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Can Personal Fuel Permit Trading Be Effective?-An Investigation into Permit Demand

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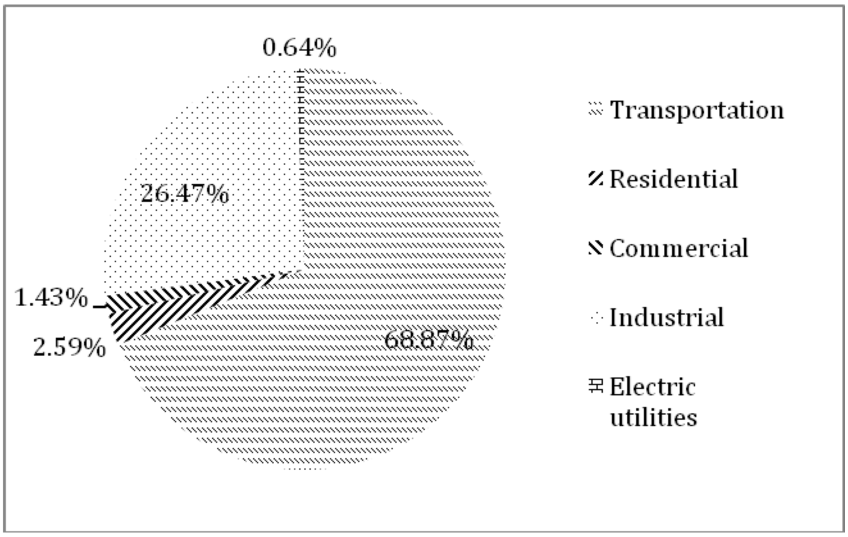
Abstract: This study proposes a personal fuel permit trading scheme to limit the total consumption of motor fuels (including diesel and gasoline), thus reducing its environmental impact. We studied the effectiveness of this scheme by analyzing the permit demand of a benchmark gasoline-driven vehicle in transportation sector. A general utility optimization model is formulated and a Cobb-Douglas utility function is further assumed to analyze the response of permit demand to its price changes with the Slutsky decomposition of price effects. The results, when defined in economic terms, indicate that the permit demand of consumers in higher income groups are negatively related to permit price; permit demand are also negatively related to permit price for consumers in medium income groups, but with positive income effect; and the direct relationship between permit demand of lower income groups and the price is defined as a Giffen-good effect. That is, for those low income groups, when the permit price rises their demand for permits would also increase. Then a US household expenditure data is used to show illustrative results if a pilot of personal fuel permit trading scheme. Further, some regulations on critical parameters, such as permit allocation and permit prices in the policy design are proposed to make the scheme feasible in different income groups. Based on these results, implications, limitation and suggestions for future study are discussed.

Keywords: Personal fuel permit trading; Permit demand; Price effect; Private transportation sector

1. Introduction

In the last decade, petroleum consumption in the world has risen by 8% from the year of 2005 to 2013 (EIA, 2015). The USA has contributed to 33.5% in the world petroleum consumption in 2013 (EIA, 2015). Among several other sectors, transportation sector ranks the first, consuming almost 70% of petroleum in 2013 (see figure 1) and the increasing ownership of vehicles is the main driving force (EIA, 2015). While vehicles provide convenience, comfortability and personal identity, they would also bring about unwanted side effects such as exhausting non-renewable energy source, air pollution, congestion, and other negative externalities (Verhoef, 1994; Santos et al., 2010).



To alleviate these negative effects, and particularly to mitigate climate change, several regulatory policies and technological upgrading have been proposed to manage these non-point sources. For instance, in the United States, the Corporate Average Fuel Economy (CAFE) standard is a policy instrument that aims at decreasing greenhouse gas (GHG) emissions and foreign dependence on oil, but it is uncertain that whether fuel savings would exceed the cost of fuel economy standards (Dreyer et al., 2015). In China, purchase restrictions and traffic restrictions based on even- and odd-numbers of license plates have been launched in some pilot cities. However, in the long run, as proved in the Mexican case by Davis (2008), such policies may cause a sharp increase in the demand of old, cheap and high-polluting second-hand cars (Mahendra, 2008). Debates are still going over the adoption of hybrid electric vehicles (HEV) and electric vehicles (EV) , which are emerging as alternatives to the traditional internal combusted engine vehicles (Faria et al., 2013). The limitation of charging infrastructure, long recharging time and high maintenance costs make it difficult to popularize them (Hannan et al., 2014; Efroymson et al., 2013).

Researchers have gradually shifted their focus of reducing transport emissions to market-based regulatory policies. Personal carbon trading (PCT) is an extension of emission trading schemes in upstream industrial sectors to individuals. It is a “cap and trade” scheme aims to deliver carbon emissions reduction with minimal costs (Fleming, 1997; Hillman et al., 2008). Specifically, personal carbon allowance mainly focuses on household and individual emitters (Roberts and Thumin, 2006; Harwatt et al., 2011). Further, more specific frameworks are proposed to curb emissions and manage mobility in transportation sector. Yang and Wang (2011) proposed tradable travel credits for mobility management and carbon abatement and investigated the resulting state of transportation system. Aziz et al. (2015) came up with the notion of personal mobility credit allowance scheme for personal travel and investigated its effectiveness using an experimental game.

The above schemes are of great advantages in abatement certainty by capping the emission cap and revenue neutrality by redistributing wealth between under-emitters and over-emitters (Aziz et al., 2015; Li et al., 2015). They are more effective in stimulating consumers’ behavior than fuel tax system where a certain price is levied (Bristow et al. 2010). However, the permit price is determined by the demand and supply in the permit market, which is of uncertainty (Starkey, 2012). This uncertainty can be a source of positive feelings and arousal, which stimulates people to invest more time, effort and money in considering energy-saving behavior (Shen et al., 2014). Moreover, permits may be viewed as a form of complementary currencies (CCs) which are used alongside conventional currency to solve environmental problems (Seyfang et al., 2007).

