를 고려하여 응답**해 주시길 바랍니다.

	카셰어링 서비스
1. 연료 종류 (일반 주유소 대비 보급률)	전기 (충전소 50% 수준)
2. 차량 종류	중형 이상
3. 차량 배송 · 픽업 서비스	미제공 (차량대여를 위해 대여소까지 도보 15분 이동이 필요함)
4. 편도운행 가능	편도사용 불가 (차량반납을 위해 빌린 곳으로 되돌아 가야함)
5.사용금액	5,000원/1시간

문 . **(현재 차량을 소유하고 있는 응답자 대상 질문)**
다음의 **카셰어링 서비스가 도입**된다면, **현재 소유하고 있는 자동차는 어떻게** 하시겠습니까?

1. 현재 소유하고 있는 자동차는 팔거나 폐차하겠다
2. 현재 소유하고 있는 자동차도 계속 사용하겠다

문 . **(3년 이내에 구매계획 있음에 응답한 응답자 대상 질문)**
다음의 **카셰어링 서비스가 도입**된다면, **자동차 구매를 미룰 의향이 어느 정도** 있으십니까?

1. 1~2년 정도 미루겠다
2. 3~4년 정도 미루겠다
3. 5~6년 정도 미루겠다
4. 미룰 의향 없음

문 . 다음의 **카셰어링 서비스가 도입**된다면, 귀하께서는 **현재 사용 중인 교통수단 사용량 중 얼마나 카셰어링 서비스로 대체**하시겠습니까?

※ 현재 사용 중인 교통수단의 **일 평균 이동시간의 몇 퍼센트를 카셰어링으로 대체**하실지 묻는 질문입니다.

현재 **자가용 주행거리·시간**의 ☐☐☐ **%**를 카셰어링으로 대체 (현재 차량을 소유하고 있는 경우 제시)

현재 **대중교통 사용시간**의 ☐☐☐ **%**를 카셰어링으로 대체

문 . 다음의 **카셰어링 서비스가 도입**된다면, 귀하의 **이동거리가 얼마나 증가하거나 감소**할 것으로 생각하십니까?

※ 앞 질문은 카셰어링 서비스가 현재 교통수단을 얼마나 대체할지에 대한 질문이며,
이 질문은 **카셰어링 서비스로 평소보다 얼마나 많이 혹은 적게 이동할지에 대한 질문**입니다.

1. +25% (이동량 25% 증가)
2. +10% (이동량 10% 증가)
3. 0% (카셰어링 사용 이전과 이동량 동일)
4. -10% (이동량 10% 감소)
5. -25% (이동량 25% 감소)

Abstract (Korean)

정보통신 기술의 발달로 온라인 모바일 앱을 기반으로 한 공유활동 및 협력적 소비가 가능해졌으며, 교통부문에서는 카셰어링 서비스가 주목 받고 있다. 카셰어링이 등장하며 차량을 소유하지 않고도 편리하게 차량을 단시간 대여할 수 있게 되었다. 전 세계적으로 환경의 중요성이 증대되고 있는 가운데, 카셰어링의 활성화는 승용차 구매를 억제하며 온실가스 감축에 기여할 것으로 기대되며 지속가능 교통의 방안으로 논의되고 있다. 하지만, 카셰어링의 이용자는 대부분이 20-30대 층으로 차량을 보유하지 않는 사람들이 대부분이다. 이에 따라, 본 연구는 개인별 이용교통수단의 변화, 보유차량 처분, 차량구매 포기, 주행거리 증감 등 카셰어링으로 인한 개인의 교통이용 행동의 변화를 분석하고, 더 나아가 사람들의 교통이용행동의 변화에 따른 환경효과를 분석하여 카셰어링의 친환경적 운용방안에 대해 논의하는 것을 목표로 한다.

본 연구는 혼합로짓모형을 이용하여 카셰어링에 대한 이질적인 선호를 파악하고 선택확률을 도출하였다. 이를 기반으로 대중교통 혹은 자차 이용이 카셰어링 차량 주행으로 전환되는 비율을 고려하였고, 차량구매 포기 혹은 자차 처분 비율 또한 고려되었다. 카셰어링의 환경적 효과를 크게 세 가지로 보았다. 먼저 카셰어링 도입으로 인해 본인 차량을 적게 이용하고 일부를 카셰어링 이용으로 전환하게 되어 연비가 좋은 카셰어링 차량을 이용하는 효과를 살펴보았다. 두번째로는 대중교통 이용이 카셰어링 차량 주행으로 전환되는 비

율을 고려하였다. 마지막으로, 차량을 보유하고 있는 사람이 차량을 처분하고 더 이상 차량을 소유하지 않거나 차량구매를 계획하고 있던 사람이 카셰어링 도입으로 인해 차량 구매를 포기하여 생겨나는 환경적 효과를 차량의 생산단계에서 배출되는 CO2e 배출량이 감소되는 효과로 살펴보았다.

마지막으로 본 연구에서는 시나리오 분석을 통해 친환경적인 카셰어링 서비스 운용방안에 대해 논의하였다. 연료효율이 좋은 전기차 카셰어링의 이용이 증가하면 주행단계에서의 온실가스 배출량 감소로 긍정적인 환경효과를 기대할 수 있다. 하지만, 현재의 전기차 충전소 인프라 수준으로는 전기차 카셰어링의 선택확률이 낮아 현실장벽이 존재한다. 따라서, 지속가능한 교통시스템으로써 카셰어링을 고려하고자 하는 경우, 효율이 좋은 차량을 카셰어링 차량으로 배치하여 카셰어링으로 인한 환경효과를 관리할 수 있지만, 이는 전기차의 충전소 보급수준이 증가하여 많은 사람들이 전기차 카셰어링에 대한 선호가 증가하였을 때에나 가능한 시나리오 임을 본 연구에서 확인하였다.

주요어 : 공유경제; 카셰어링; 자동차 공동이용; 환경분석; 이산선택모형; 온실가스 감축
학 번 : 2015-21197