Optimal Car Taxes and Toll in Beijing Considering the Marginal Cost of Public Funds

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Considering congestion, environments, and marginal cost of fund for road construction in Beijing, this paper optimizes highway toll, car ownership tax, and fuel tax. We establish a model with two departments (Government and highway company) with their fiscal revenue budgets, taxes and tolls are optimized in three scenarios: scenario 1 optimizes all tax/toll items simultaneously; scenario 2 optimizes all tax/toll items but government and highway company keep their own revenue budget balanced; scenario 3 optimizes only fuel tax, keeping the toll and car ownership tax at the current level. Our calculation results show that 1) fuel tax should be increased while highway tolls and car ownership should be decreased in Beijing, 2) that distortionary taxes/tolls have strong interactions, and 3) that consolidation of the fiscal revenues is vital.

Keywords : *Optimal taxation, Toll, Marginal cost of public funds, Externalities*

1. INTRODUCTION

Every household who owns private vehicle must pay for car ownership tax, fuel tax and highway toll. These taxes and tolls are useful tools to reduce automobile externalities like local and global air pollution, traffic congestion and accident (Parry, Walls & Harrington, 2007[1)]). Car-related taxes also provide revenues for government as public funds; the highway toll provides revenue for highway companies as road construction and maintenance fund. To effectively alleviate severe congestion and air pollution in Beijing, this research manages to explore the efficient solution to these externalities by optimizing multiple car-related taxes and highway toll simultaneously.

China has been through a rapid growth on the automobile market since 21st century, especially in the mega city like Beijing with a sharp increase in the population, enormous car demand makes citizens face severe air pollution and traffic congestion problems.

Theoretically, Pigouvian tax can perfectly offset the negative impact on citizens' car usage. The same efficiency of emission tax can be obtained by a vehicle-specific gas tax or vehicle-based tax depend on mileage (see Fullerton & West, 2002[2)]), so we can mimic the emission tax and distance tax by imposing fuel tax , car ownership tax and highway toll.

Pre-existing distortion of other taxes should be considered when we optimize car-related taxes and toll. Car-related taxes or toll affect the social welfare because they reduce driving demand and car ownership demand. Meanwhile, these taxes/toll can affect social welfare by discouraging labor supply. The net welfare change depends on both car usage demand and labor supply (see Fullerton & Metcalf (2001)[3)]). The tax-interaction effect should not be ignored since this effect is large enough to make the impact of environmental taxes to compound the welfare cost of the tax system (Parry I. , 1997)[4)]. We should consider the interaction with the other taxes particularly the labor wage tax, as it takes a larger part of the government's revenue.

To take tax distortion into account, we use Marginal cost of public funds (MCF) to measure the tax efficiency. MCF is the direct tax burden plus the marginal welfare cost produced in acquiring the tax revenue (Browning, 1976)[5)]. According to the optimal tax theory, MCF of all the tax items and tolls should be equal in the optimal status.

Many papers explored the optimization of car-related taxes. Parry & Small (2005)[6] develops an analytical framework for assessing the second-best optimal level of gasoline taxation considering unpriced pollution, congestion, and accident externalities, and interactions with labor wage tax. Follow their research, Lin & Zeng (2014)[7] used the same method with Chinese data to optimize gasoline tax. But these two researches considered only single tax item. Anas, Timilsina & Zheng (2009)[8] did a research on optimal congestion toll and fuel tax respectively with a logit model and compared taxation efficiency on reducing traffic-related externalities. But they didn't optimize multiple taxes/tolls simultaneously. Fullerton & West (2010)[9] considered multiple taxes for gasoline, engine size and vehicle age, to find the second-best policy for reducing the pollution in the U.S.; Feng, Fullerton & Gan (2013)[10] did research on discrete and continues demand of heterogeneity consumers to find optimal pollution policies and capture the interactive effects of simultaneous decisions, but they didn't consider the government's fiscal revenue in the optimization.

