공학석사학위논문

Personal Carbon Trading and Equilibrium Permit Price for Road Transport

개인 탄소 배출권 거래제와 도로 교통의 배출권 가격

2016년 8월

서울대학교 대학원

건설환경공학부

이 현 경

Abstract

Personal Carbon Trading and Equilibrium Permit Price for Road Transport

Lee, Hyunkyung
Department of Civil and Environmental Engineering
The Graduate School
Seoul National University

The implementation of personal carbon trading (PCT) on transport mode choice has recently been considered in the literature in order to mitigate CO_2 emissions. This paper focuses on the importance of analyzing the consequences of application of the scheme, thus it examines the differences between the initial equilibrium state and the long-run equilibrium state. The initial equilibrium price is set after the policy employment, and then this price is put on the cost of using carbon-intensive mode. This additional price leads to demand less carbon-intensive modes. The decrease in the demand decreases the price of permits then an iteration of prices and the demand for carbon-intensive modes starts. The long-run equilibrium price is achieved after this iteration ends. The model is formulated for various modes with various origin and destination pairs (O-Ds) and the example problem is illustrated for 2 modes with 1 O-D. The equilibrium price setting is formulated by optimization tool to maximize utility. The changes in the demand for transport modes are demonstrated by the logistic distribution. By using an algorithm, the long-run equilibrium price is derived and the analysis of distributional effects is evaluated. In the long-run equilibrium state, 41% decrease from initial equilibrium price, 36% increase in automobile demand, and 4% increase in welfare are observed. Of those 4%, surplus for under-emitters, who are regarded as relatively lower income earners, increased by 5%, whereas surplus for over-emitters only increased by 3%. Thus the feature of progressivity still remains after the implementation of the policy. Since the significant changes are still observed after the application of the policy, long-run state should be considered in the PCT analysis in the future.

Keywords: Personal Carbon Trading, Transportation Demand Policy, Equilibrium Price Setting, Distributional Effect.

Student Number: 2014-22712

List of Contents

List of Tables

List of Figures

Chapter 1. Introduction

1.1. Introduction

The greenhouse gas emissions from human activities, of which carbon dioxide (CO_2) is a major element, have caused most of the observed increase in average temperatures since the middle of the 20th century (IPCC 2007a, IPCC 2007b, IPCC 2001, Manne and Richels 1991, Wadud 2008, Hoen et al. 2014). The mitigation of CO_2 emission level become now a global concern that many countries have put their effort to reduce the level at a lower cost.

Among various sources of carbon emission, this paper focuses on mobile emission sources, i.e. transportation. The transportation emission is a concern for both developing and developed countries. A study of the Organization for Economic Co-operation and Development (OECD 2002) predicted that, without an appropriate action, the carbon emissions resulting from transport would be doubled by 2020. However, yet the existing regulation for all types of transport is not sufficient to control the emission level. Moreover, this paper emphasizes the involvement of individuals' participation in conserving the environment which they are benefiting from. Since the burden of the emission production has mostly been carried by the industrial sectors and thus manufacturing firms have been paying for their consequences. However, the emission levels from household is not negligible. According to OECD statistics, the household emission rate accounts up to 40% (in Switzerland), and the average of 20% in whole Europe. Of those household emissions, up to 95% are taken by the transportation in Sweden, and the average was 56% in whole Europe. Additionally, putting too much pressure on industrial sector may not be beneficial for all since it may freeze the domestic economy. The individuals' efforts may help to relax these restrictions on industrial sector. Also, if the policy is looking over the near future, personal restriction may seem to be more applicable because, currently, in most developed countries, the number of manufacturing industries are in a declining trend whereas, the vehicle ownership is in an increasing trend (Dargay and Gately, 1999).

The number of tax schemes (e.g. fuel tax) are currently introduced that can be levied on the goods and services to restrict the demand of personal transport. However, this paper examines and evaluate a policy solution to reduce personal road transport emission level, personal carbon trading scheme (PCT). PCT is a general term used to describe a variety of cap-and-trade policies which locate rights and responsibilities for the carbon emissions from individual activities (Fawcett and Parag, 2011). Under the PCT, individuals are given out carbon allowances which restrict the amount of individuals producing emission. Individuals, who emit more than the given initial allowance, will have to buy the excess amount from the carbon permit market, but individuals, who emit less, can sell their remaining permit in the market. Because allowances can be traded, economic theory suggests enticingly that the system should result in carbon emission reductions at lowest cost across the population compared with approaches which rely more on regulation or government intervention (Defra 2006). However, this particular scheme has not yet been implemented in any countries, thus only the proposed schemes exist. The choice of the policy tool is governed by the interest in academic and government circles (especially in UK and France because the policy was first mentioned by a British politician, David Miliband) for personal carbon permits as an effective long term policy option to mitigate carbon emissions from households on a large scale (Fleming 1997, Hillman and Fawcett 2004).

The idea of personal carbon trading scheme is inherited from tradable permit scheme (TP), which allows trading of emission permit between countries and/or companies. TP have been applied to stationary emissions sources with the first scheme (the US Emissions Trading Program) beginning in the US during the mid 1970's with the aim of adding flexibility to stationary sources in meeting the air quality standards required by the Clean Air Act 1975 (Tietenberg 1985). More recently, phase I of the European Emissions Trading Scheme (EU ETS) was introduced across Europe in 2005, with phase 2 beginning in 2008, coinciding with the first Kyoto Protocol commitment period (Harwatt et al. 2011). The scheme was designed to promote reductions of greenhouse gas emissions in a cost-effective and economically efficient manner (DIRECTIVE 2003/87/EC). Under the TP, the price of carbon plays a key role to assess the impact of the policy. Although EU ETS is the largest emission trading market, it is now criticized for failing in estimating the carbon price. The carbon price in 2014 is only about 15USD, which was not enough to incentivize firms to produce with less carbon. On the other hand, Japanese carbon market has successfully estimated the number of initial allocation and predicted the price so that the price of carbon in Tokyo cap-and-trade market, is about 98USD (2014 price) which is high enough to restrict participants' behavior. Thus the initial allocation and the price setting can also be the key elements to consider in modeling PCT. This study focuses on setting the equilibrium price of carbon permit and changes in travelers' behavior after the implementation of the policy.

1.2. Research Objectives

The paper contributes to the study of the environmental policy issue to reduce carbon emissions from road transportation and regulate the demand for road transportation. Only a limited number of literatures have touched on the quantitative analysis of personal carbon trading and of those, study on transportation is even more restrictive.

This paper suggests a method of analyzing the policy by deriving the initial equilibrium price, capturing the changes in the behavior of transportation mode choice of consumers, and derivation of the long-run equilibrium price. Here, the initial equilibrium price is defined as the equilibrium price of carbon permit straight after the implementation of the policy. The long-run equilibrium price is defined as the equilibrium price of carbon when all the fluctuations settled down. These terms, initial and long-run equilibrium price, are used specifically in these particular definitions, which do not imply any other meanings. The studies on carbon permit equilibrium price setting only address the initial equilibrium state (Li et al., 2014, Fan et al., 2015a, Fan et al., 2015b). However, the implementation of the policy can incentivize consumers monetarily who consume more environmental friendly transport. This may lead to a change in consuming pattern for modes of transport and this change can make equilibrium prices to fluctuate. This fluctuation in the price affects the demand for transport and so on. After iteration of changes in the permit prices and the demands for automobile, the equilibrium price of carbon permit may converge to a single price.

The dissertation begins with reviewing the literature on personal tradable permit scheme in Chapter 2. The literature covers the scheme in general, its effects on wealth and equity. Followed by the literature review, the model formulation is introduced in Chapter 3. The example problem of 2 modes and 1 Origin and Destination pair is formulated and the choice behavior of individuals who participate in the trading carbon permits is described. The result for the example problem is listed in Chapter 4. The specific objectives of the research are:

1. To find utility maximizing equilibrium price of carbon permit.
2. To investigate the change in the individuals' road transportation choice and formulate the algorithm of searching the long-run equilibrium price of carbon.
3. To analyze distributional effect on people participating in this scheme between the initial equilibrium state and the long-run equilibrium state.
4. To observe further changes between the initial and the long-run state.