As shown in a personal carbon trading (PCT) scheme, transport fuels have low emission alternatives and relatively high demand elasticity among the various energy carriers (Ramanathan, 1999) and should be regulated at first. In most developed countries, the demand for transport fuels can be reduced through switching to public transportation where is available and easily accessible. For residents in cases that there is no sufficient public transportation, the fuel consumption still could be reduced through reduction of travels. For instance, residents could choose to join in the "car-sharing" activity (Efthymiou et al., 2013) or adopt electric vehicles (Tamor et al., 2013). Moreover, there are large amount of low carbon alternatives to gasoline and diesel, such as bioethanol and biodiesel, which have been used in many parts of the world. Therefore, it is feasible and essential to build a specific "cap and trade" system to regulate the abundant use of transport fuels.

This paper proposes a new notion of personal fuel permit trading (PFPT) scheme as a means of implementing PCT. It will cap the total carbon emissions from transport fuels and thus the total demand of liquid fossil fuels. The permit price in this scheme would serve to offset the costs of externalities of fossil fuels. Such a trading scheme would minimize the cost of compliance (Braun et al., 2015). We aim to explore whether such a PFPT scheme may generate effective behavioral changes among consumers and gain insight into policy design. This idea has not been proposed elsewhere.

The remainder of this paper is organized as follows. The next session introduces the concept of personal fuel permit trading scheme. Section 3 constructs a general utility optimization model and analyses the price effects of PFPT. Section 4 assumes specific Cobb-Douglas utility function, and on this basis investigates consumers' demand for fuel permits in different income groups. Section 5 studies several critical parameters in this policy design, such as consumers' income, initial permit allocation, and permit price and fuel economy based on the US household expenditure survey. Section 6 concludes the paper and discusses the implications and limitations.

2. Personal fuel permit trading scheme

2.1 The feasibility of PFPT scheme

PFPT scheme is proposed as a branch of PCT, which specifically regulates carbon emissions generated by fuel consumption. Several studies have demonstrated the feasibility of PCT scheme (Starkey, 2012; Fan et al., 2015). The PFPT scheme is technically and institutionally feasible. First, the driver registration records are available in the transportation sector and thus could be used as the base for allocating the credits. Second, the refueling cards registered to specific vehicles are available, which can also be used to record information of gasoline permits. With the rapid development of mobile Internet, permits could be traded through mobile phone based platforms. Thus, the costs of constructing and maintaining such a scheme are not likely to be high.

The enforcement of such a scheme requires an initial government guidance, which could be established gradually. The fuel credits would be issued and withdrawn under the regulation of the authority in the set-up of PFPT scheme. And the credit price should also be regulated within a reasonable range. For instance, the “ceiling” and “floor” price mechanisms (Fankhauser & Hepburn, 2010) in European Emissions Trading Scheme could be adopted in the PFPT scheme design. In a centrally planned economy such as China, it is easier to enforce such a policy from top to bottom. While in a free and open market such as the US, the pilot cities or demonstration zones should be established to initialize the PFPT scheme until it could be accepted in the broader areas. This feasibility of this scheme in a market economy could be demonstrated by the emission trading systems in developed countries.

2.2 Define of the scope of regulated fuels

Among the petroleum products in the transportation sector, it is better to focus on gasoline and diesel initially. These two products have contributed approximately 80% of the total consumption in the transportation sector (see Figure 2). The third major, jet fuel, has different characteristics than diesel and gasoline, which makes it hard to cause leakage of regulating transport fuels if it is not regulated. However, the scheme is capable of incorporating the jet fuels because there are only a few, but large consumers.

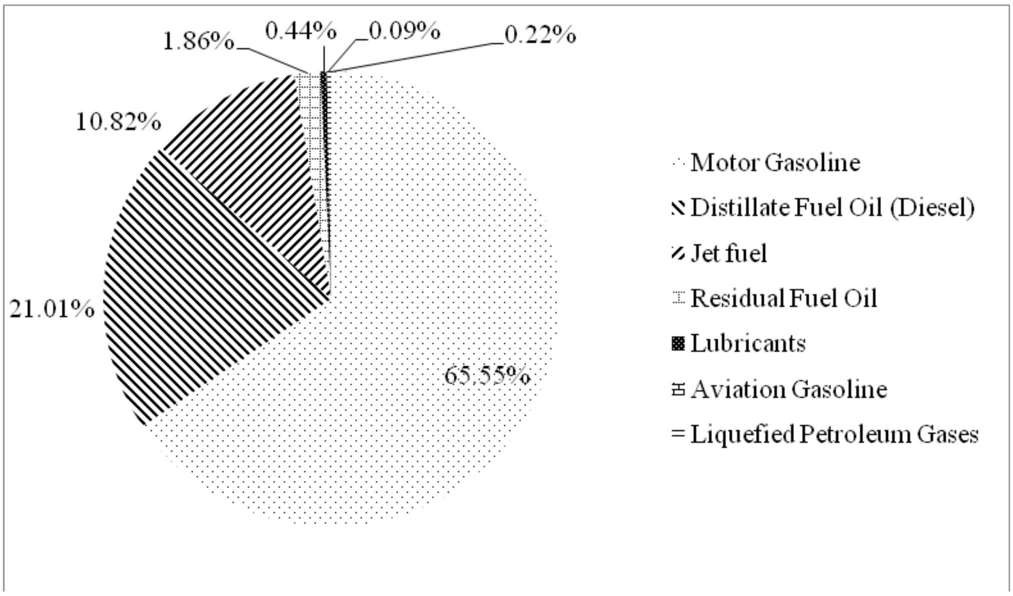


Figure 2 US transportation sector petroleum consumption in 2013 (Source: EIA 2015)

2.3 Define the unit of permits

The unit of permits should be defined as 1 litter of gasoline equivalent (LOGE) in terms of carbon emissions. According to EIA (2015), the ratio of emission intensity between gasoline and diesel is about 0.88 (19.64 pounds/gallon vs. 22.38 pounds) [1] and thus 1 litter of diesel is equivalent to 1.16 LOGE. Biofuels are considered as zero-emission sources and thus transport fuels containing biofuels could have lower LOGE. Each petrol station should publish LOGEs of each type of fuels, which subjects to regulatory approval.