In this research, we use the method in (Kono, Mitsuhiro, Morisugi, & Yoshida (2016)[11] with data in Beijing. Our purpose is to find the optimal rates of car ownership tax, fuel tax and highway toll to correct the excess tax burden. The features of our study are:

- Simultaneously optimized multiple car-related tax/toll items to reduce traffic-related externalities.
- MCF of these tax/toll revenues are set at same magnitude as the MCF of labor wage tax revenues.
- There are two policy-related departments in our model, the government and the highway road company, and the fiscal revenues of them are both balanced in the optimization procedure.

2. MODEL AND OPTIMIZATION OF TOLLS AND TAXES

A consumer drives on highway roads or on the urban roads; or he/she can choose the public transport mainly composed by subway or bus. To analyze the car-related system, we concentrate mainly on gasoline automobiles. The reason is that the private gasoline automobiles take 92.7% of the traffic volume in Beijing city (see Beijing traffic development annual report (2011)[12]). Besides, we ignored the purchase lottery policy effect on the car ownership demand function and assume that one consumer can buy a car if he/she has the willingness, because the mandatory regulation on car purchasing is non-market factor. We assume that consumer's behavior is completely based on the market.

(1) A static model of individual behavior

a) Budget constraint

The consumers are heterogeneous in our model. A consumer i can choose to own a car or not, car ownership status is noted by δ^i, if consumer i choose to own a car and drive, then $\delta^i = 1$; on the other hand, when he/she choose public transport, then $\delta^i = 0$. Consumer i has the demand of driving on highway road at a distance of x_H^i (km), or drive on the urban road at a distance of x^i (km). Fuel efficiency on highway is $\overline{l_H}$ (liter/km) while it's $\bar{l}$ (liter/km) on urban road. Under this setting, the fuel consumption on highway road is $x_H^i \cdot \overline{l_H}$ (liter) while $x^i \cdot \bar{l}$ (liter) on urban roads. Both car owner and consumer without car can choose public transport, with a travel distance of x_p^i (km). The existence of public transport makes the car ownership demand and car driving demand elastic.

The annual car ownership tax of consumer i 's car contains annualized purchase tax and an annual vehicle and vessel tax in China, noted as s (dollars/year). Other expenditures like insurances and maintenance fee, parking fee are included in annualized car price $\bar{c}$ (dollars/year). Meanwhile, the toll on highway is set as p (cents/km) as most of Beijing's highway roads are charged by distance, the fuel tax is at a rate of f (cents/liter). The fare on public transport means is noted as $\overline{p_p}$ (dollars). The symbol * denotes the optimal value in the model. A variable with overline is a constant value.

The budget constraint of consumer i is,

$$z^i + \delta^i\left[\left(p + f\overline{l_H}\right)x_H^i + f\bar{l}x^i + s + \bar{c} + \overline{p_p}x_p^i\right] + \left(1-\delta^i\right)\overline{p_p}x_p^i = \left(\overline{w^i} - \tau\left(\overline{w^i}\right)\right)L^i. \qquad (2.1)$$

Right side of the equation represent the total cost of consumer i, left side represent the net wage income. Where z^i is the composite goods with numerical value normalized to 1. $\overline{\mathrm{w}^\mathrm{i}}$ (cents/hour) represents wage rate of consumer i, τ stands for labor tax rate and L^i is the labor time. This budget constraint explains consumer i's annual expenditure on highway driving, urban road driving, car ownership, public transport and his/her annual labor wage income.

b) Time budget

To take congestion externality into account, we must consider consumer i's time spent on the road. The composition of one's time contains leisure time y^i, labor time L^i, time spent on highway road driving $T_H x_H^i$ (hours) and on urban road Tx^i (hours), time spent on public transport $\overline{T_p}$ (hours/km), all the time spent should meet the budget of consumer i's available time $\overline{M}$,

$$y^i + L^i + \delta^i\left(T_H x_H^i + T x^i\right) + \left(1-\delta^i\right)\overline{T_p} x_p^i = \overline{M}, \qquad (2.2)$$