Chapter 2. Literature Review

2.1 Personal Carbon Trading scheme

The majority of literatures have dealt with qualitative analysis; whether the policy is socially acceptable, and whether the policy is feasible and fair. According to these features, different types of policy schemes are proposed. They are differentiated by their principles such as the cap distribution, participation, allocation, and management principles. There are several other schemes are suggested. For example, the first discussion was made by Fleming (1997) about household energy use, and followed by Barnes (2001) and so on. However, only the recent schemes are discussed in this paper; TEQ, DTQ, PCA, and DTPS. Their differences are summarized in Table 1 as follows

Table 1 Proposed personal carbon trading scheme

Scheme	Scope	Participation	Allocation rule	Reference
Personal Carbon Allowances (PCA)	Gas, electricity, coal, oil, road fuels, personal aviation, not public transport	Individuals only	Adults full equal allowance : children under 18, half allowance	Hillman and Fawcett(2004)
Decentralized Transferable Permit System (DTPS)	Fuels for personal transport	Individual only	Adults full equal allowance but families with children and people live in non-capital region receive more allowance	Raux and Merlot (2005)
Tradable Energy Quotas(TEQs)/ Domestic	gas, electricity, coal, oil, road fuels (**DTQ** : plus personal	Individuals and organizations	Only adults are equally and organizations are auctioned	Starkey and Anderson (2005) Fleming (2007)

Tradable Quotas (DTQs)	aviation)			
Tradable Carbon Permits	Private road transport	Individual only	adults equally and freely distributed	Watters and Tight (2007)
Household Carbon Trading	Household energy consumption	Households	Equal and free distribution to each households	Niemeier et al. (2008)

Most suggested PCT scheme distributes equal amounts freely to individuals so the scheme is generally perceived as fair and fiscally progressive. If allocated freely, permits are seen as property rights (Pezzey, 2003) that everyone has equal rights to the environment and thus the permits should be given to every individual whether they drive or not (Wadud, 2011). The scheme is also fiscally progressive because in general, 'the poor' emit less than an average, and 'the rich' emit more than the average. The rich will therefore need, on average, to buy allowances from the poor if they wish to sustain more carbon-intensive lifestyle (Roberts and Thumim, 2006). On the other hand, the fairness always can change between situations. Also, the problem is still remained about allocation to the children and the definition of the age that a person moves from a child to an adult (Keay-Bright et al., 2008).

These various suggested policies share the basic idea of downstream cap-and-trade permit scheme. In the sense of technical feasibility, carbon cards like bank credit cards with ID, and carbon accounts like bank accounts are issued to regulate the consumed amount of carbon allowances. The carbon cards are used whenever a person needs to buy fuel so it can automatically calculate amount a person has used. The carbon accounts can be used to trade but this system can be dangerous as it is exposed to the fraud and infringement of civil liberties.

The effects of PCT scheme are very often compared with existing policies such as fuel tax. However, most studies evidenced that the tradable permit scheme is more effective not only in the sense of carbon emission mitigation but also the public acceptability. Lyons and Chatterjee (2000) argued that the 'tax rebellion' that took place in several European countries in September 2000 shows how sensitive public opinion is to fuel taxation. From the survey taken by Harwatt (2008), the respondents were much more positive about the tradable permit scheme than carbon tax. Also, Raux et al. (2014) carried out a quantitative research using logit model for the effectiveness of tradable permit scheme. The study witnessed that PCT definitely can change travel behavior and people tend to reduce shorter trips.

The economic theory behind this pollution permit markets is based on the work of Coase (1960) on external costs that when the property rights are involved with relatively low transaction cost, parties naturally gravitate toward the most efficient and mutually beneficial outcome through trade. Then the work is followed by Crocker (1966) and Dales (1968) who developed the idea of using transferable permits to allocate the pollution control burden among firms or individuals. Later, Montgomery (1972) provided a structured proof that a tradable-permit system could, in theory, provide a cost-effective policy instrument for pollution control. This sound theory built up on the assumption of low transaction cost, however Coase theory often criticized that the real-world transaction costs are not rarely low enough to allow for efficient trading.

Regarding the possibility of high transaction costs, Raux and Marlot (2005) stated that an economic incentive instrument achieves its maximum efficiency when it operates at the most decentralized level possible. This represents the reason why Winkelman et al. (2000) argued that the personal tradable permit scheme should be adapted instead of upstream permits to fossil fuel producers and importers.

The application of tradable permits for the road transport sector has been suggested (Fleming 1997, Verhoef et. al. 1997, Fawcett 2004, Hillman and Fawcett 2004, Raux and Marlot 2005). There are few literatures which illustrate the impacts of carbon permit on road transport. Wadud 2007, Wadud et al. 2008, Wadud 2011, and Kim 2011 have estimated the fuel demand elasticity for vehicle-owning households of different income quintiles. They did not concentrate on the price of permit and the permit market, rather they focused on the distributional effects of individuals in different income quintiles. Also Abrell 2011 studied on the transport under emission trading which presented a small open economy model with formulations for a representative agent, production, and international trade and government. Abrell succeeded to include private transport, congestion, and freight transport but did not explain the utility function of household in detail. Therefore, this paper focuses on the utility of household which can be solved analytically.

2.2 Equilibrium price

In many literatures on downstream PCT analysis, the equilibrium price of the carbon permit is taken as given (Wadud 2007, Wadudet al. 2008, Hobbs et al. 2010, Wadud 2011, Kim 2011, Tirumalachetty and Kockelman 2011). However, in more recent papers, the equilibrium price of carbon is estimated by the theory of consumer choice behavior (Li et al., 2014, Fan et al. 2015a, Fan et al. 2015b), which proposes that a rational consumer always chooses consumption bundles within his budgeting process in order to maximize the utility (Becker, 1976).

Therefore, the objective function is maximization of utility and constraints are organized as budget constraints and definitional constraints. Li et al. (2014) and Fan et al. (2015a) used only two commodity bundle; energy and non-energy commodities. Whereas Fan et al. (2015b) categorized into 3 commodities; dirty energy, clean energy, non-energy goods. These models are formulated to restrict the household energy consumption in general, thus, transportation related constraints are ignored.

The equilibrium price is achieved when the supply and the demand of carbon permit meet. In the permit market, the supply is represented by under-emitters' traded volume, and the demand is designated by over-emitters' traded volume. Under-emitters are who emit less than their initial allowances, while over-emitters are who emit more than their given allowances.

2.3 Welfare analysis

The effect of personal carbon trading is mostly analyzed by the welfare effect. (Wadud 2007, Wadudet al. 2008, Wadud 2011, Kim 2011, Tirumalachetty and Kockelman 2011, Li et al., 2014). This is because public acceptability of a policy may critically hinge on its distributional consequences (Mayeres and Proost 2004, Santos and Rojey 2005).

The welfare analysis only takes account the direct effects of reduced demand for automobile or carbon emission. The number of studies on welfare analysis on PCT is summarized in Table 2.