2.4 Define the scope of regulated vehicles

According to EIA (2015), vehicles are classified into several categories:

- Passenger vehicles, including Private cars, heavy trucks, and public transportation (not include metro and train). The public transportation could be subsidized later, but not directly link to petrol consumption to avoid leakage;

[1] http://www.eia.gov/tools/faqs/faq.cfm?id=307&t=11

- Motorcycles, if included, should be allocated the amount of permit allowance in a proportion to its fuel consumption compared with the benchmark car.
- Electric vehicles: These zero-emission vehicles are included so as to provide additional incentive for their adoption among consumers.

The government may also set minimal fuel standards for the regulated vehicles that are eligible for receiving initial free permits. Those vehicles that fall below such standard will not be qualified for receiving initial free permits.

2.5 Determine the annual total amount of fuel permits to be issued

To avoid mass objections and resistances when implementing the PFPG scheme, certain pilots or demonstration zones should be established first. The amount of targeted fuel consumption that may be different in each year, which is then translated into the total number of LOGE permits. The percentage of LOGE permits that will be freely distributed should also be determined according to the reduction target and the projection growth of vehicle ownership. A public consultation for determining the amount of total and free distributed permits would be recommended to increase public acceptance.

Not all the amount of permits has to be freely allocated. Governments could remain certain amount for trading when the prices are deemed too high or new vehicles are purchased. In contrast, the permit prices are too low, the government can buy back to avoid crash of the permit market.

2.6 Allocate permits to individual car owners

Similar to the PCT scheme, it is a critical issue to determine the amount of the initial permit allocation for each vehicle driver in the PFPT scheme. In the PCT scheme, most scholars argued for the egalitarian principle of equity, which is consistent with the international proposal “contraction and convergence” (Meyer, 2000; Fawcett, 2004; Wadud, 2011). Following this principle, we assume an equal per capital permit allocation as our starting point.

Each regulated vehicles should have a permit account and the free permits will be deposited into the account. The account should be transferred to the new owners when a vehicle is sold. A new vehicle is eligible to claim amount of free permits in pro rata. The EVs should also be allocated standard amount of allowance, the sales of which could provide additional economic incentives for electric vehicles.

2.7 Operation rule of PFPT scheme

When the regulated vehicle drivers purchase gasoline from petrol stations, they should surrender corresponding permits (LOGEs). The number of LOGEs would then be deducted from the drivers' account held on a permit debit card electronically. Petrol stations should also surrender corresponding permits for their fuel sales to the regulating authority. Drivers could store permits or sell the extra permits to the market voluntarily. Drivers who consume more than their allocated credits (called an "over-consumer") have to buy credits from the consumers who consume less (called an "under-consumer"). Such transactions can be done through various Internet platforms.

3. Model development

In this section, we take a standard gasoline-driven vehicle owner as an example and formulate the utility optimization model that subjects to income constraint and available permit constraint. Then according to the Slutsky-Hicks theory of value(Allen and Hicks, 1934), the effect of permit price change on demand could be divided into two parts-that due to change in real income (income effect) and that due to change in relative prices with real income constant (the substitution effect). On this basis, permit demand will be analyzed.

3.1 Model formulation

The consumer with private vehicles would make decisions upon vehicle miles traveled meanwhile being mind of their gasoline consumption due to the gasoline permit cap (Glover, 2011). This decision-making process can be framed as a budgeting process which may encourage self-control over one's gasoline consumption through basic economic mechanisms (Parag and Strickland, 2009).

The model is based on the utility theory of consumer choice that a consumer would make decisions upon consumption bundles to achieve utility maximization (Houthakker, 1950). And it is assumed that consumers in this model are homogenous similar to the assumption in Parry (2004). We consider that a consumer would be confronted with consumption decisions on vehicle miles traveled m and other general consumption good x (Parry and Small, 2005; Capstick and Lewis, 2009; Parry and Timilsina, 2010). m would emit carbon emissions directly. As previously noted, other consumption goods x will not cost gasoline permit because the emission reduction scheme should first cover the transport-generated carbon emissions due to its relatively high demand elasticities similar to the PCT scheme (Wadud, 2011; Raux et al., 2015). Moreover, the indirect carbon emissions from goods x are difficult to track and measure (Eyre, 2010), and therefore are excluded from the PFPT scheme. Under such a scheme, consumers have not only been subject to monetary budget but also permit budget when they purchase gasoline from the petrol station. We assume that consumers under the scheme are price-takers. Symbolically,

$$Max\, u(m,x)$$

$$s.t.\begin{cases} p_G gm + c/\sum_{t=1}^{T}\gamma^t + p_x x + \psi\, p_g - I \le 0 & (shadow\ price\ \phi_1) \\ gm - \psi \le \omega & (shadow\ price\ \phi_2) \end{cases} \quad (1)$$

where $u(m,x)$ represents a consumer's general utility function, m is vehicle miles traveled, x is general good consumption, I is income budget, T is vehicle lifespan, $c/\sum_{t=1}^{T}\gamma^t$ is levelized vehicle purchased cost, p_G is gasoline price, g is the gasoline consumption per mile, p_g is gasoline permit price, and ψ is the gasoline permit traded. If $\psi > 0$, the consumer is an over-consumer; Conversely, if $\psi < 0$, the consumer is an under-consumer. Let ω (LOGE) denote the free permit allocation from regulatory department for each vehicle. In the first constraint in Equation (1) $p_G gm + c/\sum_{t=1}^{T}\gamma^t$ denotes the expenditure on vehicles, $p_x x$ denotes the expenditure on general consumption good and $\psi\, p_g$ denotes the expenditure on allowances. The sum of these expenditure should be no more than the consumers' disposable income.