Eq. (2.2) represents consumer's aggregate annual time spent. In this equation, travel time function on highway road T_H (hours/km) and on urban road T (hours/km) can measure the congestion level on the road, congestion traffic may lead to higher T_H and T. Also, traffic accident probability rises as T_H or T grows. Travel time is determined by the total traffic demand on the respective road,

$$T_H = T_H(X_H), \qquad T = T(X), \qquad (2.3)$$

where the $X_H \equiv \sum_i \delta^i x_H^i$ is the total travel distance demand on highway roads and $X \equiv \sum_i \delta^i x^i$ is the total travel distance demand on urban road. Meanwhile, these functions satisfy $dT_H/dX_H \geq 0,\ dT/dX \geq 0$ because the more people drive the more congestion will be produced.

c) Utility function

We define the environmental damage caused by car use on highway road as E_H and on urban road as E, repectively. To a better description of real-life context, E_H and E contains air pollution costs, noise costs and a greenhouse effect. With the technical development, the tailpipe emissions now vary primarily with VMT (vehicle miles traveled) rather than total fuel consumption (see Parry, Walls & Harrington (2007)[1)]). This implies that car-related environmental damage can be a function of the total travel distance. So that we can define the functions of E_H and E respectively as

$$E_H = E_H(X_H), \qquad E = E(X). \qquad (2.4)$$

We have $dE_H/dX_H \geq 0,\ \ dE/dX \geq 0$ here, as higher traffic volume brings more air pollutions.

The utility function of consumer i who owns a car can be expressed as:

$$U^i = \delta^i u^i\left(x_H^i, x^i, y^i, E_H, E\right) + (1-\delta^i) u^i\left(x_p^i, y^i\right) + z^i\,, \qquad (2.5)$$

$$du^i/d\zeta \geq 0, \qquad d\left(u^i\right)^2/d^2\zeta < 0,$$

$$\zeta \in \left\{x_H^i, x^i, x_p^i, y^i, E_H, E\right\}.$$

The reason that travel time T_H and T is not included in direct utility function is that when consumer drives, the marginal congestion affect caused by himself/herself is hardly to cognize, since the individual travel demand can be negligible to total traffic volume change. The existence of composite goods z^i have effect on the utility and makes the utility can be measured by monetary values.

A rational consumer will always pursue the maximization of individual utility. To do this with the utility function in our model, we can substitute equation (2.1) and (2.2) into (2.5), and have the individual's optimal demand function on highway travel distance $x_H^{i^*} \equiv x_H^{i^*}\left(p, f, s, T_H, T, E_H, E, \tau\left(w^i\right)\right)$, optimal demand function on urban road travel distance $x^{i^*} \equiv x^{i^*}\left(p, f, s, T_H, T, E_H, E, \tau\left(w^i\right)\right)$ and individual's car ownership demand function $\delta^{i^*} \equiv \delta^{i^*}\left(p, f, s, T_H, T, E_H, E, \tau\left(w^i\right)\right)$. Labor supply change caused by driving demand change is not as sensitivity as travel demand and car ownership because travel time and travel distance can hardly affect one's labor time. In this model we set labor time as an exogeneous variable.

d) Indirect individual utility

Substitute the individual demand functions into the utility function (6) and we can have the indirect individual utility,

$$V^i = \delta^i v_1^i\left(p, f, s, T_H, T, E_H, E, \tau\left(\overline{w^i}\right)\right) + \left(1-\delta^i\right) v_0^i\left(\overline{p_p}, E_H, E, \tau\left(\overline{w^i}\right)\right), \qquad (2.6)$$