Table 2 Literatures on welfare analysis of PCT

Authors	Scope of the model	Utility Model	Price of permit	Data used (country)	Welfare analysis

					model
Wadud (2007)	Transportation	Regression	Taken as a given. (Determined by the specified amount of reduction in gasoline or carbon consumption from the log-linear regression model)	consumer expenditure survey micro data for years 1997–2001 (US)	Consumer surplus + Compensating variation
Wadud et al. (2008)					Consumer surplus
Wadud (2011)					Consumer surplus + Compensating variation
Kim (2011)				annual data from 1991~2009 (Korea)	Equivalent variation
Tirumalachetty and Kockelman (2011)			Taken as given. (same rate as carbon tax)	consumer expenditure survey data in 2002 (US)	Consumer surplus
Li et al. (2014)	Energy use (electricity)	Cobb-Douglas	Calculated from the demand model	2011 data (China)	Consumer surplus

The welfare effect can be estimated through several methods. As shown in Table 2, Compensating Variation (CV), Consumer Surplus (CS), Equivalent Variation (EV) are used. CS is often used due to its simplicity of calculation. However, CS involves the income effects, which means that the changes in the prices change the purchasing power of the fixed income. Therefore, CS may not be appropriate to calculate the changes in utility only.

The income effects are separated in CV and EV by adjusting income to maintain the same level of utility before or after the policy. CV represents the increase (or decrease) in income such that the consumer is on the same pre-policy level of utility if the policy leads to an increase (or a decrease) in price. EV represents the changes in income that would result in the same post-policy level of utility.

The work of Wadud et al., 2008 evidenced only a little difference between CS and

CV. Thus in this paper, only CS is calculated to see the distributional effects. All of the literatures in Table 2 observed that the higher income households lose more in terms of welfare than relatively lower income households. Thus PCT appears to be progressive while carbon taxes appear to be regressive and moreover, taxes have very little impact on the behavior of higher income households (Tirumalachetty and Kockelman, 2011)

Chapter 3. Methodology

3.1 The scope of the model

Since the policy itself does not have a solid practical foundation yet, the policy in this model restricts individuals consuming road transportation energy. The emission produced by individuals are assumed to be collected precisely. The initial allowances are distributed equally only to adult population and all adult populations will actively interact in this permit market. The equal distribution is regarded as the most equitable method (Watters and tight 2007). All of the excess emission levels produced by over-emitters have to be traded by the specified period. Otherwise, over-emitters will be heavily fined. The carbon permits can be traded without any transaction costs, and all participants are regarded as price-takers and behave competitively to the price. Moreover, total trip number for each Origin and Destination (O-D) per person is fixed.

3.2 Model Formulation

The carbon permit market is organized by buyers and sellers of the permits. The buyers, in this case, are over-emitters and the sellers are under-emitters. These participants are assumed that they can take I number of transport modes to go to J number of O-D. For a given period, x trips can be consumed under their budget on transport, P_t. The consumption for transport can be determined by selling (under-emitters) or buying (over-emitters) of carbon permit which can be added on to the budget as an extra income (under-emitters) or taken away from the budget for transport (over-emitters).

Therefore, amount of sold permit and purchased permit needs to be identified. These traded volumes are formulated by the objective function of utility maximization with several linear constraints. The equilibrium price-setting optimization model is based on the theory of consumer choice behavior which states that the rational consumer always chooses consumption bundles within his budgeting process in order to maximize the utility (Mas-Colell et al., 1995). The optimization formulation for an under-emitter is as follows;

$$Max\ utility\ \mathrm{u}(x_{i,\mathrm{j}}) = \prod_{i}^{I} x_{i,j}^{u,\alpha_i} \qquad \text{for } \forall\, \mathrm{j} = 1, \dots, \mathrm{J},\ \sum \alpha_{\mathrm{i}} = 1$$

$$\mathrm{s.}t.\ \ \textstyle\sum_i^I x_{i,j}^u = q_j^u \qquad \text{for } \forall\, \mathrm{j}$$

$$\textstyle\sum_a^A d_j p_i x_{i,j}^u - d_j P_c \mathrm{m^u} \le P_t^u \qquad \text{for } \forall\, \mathrm{j}$$

$$\textstyle\sum_i^I e_i x_{i,j}^u \ + \mathrm{m^u} \le \mathrm{w^u} \qquad \text{for } \forall\, \mathrm{j},$$

The objective function is adopted from the Cobb-Douglas utility function (Rosenzweig and Schultz, 1983). The under-emitter's utility can be maximized by consuming an optimal bundle of transport modes, x_i, for various O-D pairs, $x_{i,j}$. The sum of exponent parameters of the utility function, α_i, equals to 1, assuming $x_{i,j}$ are in a weak order of preference (Diecidue and Wakker , 2002, Thm. 2). The first constraint represents the fixed number of trips for each under-emitter. The second constraint indicates a budget constraint. The total spending in automobile transport modes, $\sum_a^A d_j p_a x_{a,j}^u$, plus total spending in public transport, $\sum_b^B p_b x_{b,j}^u$, minus the profit gained from selling carbon permits, $d_j P_c \mathrm{m^u}$, should be less than or equal to the budget spent to the transportation, P_t^u. Total spending of auto is calculated by the price of automobiles per km, p_a, multiplied by the distance travelled, d_j, times the consumption of auto by an individual for an O-D, $\mathrm{x}_{a,j}^u$. The price of automobile increases by the distance travelled in each O-D pair so it is multiplied by d_j, whereas the cost of using public transportation is fixed by the fare for each trip. The last constraint defines the relationship between initial allocation of permits and produced emission. For an under-emitter, the summation of total emission produced by transport, $\sum_i^I e_i x_{i,j}^u$, and the sold amount of permits, $\mathrm{m^u}$, should be less than or equal to the initial allowances, $\mathrm{w^u}$. For the case of over-emitter, $-\mathrm{m^o}$ instead of $\mathrm{m^u}$ can be applied. The used notations are displayed in

Table 3.

Table 3 Notations

Decision variable	
x_i	Transport mode i consumed (trips/person/period)
P_c	Price of carbon permit (KRW/km/kg-co_2 eq)
m	Traded permit (kg-co_2 eq/km/period)
Parameters	
q	Total consumption (trips/person/period)
d	Distance travelled (km/trip)
P_t	Budget for transportation (KRW/km/trip)
P_i	Price of consuming mode i (KRW/km/trip)
e_i	Emission rate for transport mode i (kg-co_2 eq/km)
w	Initial allowance (kg-co_2 eq/person)
M	Number of over-emitters (persons)
N	Number of under-emitters (persons)
α	Share of auto in the total expenditure
β	Share of bus in the total expenditure
Index	
i	Transport mode
t	Time step
o	Over-emitter
u	Under-emitter
j	origin and destination

By solving the equations for all under-emitters and over-emitters for their traded volume, the supply, $\sum_u^N m^u$, and demand, $\sum_o^M m^o$, for permits can be derived. In a market with numerous suppliers and consumers, albeit the traded volume of carbon allowances are discrete numbers, the total supply and demand curves are continuous (Fan et al., 2015a). At the price when $\sum_u^N m^u = \sum_o^M m^o$, the initial equilibrium can be obtained.

The equilibrium price of permit is added on the price of consuming emission-producing transport modes which lead the demand for these modes to decrease.

This decrease in demand will lead demand and supply in the permit market to shift. The demand may shift inward whereas supply increases. Hence, the permit price may decrease and this will bring an increase in the demand for non-environmentally friendly mode consumption which will lead to an increase in price of permit again. This iteration process will occur and the price may converge into a single price and the demand for transportation may have changed further.

The changes after the initial equilibrium price can be analyzed by the changes in the prices, changes in the demand for transportation, and changes in welfare of people engaged in this market.