In the second constraint, gm signifies the permit needed to travel m miles for the consumer, which should be no more than the sum of the permit allocated and the permit traded ($\psi + \omega$).

3.2 Further analysis

According to the constraint conditions of equation (1), we have

$$(p_G g + gp_g)m + P_x X \le I + p_g \omega - c / \sum_{t=1}^{T} \gamma^t \qquad (2)$$

Let $P = p_G g + gp_g, W = I + p_g \omega - c / \sum_{t=1}^{T} \gamma^t$, we have

$$Pm + P_x x \le W \qquad (3)$$

where $P = p_G + p_g g$ is the total price and W is the total income budget. We define equation (3) as the total income budget constraint.

In order to explore the effect of permit price on permit demand, we should derive the partial derivative of ψ with respect to p_g . According to the constraint condition of equation (1), we have

$$\psi(P, p_x, W) = gm(P, p_x, W) - \omega \qquad (4)$$

Deriving the partial derivative of equation (4) with respect to p_g , we obtain

$$\partial \psi(P, p_x, W) / \partial p_g = g \partial m(P, p_x, W) / \partial p_g \qquad (5)$$

Thus, to obtain the effect of permit price on its demand we should first investigate the effect of permit price on vehicle miles traveled. Based on equations (1) and (3), we define the indirect utility function (Van Praag, 1991; Mas-Colell et al., 1995), $v(P, P_x, W)$ as the highest level of utility the consumer could reach if he faced prices P and P_x and budget W . Thus we have

$$\partial v(P, P_x, W) / \partial p_g = (\partial v / \partial P)(\partial P / \partial p_g) + (\partial v / \partial W)(\partial W / \partial p_g) \qquad (6)$$

Using Roy's identity (Newey, 2007), we obtain

$$\partial v / \partial P = -v_W m \qquad (7)$$

Thus, we have

$$\partial v(P, P_x, W) / \partial p_g = -v_W mg + v_W \omega = -v_W \psi \qquad (8)$$

According to the Duality Theorem (Mas-Colell et al., 1995), we have

$$m(P, P_x, W) = h(P, v(P, P_x, W)) \qquad (9)$$

where $m(P, P_x, W)$ is the Marshallian demand function, and $h(P, v(P, P_x, W))$ is the Hicksian demand function.

Deriving the partial derivative of equation (9) with respect to W and p_g, we have

$$m_W(P, P_x, W) = h_v v_W \tag{10}$$

$$\partial m(P, p_x, W) / \partial p_g = (\partial h / \partial P)(\partial P / \partial p_g) + (\partial h / \partial v)(\partial v / \partial p_g) = h_1 g + h_v \partial v / \partial p_g \tag{11}$$

Substituting equations (8) and (10) into equation (11), we have

$$\partial m(P, p_x, W) / \partial p_g = h_1 g - m_W(P, p_x, W)\psi \tag{12}$$

The equation (12) is the Slutsky decomposition of permit price effect on vehicle miles traveled. Substituting equation (12) into equation (5), we derive

$$\partial \psi(P, p_x, W) / \partial p_g = g \partial m(P, p_x, W) / \partial p_g = g[h_1 g - m_W(P, p_x, W)\psi] \tag{13}$$

Deriving the partial derivative of equation (4) with respect to W, we have

$$\psi_W(P, p_x, W) = g m_W(P, p_x, W) - 1 / p_g \tag{14}$$

Substituting equation (14) into equation (13), we have

$$\partial \psi(P, p_x, W) / \partial p_g = g \partial m(P, p_x, W) / \partial p_g = g^2 h_1 - [\psi_W(P, p_x, W) + 1 / p_g]\psi \tag{15}$$

According to the consumer behavior theory (Mas-Colell et al., 1995), equation (10) is the Slutsky decomposition of permit price effect on permit demand. The substitution effect (SE) and income effect (IE) can be represented as

$$SE = g^2 h_1 \tag{16}$$

$$IE = [\psi_W(P, p_x, W) + 1 / p_g]\psi \tag{17}$$

4. Example with a specific utility function

We will use a classical Cobb-Douglas utility function to obtain the specific formulae of the price effect, substitution effect and income effect, given that the consumer choice models with Cobb-Douglas utility function are simple and tractable and can generate clear and testable empirical predictions (Rosenzweig and Schultz, 1983; Heffetz, 2007). Assume that the utility function $u(m, x)$ takes the form of Cobb-Douglas function $m^\alpha x^{1-\alpha}$.The constraints and parameters in this specific model are similar to those in the general model. Thus, the utility maximization problem can be transformed to the following canonical form:

$$\begin{aligned} & Max\ m^\alpha x^{1-\alpha} \\ & s.t. \\ & \begin{cases} p_G g m + c / \sum_{t=1}^{T} \gamma^t + p_x x + \psi p_g - I \le 0 & (shadow\ price\ \phi_1) \\ g m - \psi \le \omega & (shadow\ price\ \phi_2) \end{cases} \end{aligned} \tag{18}$$

The shadow prices ϕ_1 and ϕ_2 are defined as the marginal changes in the objective function with respect to an increase in the right-hand side of the constraint conditions. The constraints in the optimization problem (18) imply that the shadow prices are positive. Solving the problem in equation (18) involves a linear program of which Karush-Kuhn-Tucker (KKT) optimality conditions are shown in Appendix A.