Function V^i represents utility of driving a car when $\delta^i = 1$ plus utility of using public transport when $\delta^i = 0$. Total car ownership is $N_1 = \sum_i \delta^i$. Utility of driving a car is determined by highway toll p, fuel tax f and car ownership s, these are policy variables in our model; the utility is also determined by exogenous values like congestion level T_H and T, the environmental damage E_H and E as well as the labor wage tax $\tau\left(\overline{w^i}\right)$. As for the utility of public transport, the determinant factors are constant transport fare, environment damage and a constant labor wage tax $\tau\left(\overline{w^i}\right)$. The determination of δ^{i^*} is, when $v_1^{i^*} > v_0^{i^*}$, $\delta^{i^*} = 1$, and consumer choose to drive; when $v_1^{i^*} < v_0^{i^*}$, $\delta^{i^*} = 0$, consumer choose to use public transport means. The change in the utility level associated with toll p and fuel tax f and car ownership tax s can be obtained by the envelope theorem as $\partial V^i/\partial p = -\delta^{i^*} x_H^{i^*}$, $\partial V^i/\partial f = -\delta^{i^*}\left(\overline{l_H} \cdot x_H^{i^*} + \overline{l} \cdot x^{i^*}\right)$ and $\partial V^i/\partial s = -\delta^{i^*}$.

(2) Model of social planners' behavior

In China, highway roads are constructed and maintained by highway road companies, some of these highway companies are independent and enact their own tolling rates, while the others are owned by governments with passivity tolling management; all the tax items are controlled by governments, so that we should consider social planner as two departments as a correspondence.

The government expenditure must meet the revenue budget,

$$\overline{G} = K \equiv \sum_{i}^{N} \delta^{i^*}\left[f\left(\overline{l_H} x_H^{i^*} + \overline{l} x^*\right) + s\right] + \sum_{i=1}^{N} \tau\left(\overline{w^i}\right) L^{i^*}, \quad (2.7)$$

where $\overline{G}$ is the expenditure of Beijing's government and K represent the tax revenue, including fuel tax, car ownership tax and labor wage tax revenue. N denotes the number of population in Beijing.

Another department is the highway company. In our study, we also consider the condition when the highway companies have a budget on their tolling revenue,

$$\overline{H} = R \equiv \sum_{i}^{N} \delta^{i^*} \cdot p \cdot x_H^{i^*} \quad (2.8)$$

In function (2.9), $\overline{H}$ denotes the expenditure on road construction and maintenance for independent highway companies, R is the revenue which is collected from tolling on highway roads.

(3) Three optimization scenarios

We want to explore the interactions between fuel tax, car ownership tax and highway toll, and verify the importance of consolidation of fiscal revenue, so we use 3 kinds of scenarios to do the optimization. Frist of all we want to verify the scenario where a sole department (government) manages the market, secondly, we choose a scenario where two departments manage the market and the government manages the car-related tax revenue, while the highway companies manage the highway toll revenue; the third scenario the government optimize only fuel tax, keeping the other two items as current rate. To give a more specific view of the three scenarios, we can give the exact functions,

- Scenario 1 optimizes fuel tax f, car ownership tax s and highway toll p simultaneously, the government use tax revenues K and highway toll revenue R to meet the budget of highway expenditure $\overline{H}$ and other government expenditures $\overline{G}$.

$$\max_{\left\{p,f,s,\tau\left(\overline{w^i}\right), i\in(1,2,\ldots N)\right\}} \sum_{i}^{N} V^i$$
$$s.t.\, \overline{G} + \overline{H} = K + R \quad (2.9.1)$$

- Scenario 2 optimizes fuel tax f, car ownership tax s, government's tax revenue K meets government expenditures $\overline{G}$, and highway company impose highway toll p and use all the toll revenue R on the highway expenditure $\overline{H}$.

$$\max_{\left\{p,f,s,\tau\left(\overline{w^i}\right), i\in(1,2,\ldots N)\right\}} \sum_{i}^{N} V^i$$
$$s.t. \begin{cases} \overline{G} = K \\ p = \left\{p: \overline{H} = R\right\} \end{cases} \quad (2.9.2)$$

- Scenario 3 optimizes fuel tax f, government's tax revenue K meets government expenditures $\overline{G}$, car ownership tax s keeps at current rate as $\overline{s}$, highway toll p keeps at current rate as $\overline{p}$.

$$\max_{\left\{p,f,s,\tau\left(\overline{w^i}\right), i\in(1,2,\ldots N)\right\}} \sum_{i}^{N} V^i$$
$$s.t. \begin{cases} \overline{G} = K \\ p = \overline{p} \\ s = \overline{s} \end{cases} \quad (2.9.3)$$