3.3 Example of 2 modes and 1 O-D

In the example of 2 modes (I = 2), and 1 O-D (J = 1), the choice of mode can be made among automobile and bus. The formulation for an under-emitter and an over-emitter are as follows;

Under-emitter	Over-emitter
$Max\,utility\ \mathrm{u}(x_{1,1}^{u}, x_{2,1}^{u}) = x_{1,1}^{u,\alpha_1} * x_{2,1}^{u,\alpha_2}$	$Max\,utility\ \mathrm{u}(x_{1,1}^{o}, x_{2,1}^{o}) = x_{1,1}^{o,\alpha_1} * x_{2,1}^{o,\alpha_2}$
$s.t.\ x_{1,1}^{u} + x_{2,1}^{u} = q_1^{u}$	$s.t.\ \ x_{1,1}^{o} + x_{2,1}^{o} = q_1^{o}$
$d_1P_1x_{1,1}^{u} + d_1P_2x_{2,1}^{u} - d_1P_c\mathrm{m^u} \le P_t^{u}$	$d_1P_1x_{1,1}^{o} + d_1P_2x_{2,1}^{o} + d_1P_c\mathrm{m^o} \le P_t^{o}$
$e_1x_{1,1}^{u} + e_2x_{2,1}^{u} + \mathrm{m^u} \le \mathrm{w^u}$	$e_1x_{1,1}^{o} + e_2x_{2,1}^{o} - \mathrm{m^o} \le \mathrm{w^o}$

From the above, $x_{1,1}^{u}$ denotes the auto consumption of an under-emitter for a given period, whereas $x_{2,1}^{u}$ indicates the number of bus trips of an under-emitter for a given period of time. These problems can be solved by the Karush-Kuhn-Tucker (KKT) optimality condition since the objective function is concave and the constraints are linear. Using the conditions to satisfy the constrained optimality problem, the traded volume for an under-emitter and an over-emitter are derived. For an example, such conditions are listed as below.

$$0 \le x_{1,1}^{u} \perp \alpha_1 x_{1,1}^{u,\alpha-1}\left(q_1^{u} - x_{1,1}^{u}\right)^{\alpha_2} - \alpha_2 x_{1,1}^{u,\alpha}\left(q_1^{u} - x_{1,1}^{u}\right)^{\alpha_2-1} - \lambda_1(\mathrm{d}_1P_1 - d_1P_2) - \lambda_2(e_1 - e_2) \ge 0 \quad (1)$$

$$0 \le q_1^{u} \perp \alpha_2 x_{1,1}^{\alpha_1}\left(q_1^{u} - x_{1,1}^{u}\right)^{\alpha_2-1} - \lambda_1 d_1P_2 - \lambda_2 e_2 \ge 0 \quad (2)$$

$$0 \le m^{u} \perp \lambda_1 d_1 P_c - \lambda_2 \ge 0 \quad (3)$$

$$0 \le \lambda_1 \perp d_1P_1x_{1,1}^{u} + d_1P_2\left(q_1^{u} - x_{1,1}^{u}\right) - d_1P_c m^{u} - P_t^{u} \ge 0 \quad (4)$$

$$0 \le \lambda_2 \perp e_1x_{1,1}^{u} - e_2\left(q_1^{u} - x_{1,1}^{u}\right) + m^{u} - \mathrm{w^u} \ge 0 \quad (5)$$

Where $\perp$ indicates orthogonality between two vectors. $\lambda_1$and λ_2 are defined as lagrangian multipliers. These values indicate the marginal change in the objective function and according to Hobbs et al. (2010), the shadow prices are positive. In this case, the above formulations simply express the complementary slackness condition in linear programming (Zhao et al. 2010, Chen et al. 2011, Li et al. 2014). By solving this linear algebra, traded permit volumes for under-emitters are achieved. Detailed explanation is described in the appendix.

$$m^u = \frac{-\alpha_2 P_t^u - x_{1,1}^u d_1 P_c e_1 + d_1 P_2 \left(q_1^u - x_{1,1}^u\right) + \alpha_1 d_1 P_c \mathrm{w}^{\mathrm{u}}}{d_1 P_c} \tag{6}$$

Following the definition of under- and over-emitter, the traded volumes of over-emitters are expressed as;

$$m^o = \frac{\alpha_2 P_t^o + x_{1,1}^o d_1 P_c e_1 - d_1 P_2 \left(q_1^o - x_{1,1}^o\right) - \alpha_1 d_1 P_c \mathrm{w}^{\mathrm{o}}}{d_1 P_c} \tag{7}$$

By adding all participating individuals in this market, the total supply and demand function of permits are as follows;

$$\mathrm{S} = \sum_o^M m^o = \frac{\alpha_2 \sum_o^M P_t^o + d_1 P_c e_1 \sum_o^M x_{1,1}^o - d_1 P_2 (\sum_o^M q_1^o - \sum_o^M x_{1,1}^o) - \alpha_1 d_1 P_c \sum_o^M w^o}{d_1 P_c} \tag{8}$$

$$D = \sum_u^N m^u = \frac{-\alpha_2 \sum_u^N P_t^u - d_1 P_c e_1 \sum_u^N x_{1,1}^u + d_1 P_2 (\sum_u^N q_1^u - \sum_u^N x_{1,1}^u) + \alpha_1 d_1 P_c \sum_u^N w^u}{d_1 P_c} \tag{9}$$

The market clearing position indicates the point where the supply of permits meets the demand for permits. In other words, the equilibrium price is obtained when $\sum_u^N m^u = \sum_o^M m^o$ The equilibrium price can be written as following;

$$P_c^{eq} = \frac{\alpha_2 (\sum_o^M P_t^o + \sum_u^N P_t^u) + d_1 P_2 [\sum_o^M x_{1,2}^o + \sum_u^N x_{1,2}^u - (\sum_u^N q_1^u + \sum_o^M q_1^o)]}{d_1 \{\alpha_1 (\sum_u^N w^u + \sum_{o=1}^M w^o) - e_1 \left(\sum_o^M x_{1,1}^o + \sum_u^N x_{2,1}^u\right)\}} \tag{10}$$

3.3.1 Iteration Process

The iteration process between demand for automobile and the price of permit is described in Figure 1. Until the differences between $\mathrm{P_c^t}$ and $\mathrm{P_c^{t+1}}$ are smaller than a specified value, ϵ, the iterations should be carried out. This study suggests that when the price may converge into a single price and the price is called a long-run equilibrium price.

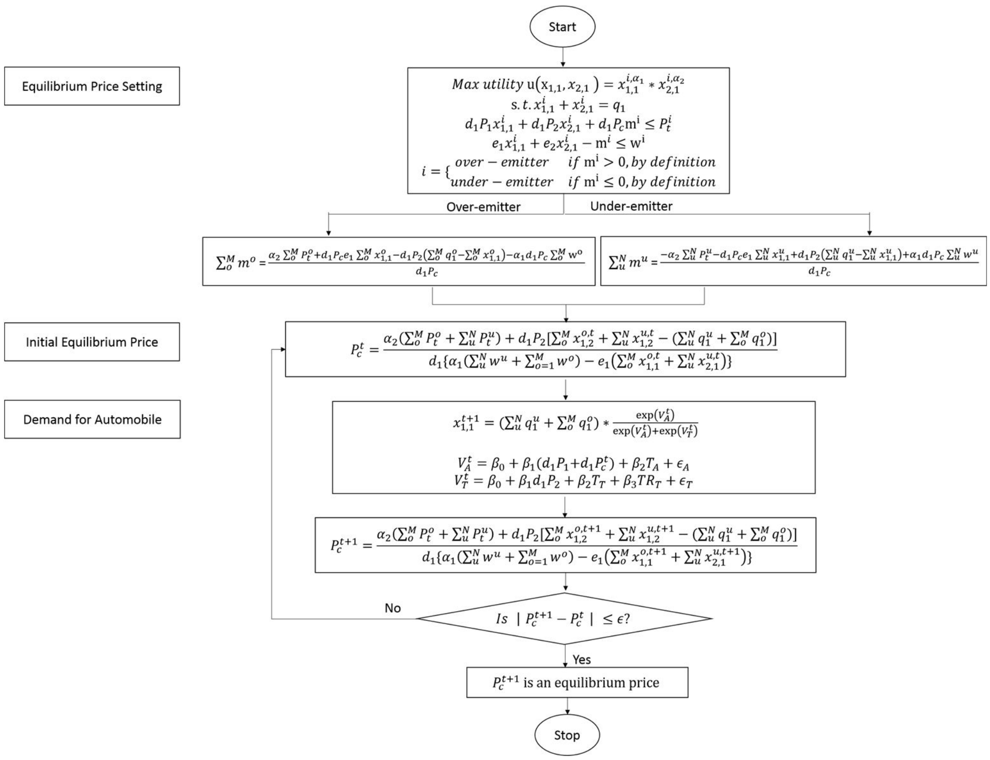

Figure 1 The iteration process of searching for a final equilibrium price of permit

The demand for automobile is adopted from mode split model which follows logistic distribution. This particular model assumes all disturbances, ε_A *and* ε_T, are independently distributed, identically distributed, and Gumbel-distributed (Ben-Akiva and Lerman, 1987). If the initial equilibrium price, P_c^1, is added on the price of consuming auto which renews the demand for auto into $\mathrm{x}_{1,1}^2$ which is calculated by the mode split model. This new demand is asserted into the equilibrium price equation to derive second equilibrium price, P_c^2, and so on until it reaches to a long-run equilibrium price, P_c^{eq}.