4.1 Substitution effect

According to (A.11), (A12) and (B8), we have

$$SE = g^2 h_1 = -\beta U (\alpha P_x / \beta)^{\beta} P^{-\beta-1} g^2 < 0 \tag{19}$$

Where U is the minimum utility level required by the consumer. We find that the substitution effect is always negative. According to Koutsoyannis (1963), the negative substitution effect is an inevitable consequence of the “preference hypothesis”. When a price increase occurs in one good, it would alter the relative prices and induce substitution of the relatively cheaper good for the relatively more expensive good. Likewise, when the permit price rises, consumers would tend to reduce gasoline consumption and turn to general good consumption. This is consistent with the traditional economic theory of consumer choice (Varian, 1992)

4.2 Income effect analysis

However, the income effect will be different for the under-consumer and the over-consumer. According to equations (A13), we have

$$\psi_W = \alpha g / P - 1 / p_g \tag{20}$$

According to equation (17), the income effect is

$$IE = -g \alpha \psi / P \tag{21}$$

When the consumer is an over-consumer ($\psi > 0$), his income effect is negative. The real income will decrease with permit price rises and thus generating negative income effect. According to equations (15), (19) and (21), the consumer’s total price effect is negative. That is to say, the over-consumer’s permit demand will always decrease when the permit price increases. In a PFPT scheme, consumers should be required to surrender a certain amount of permits when they consume gasoline. The energy goods and permits are complementary goods. When the permit price rises (i.e. total price rises), the over-consumer will consume less gasoline and then need fewer permits. Therefore, his permit demand will decrease as permit price rises.

However, when the consumer is an under-consumer ($\psi < 0$), his income effect is positive, which makes the total price effect ambiguous. Koutsoyannis (1963) argued that, for the inferior goods, the income effect is positively related to the price change.[2] Intuitively, the allowances could be perceived as "inferior goods" by the under-consumers. However, the mechanism is different from that of conventional inferior goods. For conventional inferior goods, the mechanism is such that when the price of these goods rises, the consumer's real income will fall and he will purchase more inferior goods (Baumol, 1973; Atkinson and Stern, 1974). In term of PFPT permits, when the price rises, the under-consumer's real income will increase, since he could sell his surplus permits to gain extra income. Thus, the income effect is positive and the permits are somewhat like inferior goods for the under-consumer.

4.3 Price effect

To explore the price effect, we could compare the absolute values of the income effect and the substitution effect and investigate which plays a dominant role. Substituting equation (20) and (A13) into equation (17), we have

$$|IE| = [\psi_W(P, p_x, W) + 1/p_g]\psi = g\alpha P^{-1}\omega - g^2\alpha^2 P^{-2} W \quad (21)$$

According to equations (16), (B8), (A11) and (A12), we obtain

$$|SE_x| = \alpha\beta W P^{-2} g^2 = \alpha W P^{-2} g^2 - \alpha^2 W P^{-2} g^2 \quad (22)$$

According to equations (21) and (22), when $I^{**} < I < I^*$, we have $|IE| < |SE|$ (see more details in Appendix C).[3] That is, the substitution effect dominates the income effect, and thus the total effect will be negative. In this situation, the permit demand of the under-consumer will decrease as the permit price rises. An under-consumer will

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[2] Giffen goods are extreme examples of inferior goods.

[3] $I^{**} = \omega P / g + c / \sum_{t=1}^{T} \gamma^t - p_g \omega$,

$I^* = \omega P / (g\alpha) + c / \sum_{t=1}^{T} \gamma^t - p_g \omega$

consume less gasoline when the permit price rises. Therefore, he will need fewer permits and can sell more.

When $I < I^{**}$, we have $|IE| > |SE|$. That is, the income term dominates the substitution term, and thus the price effect will be positive. In this situation, the permit demand will increase as the permit price increases. The observed supply pattern of permits might run counter to the second law of supply and demand, which states that a rise in price tends to increase supply (Henderson, 1922).

In summary, the demand for gasoline permits among consumers with different income levels might be quite different. For the over-consumers, the substitution and income effect are both negative. Therefore, for over-consumers, they will demand less permits when the price rises. For the under-consumers with higher income ($I^{**} < I < I^{*}$), the substitution effect is negative while the income effect is positive. Furthermore, the negative substitution effect dominates the positive income effect, making gasoline permits somewhat like inferior good. For these two income groups ($I > I^{*}$ and $I^{**} < I < I^{*}$), the permit price will play a role in stimulating the less use of gasoline.

For the under-consumers with lower income ($I < I^{**}$), the positive income effect dominates the negative substitution effect. The permits are somewhat like Giffen goods for these consumers. These phenomena could be further explained by the superimposed effect of the price and the quantity of permits. When permit price rises, the under-consumers' real income will also increase because a certain quantity of permits could be sold at higher prices. Thus, the income effect is positive although the mechanism is different from that of conventional inferior goods. Therefore, the "permit demand paradox" —some consumers would need more permits for surrender when the permit price rises—appears in the low income groups. Actually the main purpose of introducing a PFPT scheme is to provide an additional financial incentive for consumers to reduce gasoline consumption (Wallace et al., 2010). However, the Giffen-good effect in low income groups proves the ineffectiveness of a PFPT scheme theoretically.

5. Data calibrations and discussion

In this part, we will use the US household expenditure data to investigate the heterogeneity of permit demand over different income groups and examine how to steer the policy design into an effective direction. The US data was chosen because it has the most comprehensive dataset that are public available. In addition, transportation sector has been one of the largest source of greenhouse gas emissions, which accounts for almost 28 percent of total emissions in 2012 (EIA, 2013). These carbon emissions are due to the widespread use of gasoline in private vehicles. Although apart from a national priority, environmental protection has been paid great attention among different states and private organizations. For example, best known cap-and-trade program in the Chicago Climate Exchange (CCX) was established to promote low carbon transitions. PFPT scheme is another type of cap-and-trade program which extends the carbon reduction activity to individual fuel consumers. Besides, the data are used to show the results intuitively and it does not intend to explain the political reality in the USA. We also tried the calibration with data from other countries and the findings are not significantly different from those of the US data.

5.1 Parameters

Average household income I and vehicle purchase cost c are collected from the US household income quintiles (see Table 1). According to Mankiw (1998), α in the above utility function stands for the expenditure share of personal transportation. Generally, consumers in different income groups would have different revealed preference on personal transportation. Here we use the average private transportation expenditure share from year 2004 to 2013 in household expenditure survey (seen in Table 2) to estimate α given that the aggregate data would satisfy the Generalized Axiom of Revealed Preference (Varian, 1992). After calibrations, we get $\alpha = 1.5\%$.