(4) Optimization of the social utility

In this model we considered 3 scenarios, to give a direct explanation of how we do the optimization, we choose scenario 1 as an example. To solve the maximization in function (2.9.1), the Lagrangian function is represented by

$$\Phi = \sum_{i=1}^{N} \delta^{i^*} v_1^{i^*} \begin{pmatrix} p, f, s, T_H(X_H^*), T(X^*), \\ E_H(X_H^*), E(X^*), \tau\left(\overline{w^i}\right), \varepsilon^i \end{pmatrix} + \sum_{i=1}^{N} \left(1-\delta^i\right) v_0^{i^*}\left(p_p, E_H(X_H^*), E(X^*), \tau\left(\overline{w^i}\right), \varepsilon^i\right) + \varphi \begin{bmatrix} \sum_{i}^{N} \delta^{i^*}\left[p x_H^{i^*} + f\left(l_H x_H^{i^*} + l x^*\right) + s\right] + \\ \sum_{i=1}^{N} \tau\left(\overline{w^i}\right) L^{i^*} - G \end{bmatrix} \quad (2.10)$$

The first order condition of function (2.11) is

$$\frac{\partial \Phi}{\partial Q} = \sum_{i=1}^{N} \frac{\partial V^{i^*}}{\partial Q} + \varphi \frac{\partial (K+R)}{\partial Q} = 0, \quad Q \in \{p, f, s\} \quad (2.11)$$

In the first order conditions, when policy variables change, φ is the proportion of the change of social welfare to the change of government revenue, we take one endogenous variable fuel tax f as an example to express this proportion, which can be represented by,

$$-\varphi = \frac{\frac{\partial V^{i^*}}{\partial f}}{\frac{\partial (K+R)}{\partial f}} = \frac{\begin{array}{c}(\overline{l_H}X_H^* + \bar{l}X^*) \\ +N_1\left[\frac{\partial v_1^{i^*}}{\partial T_H}\frac{\partial T_H}{\partial X_H}\frac{\partial X_H^*}{\partial f} + \frac{\partial v_1^{i^*}}{\partial T}\frac{\partial T}{\partial X}\frac{\partial X^*}{\partial f}\right] \\ +N\left[\frac{\partial v_1^{i^*}}{\partial E_H}\frac{\partial E_H}{\partial X_H}\frac{\partial X_H^*}{\partial f} + \frac{\partial v_1^{i^*}}{\partial E}\frac{\partial E}{\partial X}\frac{\partial X^*}{\partial f}\right]\end{array}}{\begin{array}{c}\left[(l_H X_H^* + lX^*) + \frac{\partial (l_H X_H^* + lX^*)}{\partial f} f\right] \\ + \frac{\partial X_H^*}{\partial f}p + \frac{\partial N_1^*}{\partial f}s\end{array}} \qquad (2.12)$$

In equation (2.13), N_1 notes car ownership in Beijing. This proportion or $-\varphi$ is MCF, namely the marginal cost of public funds from fuel tax, the right side of this equation is the proportion of social welfare change to the taxes and toll revenue changes. The term of $(\overline{l_H}X_H^* + \bar{l}X^*)$ is the surplus change for consumer, $N_1\left[\frac{\partial v_1^{i^*}}{\partial T_H}\frac{\partial T_H}{\partial X_H}\frac{\partial X_H^*}{\partial f} + \frac{\partial v_1^{i^*}}{\partial T}\frac{\partial T}{\partial X}\frac{\partial X^*}{\partial f}\right]$ and $N\left[\frac{\partial v_1^{i^*}}{\partial E_H}\frac{\partial E_H}{\partial X_H}\frac{\partial X_H^*}{\partial f} + \frac{\partial v_1^{i^*}}{\partial E}\frac{\partial E}{\partial X}\frac{\partial X^*}{\partial f}\right]$ stands for the change of environmental externalities and congestion externalities raised with the fuel tax change respectively. The term of $\left[(l_H X_H^* + lX^*) + \frac{\partial (l_H X_H^* + lX^*)}{\partial f} f\right]$ denotes the fuel tax revenue change and $\frac{\partial X_H^*}{\partial f}p + \frac{\partial N_1^*}{\partial f}s$ explains the interplay between these distortionary taxes.