3.3.2 Welfare analysis

Once the initial equilibrium price and the long-run equilibrium price are determined, the changes in the consumer welfare are measured. As shown in Figure 2, the consumer surplus, upper triangle, represents over-emitters' welfare. The total supply is defined as traded volume of under-emitters, hence the producer surplus, lower triangle, indicates welfare of under-emitters. By comparing the welfare at P_c^1 and at P_c^{eq}, the changes in welfare is calculated.

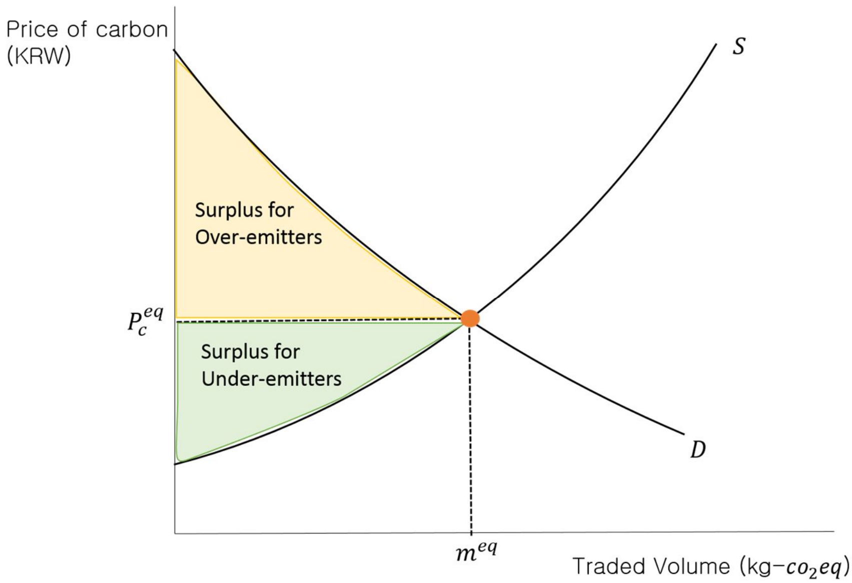

Figure 2 Illustration for surplus in the permit market

The total demand curve is represented by the prices and the traded permit volume of under-emitters at given prices. Therefore, for the demand curve, the price is a function of traded volume by under-emitter, $\sum_u^N m^u$. Whereas the total supply curve is represented by the prices and the traded permit volume of over-emitters,

$\sum_o^M m^o$, at given prices. By rearranging equation (8) and (9), $P_c(\sum_o^M m^o)$and $P_c(\sum_u^N m^u)$ are defined as below.

$$P_c(\sum_o^M m^o) = \frac{\alpha_2 \sum_o^M P_t^o - d_1 P_2(\sum_o^M q_1^o - \sum_o^M x_{1,1}^o}{d_1\{\sum_o^M (m^o) - e_1 \sum_o^M x_{1,1}^o + \alpha_1 \sum_o^M \mathrm{w}^o\}} \quad (10)$$

$$P_c(\sum_u^N m^u) = \frac{d_1 P_2(\sum_u^N q_1^u - \sum_u^N x_{1,1}^u) - \alpha_2 \sum_u^N P_t^u}{d_1\{\sum_u^N \left(\mathrm{m^u}(P_c^1)\right) + e_1 \sum_u^N x_{1,1}^u - \alpha_1 \sum_u^N w^u\}} \quad (11)$$

Therefore, the area under the supply curve is derived from the integral of (10),

$$\int^{m^o(P_c^{\mathrm{eq}})} P_c(x) \quad dx$$

$$= \ln(d_1 \left\{\sum_o^M \left(m^o\left(P_c^{eq}\right)\right) - e_1 \sum_o^M x_{1,1}^o + \alpha_1 \sum_o^M \mathrm{w^o}\right\}^{\left(\frac{\alpha_2 \sum_o^M P_t^o - d_1 P_2(\sum_o^M q_1^o - \sum_o^M x_{1,1}^o}{d_1}\right)}$$

Whereas the area under the demand curve is derived from the integral of (11),

$$\int^{m^u(P_c^{\mathrm{eq}})} P_c(x) \quad dx$$

$$= \ln(d_1\{\sum_u^N \left(\mathrm{m^u}\left(P_c^{eq}\right)\right) + e_1 \sum_u^N x_{1,1}^u - \alpha_1 \sum_u^N w^u\}^{\left(\frac{d_1 P_2(\sum_u^N q_1^u - \sum_u^N x_{1,1}^u) - \alpha_2 \sum_u^N P_t^u}{d_1}\right)})$$

From the equations above, the $m(P_c^1)$ indicates the traded volume at the price of P_c^1. The total welfare at price P_c^1 is calculated by subtracting $\int^{m(P_c^1)} P_c(\sum_u^N m^u) \; d\sum_u^N m^u$ from $\int^{m(P_c^1)} P_c(\sum_o^M m^o) \; d\sum_o^M m^o$. The consumer surplus, welfare of over-emitters, is calculated by deducting $\mathrm{m}_1 P_c^1$ from the integral of $P_c(\sum_o^M m^o)$. Then the producer surplus is derived from the difference between the total welfare and the consumer surplus. The welfare change is determined by the changes in welfare between P_c^1 and P_c^{eq}.

Chapter 4. Estimation and Result

4.1 Parameters used and data collection

In order to solve an example problem of I=2 and J=1, following parameters are estimated. The geographical scope of this parameter values is restricted to Republic of Korea. The individuals are assumed to travel one O-D pair, from Seoul city to GyeongGi-Do Provincial Office, which is 40km apart. This is close to the average travel distance in Korea which is 43km (Korea Transport Safety Authority, 2013). The cost of bus fare, P_2, is 116KRW per km per person (Korea Transport Institute, 2014a). All emission rate of vehicles, e_1, is supposed to 0.1415 kg-$\boldsymbol{co_2}\ \boldsymbol{eq}$/km which is the average emission rate in Korea (Korea Energy Agency, 2015). Initial allocation per person, w, is estimated as 150 kg-$\boldsymbol{co_2}\ \boldsymbol{eq}$/km. It is estimated accordingly to the plan for permit allocation by Korea Ministry of Environment who publishes the country's emission target. The personal transport is estimated to produce 15% of whole emission so they are distributed to all adult population except 10% as a reserve to the government. The coefficients of Cobb-Douglas utility function, α_1 and α_2 are estimated as 0.1 and 0.9 respectively (Li et al 2014). According to the statistics from Seoul metropolitan government, people who earn more than 5 million KRW use more automobiles than public transport. These people are defined as over-emitters who accounts for 22.7% of whole population (Seoul metropolitan government, 2015). Over-emitters use their personal vehicles for 27.9% and take buses for 21.4% of their whole travel. Whereas, people who earn less than 5 million KRW per month are defined as under-emitters who use automobiles for 13.5% and take buses for 29.4%. Therefore, the number of under-emitters, N, is 990,147 and the average trips per week is 12.72 for people living in Seoul (Korea Transport Institute, 2014b). Therfore, their total trips per month, q_1^u are 49,507,350. The sum of automobile used by under-emitters, $\sum_u^N x_{1,1}^u$, are assumed to be 19,802,940 and according to Statistics Korea, the sum of their budget for transport, $\sum_u^N P_t^u$, is estimated about 198 billion KRW. The number of over-emitters, M, are 290,768, thus their total number of trips per month, $\sum_o^M q_1^o$, are estimated to be 14,538,400. The sum of automobile used, $\sum_o^M x_{1,1}^o$, are 8,723,040 and the sum of the budget for transport of over-emitters, $\sum_o^M P_t^o$, are estimated as 112 billion KRW. The parameters for logit model is adopted from the work from Korea transport institute (Korea transport institute, 2013).