Table 1

Average household income and vehicle purchase cost in 2013

Quintile	Average household income ($)	Vehicle purchase cost ($)
Lowest 20%	10,092	261

Second 20%	26,764	614
Third 20%	43,592	1,194
Fourth 20%	67,344	1,688
Highest 20%	134,044	4,064

Note: Vehicle purchase cost mainly refers to household average expenditure on new private vehicles (Second-hand vehicles are excluded)

Based on a review of over 247 million U.S. car and light truck registrations in January, 2013, the average age has hit a record high of 11.4 years for passenger cars[4]. Therefore, we assume that the average lifespan T is 11 years. According to the estimates conducted by EPA (2008), the gasoline consumption per mile driven (g) is 0.04 gallon and the carbon emission per gallon is 9.26kg.

Table 2

Average annual consumer expenditure and personal transportation expenditure in 2004-2013

Year	Personal transportation expenditure ($)	Average annual expenditure($)
2013	8465.96	51093.41
2012	8453.86	51420.37
2011	7773.07	49666.24
2010	7182.83	48089.61
2009	7179.06	49068.62
2008	8088.52	50465.32
2007	8219.40	49633.47
2006	8003.13	48381.80
2005	7896.24	46398.22
2004	7359.84	43373.02

The current interest rate (r) is set to be 0.03 according of Bank of America[5]. The initial gasoline permit allocation is critical in the PFPT scheme, where an appropriate

4 http://www.autonews.com/article/20130806/RETAIL/130809922/average-age-of-u.s.-car-light-truck-on-road-hits-record-11.4-years

5 https://www.bankofamerica.com/deposits/bank-account-interest-rates.go

permit allocation would cause market failure (Li et al., 2014). In 2012, total carbon emissions in transportation sector reached 1841.0 million metric tons in the USA. Among them, 43.1% are from private cars, reaching 793.8 million metric tons (EPA, 2014). To be consistent with the abatement goal of “in the range of” 17 percent below 2005 levels by 2020 pledged at the Copenhagen climate meeting in December 2009 (Burtraw et al., 2011), the carbon budget for each consumer should be set at 4753.80kg. Thus the initial gasoline permit allocation (ω) could be set at 513.37 gallon.

According to McNamara and Caulfield (2013) and Brauneis et al (2013), the carbon allowance price is set equal to 0.03 $/kg in the PCT scheme. Thus the gasoline permit price could be set equal to 0.27 (0.03×9.26) $/kg. The average price of gasoline around the world (p_G) is set to be 4.17 per us gallon according to the current price level.

5.2 Permit demand and income

Based on the parameters, we use equations (21), (22) and (15) to calculate the substitution effect, income effect and price effect and gain insight into permit demand in different income group. The specific calculation results are presented as follows (see in Figure 3).

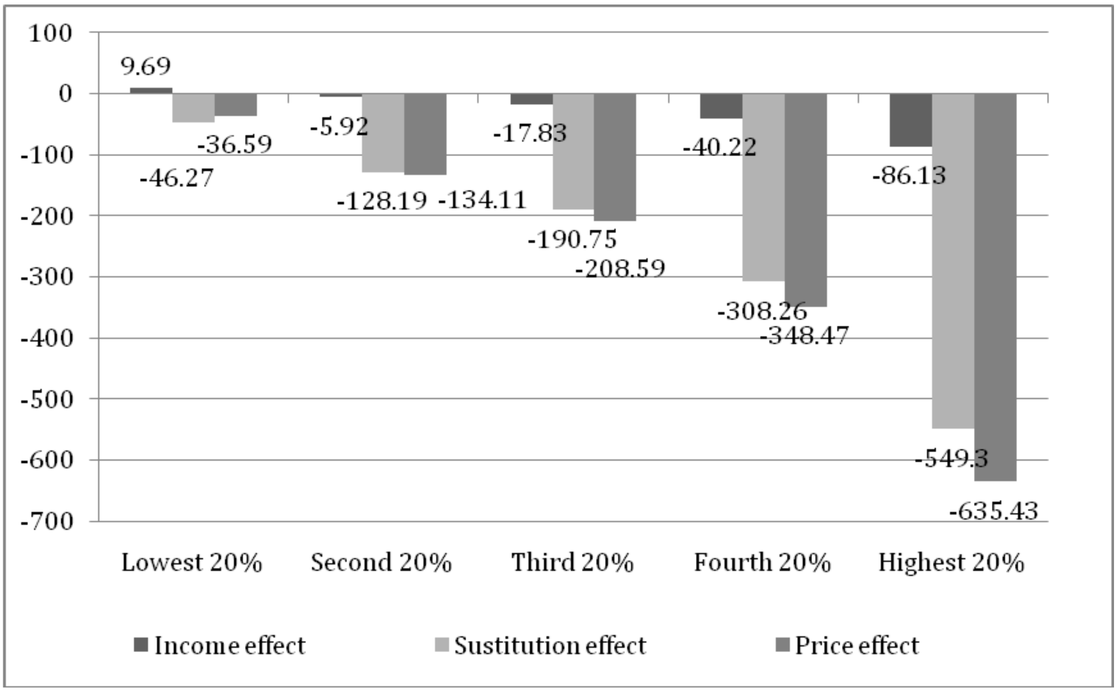

Figure 3 Income effect, substitution effect and price effect among different income groups

Specifically, as indicated by Figure 3, the substitution effects of permit demand are all negative among different income groups. This is consistent with traditional hypothesis on substitution effect (Renshaw, 1960; Varian, 1992). Moreover, the substitution effect would be strong among higher income groups.

In terms of income effect, the situation is a little different. In the lowest 20% quintile where the average income falls between $I^{**} = 5583.87$ and $I^{*} = 17550.52$, the income effect is positive, consistent with the above model result. However, the negative substitution effect dominates the income effect, making permits inferior goods for low income groups. In the second, third, fourth, highest income quintiles, the consumers' income effect are negative. Their average incomes are more than $I^{*} = 17550.52$ $, being over-consumers. These over-consumers would have to purchase extra permits for surrender (Fawcett, 2010). Thus the PFPT scheme is capable of playing the role of "income distribution", that is, permits flow from under-consumers to over-consumers and in turn money flow from the high income groups to low income groups (Parag and Eyre, 2010; Li et al., 2014).

Overall, for the lowest 20% quintile consumers, the permits are inferior goods, and for the second, third, fourth and highest 20% quintile consumers, the permits are normal goods as shown in Figure 3. These consumers other than the lowest 20% quintile would be stimulated to reduce permit consumption under the PFPT scheme. Unlike as proved in Section 4.3, when a consumer's income is below the critical value I^{**}, his permit demand would be similar to Giffen good. However, the Giffen-good effect has disappeared from Figure 3. This is due to the fact that even the average income in the lowest 20% percentiles is far more than I^{**}=5583.87 $. Therefore, in terms of the average incomes in the five quintiles, permits are never to be Giffen good, which indicates that "permit demand paradox" would only remain theoretically possible in the current parameter settings. For most people, the PFPT scheme is effective in reducing gasoline consumption, consistent with the conclusions in the PCT scheme drawn by Li et al. (2014) and Fan et al. (2015)

5.3 Regulation on the permit price and permit allocation

Using the US household expenditure data, we find that the PFPG scheme is ineffective among consumers in the lowest 20% quintiles. In the policy design, regulations could be enforced on the initial permit allocation and permit price to steer the scheme into an effective direction. If $|\mathrm{IE}| \le |\mathrm{SE}|$, the permit demand would subject to the permit price control and the PFPT scheme would be effective. According to equations (21) and (22), we have $p_g \le W/\omega - p_G$. In the current parameter setting, the permit price for the lowest 20% income should be set no more than 9.05$/gallon to keep the PFPG scheme effective. Since the permit price is determined by the permit supply and permit demand, the regulatory department should issue and withdraw permits timely so as to maintain a reasonable market price.

Permit allocation is another critical parameter that the regulatory department could exert influences upon the permit trading. As mentioned above, to keep the PFPT scheme effective in the lowest 20% quintile, we have $|\mathrm{IE}| \le |\mathrm{SE}|$, that is $\omega \le (I - c / \sum_{t=1}^{T} \gamma^t) / p_G$. In the current setting, the permit allocation should be kept at no more than 1594.46 kg for each regulated vehicle.

5.4 Consumers' choice on vehicles' fuel economy $(1/g)$

Permit trading scheme will induce abatement activities and promote consumers' transition toward the adoption of less polluted vehicles (Albrecht, 2000). In the PFPG scheme, consumers will have incentives to choose relatively high fuel economic cars to comply with the permit "cap". Letting equation (A13) equal 0, we have the minimal fuel economy that consumers in different income group has to follow when they choose a gasoline-driven vehicle. Figure 4 indicates that only the lowest income group would choose the cars whose fuel economy below the average level. The rich are subject to more stringent fuel economy standard. This will provide reference for the regulatory department to set the minimal fuel economy that could provide free permits. And this scheme helps to raise the overall fuel economy standard in the US.

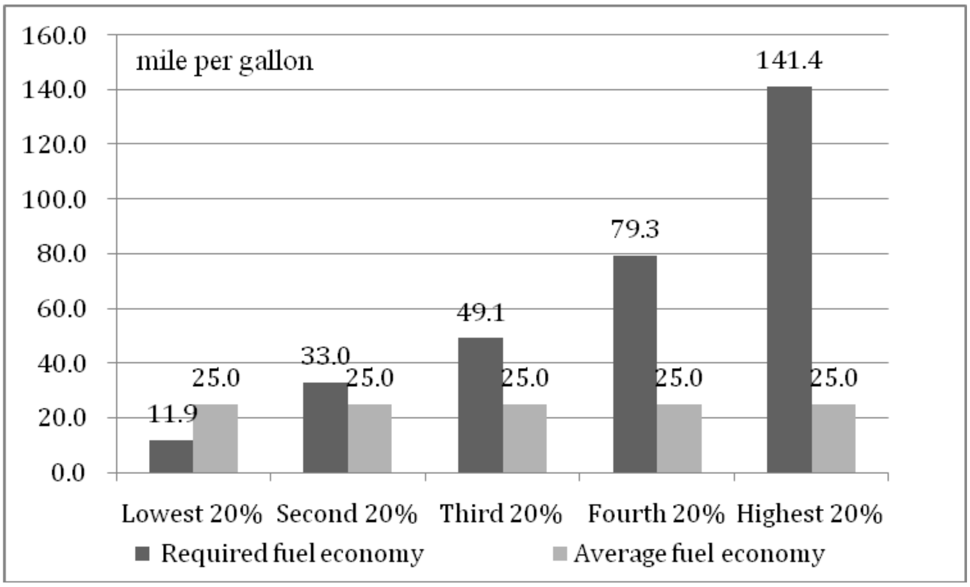

Figure 4 Consumer's choice on fuel economy and the US average fuel economy

6. Conclusions and implications

This paper specifically proposes a PFPT scheme to implement PCT in the transportation sector. Then the paper investigates the effectiveness of the PFPT scheme in reducing gasoline consumption from the perspective of permit demand across different income groups and studies several critical factors in the policy design.

The results suggest that permit demand would be varied among different income groups. For high income groups, gasoline permits are normal goods with negative income effect and substitution effect. For medium income groups under consumers, permits could be somewhat like inferior good with negative substitution effect and positive income effect. In this situation, the positive income effect is not strong enough to dominate the negative substitution effect, making the price effect remain negative. While for low income groups, the positive income effect dominates the negative substitution effect, thus resulting in a Giffen-good effect.

Yet this Giffen-good effect remains theoretically possible and will not happen in the real US situation. In reality, the results for the low income group are largely depending on the parameter settings in the scheme, for example, the free permit allocated, permit prices etc. To keep the scheme effective in reducing fuel consumption, the regulatory agency should set reasonable amount of free permit allowance and regulate the permit price at an appropriate level.