4.2 Results

After 19 iterations, the price is converged into a long-run equilibrium price, P_c^{eq}, with ϵ value of 0.1 KRW. The initial equilibrium price, P_c^1, is calculated to 188 KRW per km and the P_c^{eq}, is resulted in 118KRW per km. The example market is illustrated in Figure 3.

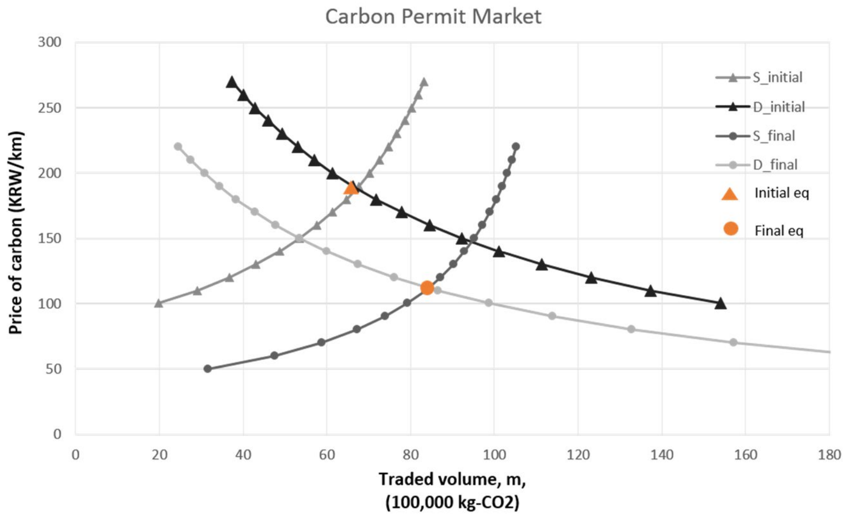

Figure 3 The Carbon permit market for the example problem

This 41% reduction in the carbon permit price lead to an increase in the demand for automobiles. The demand for auto with the initial equilibrium price, P_c^1, is 14,514,5560 but this has raised up to 19,725,910 which is 36% increase. Comparing before and after the implementation, the consumption of automobile in a society from Seoul city to Kyungki-do, decreased from 28,860,248 to 19,725,910 in total. The changes in total welfare between P_c^1 and P_c^{eq} has increased by 2.66%. Of those, over-emitters' welfare is increased by 2.05%, and under-emitters' welfare is increased by 3.71%. Therefore, all participants are gaining from a decrease in price and people who are in a relatively lower income group benefit more. This indicates that even after the implemenatation, further changes still preserve the feature of PCT which it is known as a progressive policy. However, this change in welfare is relatively smaller than other changes (i.e. price changes, and demand changes). This may be because of the assumption of the same elasticity of each individual. Albeit small changes in welfare, significant changes are observed between the initial equilibrium and the final equilibrium state.

In order to see the difference between people traveling different distance, a sensitivity analysis is carried out for varing travelled distance in Table 4.

Table 4 Sensitivity analysis of changes in distance travelled

Distance (km)	Initial price (KRW)	Longrun price (KRW)	Changes in price	Changes in automobiles	Changes in welfare		
					Total welfare	Over-emitters'	Under-emitters'
10	1569.1	1150.5	-26.7%	70.2%	1.7%	1.0%	2.2%
20	648.6	428.4	-33.9%	70.1%	2.2%	1.4%	2.8%
30	341.8	207.3	-39.4%	56.9%	2.6%	1.8%	3.4%
40	188.4	111.9	-40.6%	35.9%	2.7%	2.1%	3.7%
50	96.37	65.3	-32.3%	14.5%	1.9%	1.6%	4.6%

This suggests that as the travelled distance increases, the equilibrium price per km drops and the changes in total welfare increases until 40km. This indicates that as people travel further, they are paying smaller amount per km which may not affect drivers' behavior as much as people driving 10km. Therefore, those people traveling longer distance, less changes in automobile demand are observed. The changes in the total welfare is not significant but as the distance increases, the increase in welfare for under-emitters is greater than the increase in over-emitters.

Since the value of α_1 is estimated by the previous literature, the sensitivity analysis has been taken out. By the definition from Wing (2004), the exponent parameters α_i are the shares of each good in expenditure on consumption. From Seoul metropolitan government survey results, average share of expenditure on automobile is 0.4. Therefore, the sensitivity analysis is carried out by differing value of α_1 from 0.1 to 0.4.

Table 5 Sensitivity analysis of changes in parameter α_1

α_1	Initial price (KRW)	Longrun price (KRW)	Changes in price	Changes in automobiles	Changes in welfare		
					Total welfare	Over-emitters'	Under-emitters'
0.1	188.4	111.9	-40.6%	35.9%	2.7%	2.1%	3.7%
0.15	99.7	71.1	-28.8%	10.9%	1.7%	1.3%	2.6%
0.2	60.6	47.4	-21.8%	4.6%	1.2%	0.9%	2.0%
0.25	38.5	31.9	-17.1%	2.2%	90.0%	0.7%	1.8%
0.3	24.4	21.1	-13.5%	1.1%	0.7%	0.6%	3.3%
0.35	14.6	13.1	-10.2%	0.5%	0.5%	0.4%	0.1%
0.4	7.3	6.9	-5.7%	0.1%	0.3%	0.2%	0.2%

As the value of α_1 increases, the initial and the final prices are smaller, the changes in prices and automobile demand between the P_c^1 and P_c^{eq} are smaller. Also the changes in total welfare changes are declining but the welfare gains of under-emitters are always greater than those of over-emitters. This implies that as the share of expenditure on automobile increases, people are less likely to change their behavior after the implementation of the policy.

Chapter 5. Conclusion

5.1 Summary

This paper suggests a method of analyzing the effects of Personal Carbon Trading scheme if it is applied on road transportation. PCT is a policy to mitigate the carbon emission, which is technically feasible at an acceptable financial cost (Raux, 2004), and which guarantees the reduction in the emission rate unlike tax regulation because it sets a limitation of the amount an individual can emit. However, this policy idea is discussed relatively recently, thus the study to analyze the possible effects of PCT are very limited in their number. Most of the literature focuses on the distributional analysis of the policy and among those, only few considered the equilibrium price setting problem. The price estimation is seen as the most important indicator in PCT analysis since EU ETS is under the heavy criticism for the failure on predicting prices.

This study focuses on not only setting an initial equilibrium price but also the fact that consumers may change their consumption behavior after the implementation of the policy since it changes the price of goods. Therefore, in the example problem of two transport modes and one Origin and Destination, the initial price is found by solving the optimization problem, and the following changes in demand for automobile are observed. The final equilibrium price is achieved by checking if the changes in previous price and the current price is less than or equal to 0.1 KRW. Therefore, this final equilibrium price may provide more precise estimation of the permit price. By comparing the initial and the final equilibrium state, significant changes are detected. Therefore, the analysis for Personal Carbon Trading should include further changes after implementation to analyze its whole effects to the society. Moreover, the sensitivity analysis showed that as people travel further distance, they are paying smaller amount per km which may not affect drivers' behavior as much as people driving less distance. From another sensitivity analysis of differing α_1 indicates that as the share of expenditure on automobile increases, people are less likely to change their behavior after the implementation of the policy.