The key arguments lie in the fact that speculative behavior would not happen in the permit market. Future work should address the formulation of more realistic models. It is of vital significance to investigate how consumers would respond if gasoline permits could be banked and borrowed among different time periods (Fankhauser and Hepburn, 2010). And transactional cost is another issue the model could incorporate in the future (Fawcett and Parag, 2010). The model formulated here readily lends itself to considerations for these unsolved problems.

Appendix A

The consumer solves the following utility maximization problem

$$
\begin{aligned}
& Max\ m^{\alpha} x^{1-\alpha} \\
& s.t. \\
& \begin{cases} p_G gm + c / \sum_{t=1}^{T} \gamma^t + p_x x + \psi p_g - I \le 0 & \text{shadow price } \phi_1 \\ gm - \psi \le \omega & \text{shadow price } \phi_2 \end{cases}
\end{aligned}
\tag{A1}
$$

Solving the optimization problem (A1) involves a linear program whose Karush-Kuhn-Tucker (KKT) optimality conditions are

$$0 \le m \perp \alpha m^{\alpha-1} x^{1-\alpha} - \phi_1 p_G g - \phi_2 g \ge 0 \tag{A2}$$

$$0 \le x \perp (1-\alpha)m^{\alpha} x^{-\alpha} - \phi_1 p_x \ge 0 \quad \text{(A3)}$$

$$0 \le \psi \perp -\phi_1 p_g + \phi_2 \ge 0 \quad \text{(A4)}$$

$$0 \le \phi_1 \perp p_G gm + c / \sum_{t=1}^{T} \gamma^t + p_x x + \psi p_g - I \ge 0 \quad \text{(A5)}$$

$$0 \le \phi_2 \perp gm - \psi - \omega \ge 0 \quad \text{(A6)}$$

where $\perp$ indicates orthogonality between two vectors, which in this case simply expresses the complementary slackness condition in linear programming (Zhao et al., 2010; Chen et al., 2011).

According to the Karush-Kuhn-Tucker (KKT) conditions we have

$$(\alpha x)/(\beta m) = (gp_G)/p_x + (\phi_2 e p_g)/(\phi_1 p_x) \quad \text{(A7)}$$

$$(gp_G + gp_g)m + p_x x = I + p_g \omega - c / \sum_{t=1}^{T} \gamma^t \quad \text{(A8)}$$

$$-p_g \phi_1 + \phi_2 = 0 \quad \text{(A9)}$$

$$\psi = gm - \omega \quad \text{(A10)}$$

Let $P = p_G g + gp_g, W = I + p_g \omega - c / \sum_{t=1}^{T} \gamma^t$. According to equations (A7), (A8) and (A9), we have

$$m = (\alpha W)/P \quad \text{(A11)}$$

$$x = \beta W / p_x \quad \text{(A12)}$$

Substitute (A11) and (A12) into (A10), we have

$$\psi = g\alpha W / P - \omega \quad \text{(A13)}$$

Thus, the indirect utility function is

$$v(P, P_x, W) = (\beta / p_x)(\alpha p_x / \beta P)^{\alpha} W \quad \text{(A14)}$$

Appendix B

To calculate the substitution effect, we need to obtain the Hicksian demand function. The optimization model for the consumer can be represented as follow.

$$Min\, C(m,x) = p_G gm + c / \sum_{t=1}^{T} \gamma^t + p_x x + \psi p_g$$
$$s.t. \quad \text{(B1)}$$
$$\begin{cases} m^{\alpha} x^{1-\alpha} \ge U \\ \psi - gm \ge -\omega \end{cases}$$

U is the minimum utility level required by the consumer. The Karush-Kuhn-Tucker (KKT) optimality conditions for optimization problem (B1) are as follows,

$$0 \le m \perp p_G g - \varphi_1 \alpha m^{\alpha-1} x^{1-\alpha} + \varphi_2 g \ge 0 \quad \text{(B2)}$$

$$0 \le x \perp p_x - \varphi_1 (1-\alpha) m^{\alpha} x^{-\alpha} \ge 0 \quad \text{(B3)}$$

$$0 \le \psi \perp p_g - \varphi_2 \ge 0 \quad \text{(B4)}$$

$$0 \le \varphi_1 \perp m^{\alpha} x^{\beta} - U \ge 0 \quad \text{(B5)}$$

$$0 \le \varphi_2 \perp \psi - gm + \omega \ge 0 \quad \text{(B6)}$$

According to (B2) and (B3), we have

$$m / x = \alpha p_x / [\beta (p_G g + p_g g)] \quad \text{(B7)}$$

Substitute (B7) into (B5), we have

$$m = U[\alpha p_x / (\beta P)]^{\beta}$$

Thus, the Hicksian demand function for the consumer is

$$h(P, P_x, U) = U[\alpha P_x / (\beta P)]^{\beta} \quad \text{(B8)}$$

Appendix C

When $I > I^{**}$, Since $Y = I + p_g \omega$ and $P = p + p_g c$, we have

$$W > P\omega / g \quad \text{(C1)}$$

Multiplying equation (C1) on both sides by $\alpha g P^{-2}$, we have

$$\alpha W P^{-2} g^2 > g \alpha P^{-1} \omega \quad \text{(C2)}$$

Adding $-g^2 \alpha^2 P^{-2} W$ on both sides in equation (C2), we have

$$\alpha W P^{-2} g^2 - g^2 \alpha^2 P^{-2} W > g \alpha P^{-1} \omega - g^2 \alpha^2 P^{-2} W \quad \text{(C3)}$$

Therefore, according to equations (21) and (22), we have

$$|IE_x| < |SE_x| \quad \text{(C4)}$$

Since $\psi < 0$, we have $I < I^*$. Therefore, when $I^{**} < I < I^*$, we have $|IE_x| < |SE_x|$.

The case when $I < I^{**}$ would be similar.

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