5.2 Discussion and Limitation

There are number of assumptions made in this paper. Firstly, there are assumptions relating to the policy regulation. All emission produced from the vehicles from every individual are reported accurately and the authority is able to track the emission level for everyone. This may become possible through technological improvement that Ecopoint program in Austria proved this become possible within a defined area. Also, this model only regulates individuals which it does not specify the purpose of the trips. This may cause an issue of inclusion of commercial vehicles. However, the commercial vehicles can be regarded as the assets of companies. Therefore, those cars can be regulated through restricting emission production of firms. All individuals are assumed to access the permit market to buy and sell freely and easily.

Secondly, there are assumptions on model formulation. The biggest and the fundamental assumption lies on Cobb-Douglas utility function itself. This utility function does not represent the mode choice model fully, because it does not include various components of time, and this model is deterministic rather than probabilistic (Train and McFadden 1978). However, this model used Cobb-Douglas utility to represent the preferences of individuals and the mode choice behavior is captured through logistic distribution in the example problem. The value of coefficients in the objective function, α_i, are assumed. This model does not consider production structure and capacity of each mode. Therefore, for the further research, supply side should be dealt. Furthermore, many modes with many O-D problems need to be solved. Also, this model fails to explain the congestion effect which should be computed in the future.

References

Abrell, J. (2011). *Transport under emission trading: A computable general equilibrium assessment.* VDM Puvlishing.

Barnes, P. (2001). *Who Owns the Sky? Our common Assets and the Future of Capitalsim.* Washington DC: Island Press.

Becker, G. (1976). *The economic approach to human behavior.* Univeristy of Chicago press.

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

Coase, R. (1960). *The problem of social cost. J.Law Economics. 3, 1-44.* Palgrave Macmillan UK.

Dargay, J., & Gately, D. (1999). Income's effect on car and vehicle ownership, worldwide: 1960-2015. *Transportation Research Part A: Policy and Practice*, 101-138.

Diecidue, E., & Wakker, P. P. (2002). Dutch books: avoiding strategic and dynamic complications, and a comonotonic extension. *Mathematical Social Sciecnes 43*, 135-149.

Fan, J., Wang, S., Wu, Y. L., & Zhao, D. (2015b). Buffer effect and price effect of a personal carbon trading scheme. *Energy, 82*, 601-610.

Fan, J., Wang, S., Wu, Y., Li, J., & Zhao, D. (2015a). Energy-use choices and allowance trading under the personal carbon trading scheme. *Natural Resource Modeling 28(1)*, 1-17.

Fawcett, T. (2004). Carbon rationing and personal energy use. *Energy and Environment 15(6)*, 1067-1084.

Fleming, D. (1997). Tradable quotas: using information technology to cap national carbon emissions. *European Environemnet 7*, 139-148.

Fleming, D. (2007). *Energy and the Common Purpose: Descending the Energy Staircase with Tradable Energy Quotas (TEQs).* London: The Lean Economy Connection.

Harwatt, H. (2008). *Reducing carbon emissions from personal road transport* *through the application of a Tradable Carbon Permit scheme: Emipircal findings and policy iplications fromn the UK.* Leeds: Institute for Transport Sutdies.

Harwatt, H., Tight, M., Bristow, A. L., & Guhnemann, A. (2011). *Personal Carbon Trading and fuel price increases in the transport sector: an exploratory study of public response in the UK.*

Hillman, M., & Fawcett, T. (2004). *How we can save the planet.* London: Penguin.

Hobbs, B., Bushnell, J., & Wolak, F. A. (2010). Upstream vs. downstrea CO2 trading: a comparison for the electricty contect. *Energy Policy 38(7)*, 3632-3643.

Hoen, K. M., Fransoo, J. C., & VanHoutum, G. J. (2014).). Effect of carbon emission regulations on transport mode selection under stochastic demand. *Flexible Services and Manufacturing Jounal 26. 1-2*, 170-195.

Institue, K. T. (2013). *National transport survey and DB construction project: nationwide o/d improvement studies.* Korea Transport Institute.

IPCC. (2001). *Special report on the regiional impacts of climate change: an assessment of vulnerability. Geeneva: Intergovernmental Panel on Climate Change.* IPCC.

IPCC. (2007a). *Climate change 2007: The physical science basis. Geneva: Intergovernmetal Panel on Climate change.* IPCC.

IPCC. (2007b). *Climate change 2007: Climate change impacts, adaptation, and vulnerability. Geneva: Intergovernmental Panel on climate change.* IPCC.

Keay-Bright, S., Fawcett, T., Howell, R., & Parag, Y. (2008, November). Personal Carbon Trading (PCT) Brining together the research community. In Workshop Report.

Kim, J. (2011). Implementation of Personal permit trading scheme on transportation sector and estimation of welfare analysis (masters' dissertation). Jung-ang University.

Korea Energy Agency. (2015). *Vehicle Fuel Economy and CO2 emission: data and Analyses.* Korea Energy Agnecy.

Korea Tranpsort Institute. (2014a). *National transport survey and DB construction project: nationwide o/d improvement studies.* Korea Transport Institute.

Korea Transport Institute. (2014b). *Transport mode survey.* Korea Transport Institute.

Korea Transport Safety Authority. (2013). *Analysis on 2012 automobile mileage status* . Korea Transport Safety Authority.

Li, J., Fan, J., Zhao, D., & Wang, S. (2014). Allowance price and distributional effects under a personal carbon trding scheme. *Journal of cleaner Production*.

Lloyd, P. J. (2001). The origins of the von Thunen-Mill-Pareto-Wicksell-Cobb-Douglas function. *History of political economy 33(1)*, 1-19.

Lyons, A., & Chatterjee, K. (2000). *Transport Lessons from the Fuel Tax Protests of 2000.* Aldershot: Ashgate.

Manne, A. S., & Richels, R. G. (1991). Global CO2 Emission Reductions - the Impacts of Rising Energy Costs. *The Energy Journal12, no. 1*, 87-107.

Mas-Colell, A., Whinston, M. D., & Green, J. R. (1995). *Microeconomics.* New York: Oxford University Press.

Mayeres, I., & Proost, S. (2002). *Reforming transport pricing: An economist's perspective on equity, efficiency and acceptability.* Center for Economic studies-KU Leuven.

Niemeier, D., Gould, G., Karner, A., Hixson, M., Bachmann, B., Okma, C., & Del Valle, D. H. (2008). Rethinking downstream regulation: California's opportunity to engage households in reducing greenhouse gases. *Energy Policy 36(9)*, 3436-3447.

OECD/IPA. (2015). *Energy and Climate Change: world energy outlook special report.* IPA.

Pezzey, J. C. (2003). Emission taxes and tradable permits: a comparison of views on long run efficiency. *Environmental and Rewource Economics 26*, 329-342.

Prarag, Y., & Fawcett, T. (2014). Personal carbon trading: a review of research evidence and real-world experience of a radical idea. *Energy and emission control Techonolgies 2*, 23-32.

Raux, C. (2004). The use of transferable permits in transport policy. *Transportation Research Part D: Transport and Environemnt 0.3*, 185-197.

Raux, C., & Marlot, G. (2005). A system of tradable CO2 permits applied to fuel consumption by motorists. *Transport policy, 12(3)*, 255-265.

Raux, C., Croissan, Y., & Pons, D. (2015). Would personal carbon trading reduce travel emissions more effectively than a carbon tax? *Transportation Research Part D: Trasport and Environement, 35*, 72-83.

Roberts, S., & Thumim, J. (2006). *A rough guide to individual carbon trading- the ideas, the issues and the next steps.* Defra.

Seoul Metropolitan Government. (2014). *Seoul sruvey result report.* Seoul Metropolitan Government.

Starkey, R., & Anderson, K. (2005). *Domestic Tradable Quotas: A policy instrument for reducing greenhouse gas emissions from energy use.* Canbrudge: Tyndall Center for Climate change Research.

Tietenber.T.H. (1985). *Emissions trading, an exercise in reforming pollution policy. Resources for the Future.*

Tirumalachetty, S., & Kockelman, K. M. (2010). The welfare implications of carbon taxes and carbon caps: a look at US households. *Proceeding of the 89th annual meeting of the Transportation Research Board.* Washington DC.

Train, k., & McFadden, D. (1975). The goods/leisure tradeoff and disaggregate work trip mode choice models. *Transportation research 12.5*, 349-353.

Verhoef, E., Nijkamp, P., & Rietveld, P. (1997). Tradeable permits: their potential in the regulation of raod transport externalities. *Environment and Planning B: Planning and design 24*, 527-548.

Wadud, Z. (2007). Personal tradable carbon permits for road transport: Heterogeneity of demand responses and distributional analysis (Doctoral dissertation). Imperial College London.

Wadud, Z. (2011). Perosnal tradable carbon permits for road transport: Why, why not and who wins? *Trnaposrtation Research Part A: Policy and Practice, 45(10)*, 1052-1065.

Wadud, Z., Noland, R. B., & Graham, D. J. (2008). Equity analysis of personal tradable carbon permits for the road transport sector. *Environmental Science and Policy 11(6)*, 533-544.

Wing, I. S. (2004). Computable general equilibrium models and their use in economy-wide policy analysis. *Techinical Note, Joint Program on the Science and Policy of Global Change*. MIT.

Winkelman, S., Hargrave, T., & Vanderland, C. (2000). *Transportation and domestic greenhouse gas emission trading.* Washington DC: Center for Clean Air Policy.

Zhang, Y. J., & Wei, Y. M. (2010). An overview of current research on EU ETS: Evidence from its operating mechanism and economic effect. *Applied Energy, 87(6)*, 1804-1814.

Appendix

$$\alpha x_{a,u,r}^{\alpha-1}\left(q_{u,r}-x_{a,u,r}\right)^{\beta}-\beta x_{a,u}^{\alpha}\left(q_{u,r}-x_{a,u,r}\right)^{\beta-1}-\lambda_1(P_x-P_y)-\lambda_2(e_a-e_b)=0 \qquad (A.1)$$

$$\beta x_{a,u,r}^{\alpha}\left(q_{u,r}-x_{a,u,r}\right)^{\beta-1}-\lambda_1 P_y-\lambda_2 e_b=0 \qquad (A.2)$$

$$\lambda_1 P_c-\lambda_2=0 \qquad (A.3)$$

$$P_x x_{a,u,r}+P_b\left(q_{u,r}-x_{a,u,r}\right)-P_c m_u-P_{t,u}=0 \qquad (A.4)$$

$$e_a x_{a,u,r}-e_b\left(q_{u,r}-x_{a,u,r}\right)+m-w_u=0 \qquad (A.5)$$

Substituting equations (A.3) into equation (A.1) and into (A.2), the equations becomes as followings, respectively.

$$\frac{\alpha x_{a,u,r}^{\alpha-1}\left(q_{u,r}-x_{a,u,r}\right)^{\beta}-\beta x^{\alpha}\left(q_{u,r}-x_{a,u,r}\right)^{\beta-1}}{\lambda_1}-\mathrm{P_a}+\mathrm{P_b}-\mathrm{P_c e_a}+\mathrm{P_c e_b}=0 \qquad (A.6)$$

$$\lambda_1=\frac{\beta x_{a,u,r}^{\alpha}\left(q_{u,r}-x_{a,u,r}\right)^{\beta-1}}{P_b+P_c e_b} \qquad (A.7)$$

By substituting (A.7) into (A.6), the following equation is obtained;

$$\frac{\alpha P_b(q_{u,r}-x_{a,u,r})}{\beta x_{a,u,r}}+\frac{\alpha P_c e_b(q_{u,r}-x_{a,u,r})}{\beta x_{a,u,r}}-\mathrm{P_a}-P_c e_a=0 \qquad (A.8)$$

From equation (A.4), equation for $\mathrm{e_b}\left(q_{u,r}-x_{a,u,r}\right)$ is achieved;

$$\mathrm{e_b}\left(q_{u,r}-x_{a,u,r}\right)=w_u-m_u-e_a x_{a,u,r} \qquad (A.9)$$

From equation (A.5), equation for $\mathrm{x_a}P_a$ can be derived;

$$\mathrm{x_a}P_a=P_{t,u}+P_c m_u-P_b(q_{u,r}-x_{a,u,r}) \qquad (A.10)$$

By substituting equation (A.8), (A.9), (A.10) into equation (A.6), the traded volume of under emitters are achieved as equation (A.11).

$$m_{u,r}=\frac{-\beta P_{t,u}-P_c e_a x_{a,u,r}+P_b\left(q_{u,r}-x_{a,u,r}\right)+\alpha P_c w_u}{P_c} \qquad (A.11)$$

요약(국문 초록)

개인 탄소 배출권 거래제와 도로 교통의 배출권 가격

최근 CO_2 경감을 위하여 개인탄소 배출권 거래제도를 교통수단에 시행하는 것에 대한 연구가 많이 이루어 지고 있다. 본 연구는 제도가 시행된 이후의 변화에 대하여 주목하고 초기 균형 상태와 장기 균형 상태의 차이를 분석한다. 초기 균형 상태의 가격은 정책 시행 바로 직후에 정해지며 이 가격은 탄소를 더 많이 배출하는 수단을 이용할 때 추가적으로 지불하게 된다. 추가적으로 지불하게 된 수단은 수요가 감소하게 되고 이에 따라 배출권 가격은 하락하게 된다. 따라서 수요의 변화와 가격의 변화의 반복을 거쳐 배출권의 가격은 한 점으로 수렴하게 되는데 이 가격을 장기 균형 상태의 가격으로 정의한다. 이 연구에서 사용한 모델은 다양한 수단으로 다양한 기종점을 통행하는 모형을 표현하였고 예시 문제로 2개의 수단(자동차와 버스)와 1개의 기종점(서울시청부터 경기도청)을 통행하는 모형을 제시하였다. 균형 가격 설정은 최적화 기법을 사용하여 통행자의 효용을 최대화 시키는 가격으로 설정하였고, 교통 수단의 수요 변화는 로지스틱스 분포를 사용하여 분석하였다. 장기 균형 상태의 가격은 알고리즘을 이용하여 가격의 변동의 폭이 어떠한 엡실론 값보다 작을 때 수렴한다고 정의하였다. 단기 균형 상태의 사회적 후생과 장기 균형 상태의 사회적 후생의 변화를 분석하여 제도가 시행된 이후의 변화에 대하여 분석하였다.

장기 균형 상태의 가격은 단기 균형의 가격보다 41%가 감소한 값으로 측정되었으며 이에 따라 자동차의 수요는 36%가 증가하는 것으로 나타났다. 사회적 후생변화는 장기 균형상태 일 때 4%가 증가한 것으로 나타났다. 사회적 후생변화는 탄소 미만 배출자와 초과 배출자로 나누어 분석하였고, 미만 배출자들의 후생변화는 5%가 증가, 초과 배출자들은

3% 증가로 나타났다. 따라서, 정책 시행 이후에 일어나는 변화는 고려하기에 충분히 크게 나타났음으로 향후 분석에서는 정책 시행 이후의 변화도 고려하는 것이 바람직할 것으로 보인다.

주요어 : 개인 탄소 배출권 거래제도, 교통 수요, 균형 가격 측정, 후생분석

학번 : 2014-22712