Labor wage tax revenue takes most part of the government revenues, as the population is much higher than car owners and one always pay more on income tax than car-related taxes. Due to this huge revenue

(2) Summary of all the parameters in this study

In table 1, we summarized the parameters used in

gap, when car-related taxes and toll revenues change, subject to the government's budget constraint, the labor wage tax revenue will face a slice change due to its vast amount. As the labor wage tax rate is exogenously given, at the equilibrium status, all the MCF of fuel tax f, car ownership tax s as well as the highway toll p, should be equalized to the MCF of labor wage tax.

3. CASE STUDY OF BEIJING

To calculate the optimal rates of the highway toll, fuel tax and car ownership tax, this research uses some data in Beijing, time is set in 2010. The method is to use real data include traffic demand elasticities, traffic externalities and current traffic condition data and substitute into the equations in in our model. We calculated the optimal results in 3 scenarios with different practical significance and situations. Moreover, we use these results to do sensitivity analyses to verify the interactions of different tax items when we do the optimization.

(1) Demand functions

The former discussion gives the demand function of individual highway driving distance $x_H^{i^*} \equiv x_H^{i^*}\left(p, f, s, T_H, T, E_H, E, \tau(w^i)\right)$, demand on urban road travel distance $x^{i^*} \equiv x^{i^*}\left(p, f, s, T_H, T, E_H, E, \tau(w^i)\right)$ and individual's choice on car ownership $\delta^{i^*} \equiv \delta^{i^*}\left(p, f, s, T_H, T, E_H, E, \tau(w^i)\right)$. As the car ownership is $N_1 = \sum \delta^i$, we can assume that the demand functions have a linear form, the function of highway road demand as $X_H = \alpha_H + \beta_H \cdot p + \lambda_H \cdot f + \eta_H \cdot s$; the function of highway road demand as $X = \alpha + \beta \cdot p + \lambda \cdot f + \eta \cdot s$; the function of highway road demand as $N_1 = \alpha_N + \beta_N \cdot p + \lambda_N \cdot f + \eta_N \cdot s$. We obtain the parameters in these demand functions by evaluating the price elasticities of car-related demands.

our calculation, these parameters include the price/tax elasticities of car-related demands, congestion and air pollution externalities and others.

Table 1 Summary of parameters in this study

Parameters	Value	Source
Price elasticity of highway demand	-1.66	(Fu & Gu, 2017)[13]
Price elasticity of urban road demand	0.006	(Fu & Gu, 2017)[13]
Fuel tax elasticity of fuel consumption	-0.14	(Lin & Zeng, 2014)[7]
Fuel tax elasticity of car ownership demand	-0.18	(Lee & Kang, 2015)[14]
Car ownership tax elasticity of car ownership demand	-0.01	Estimated by us
Local air pollution externalities (cents/km)	-1.39	(Tong, Wang, & Wang, 2014)[15]
Global air pollution externalities (cents/liter)	-0.22	(Tol, 2005)[16]

Congestion externalities (cents/km)	Highway	-13.3	(Tong, Wang, & Wang, 2014)[16]
	Urban road	-14.8	
Average fuel efficiency (km/liter)	Highway	16.35	(Kang, Dror, Ding, Qin, & An, 2015)[17]
	Urban road	10.87	
MCF of labor wage tax		1.207-1.26	(Liu, 2009)[18]
Average driving demand per car (km)		21,161	Annual report 2011[12]
Car ownership in Beijing (million)		4.809	Annual report 2011[12]
GDP per capita in Beijing(dollar)		10,910	Annual report 2011[12]

* The currency rate in 2010 is set as 6.77 Yuan/Dollar.

4. OPTIMAL LEVELS OF TOLLS AND CAR-RELATED TAXES IN BEIJING

(1) Efficient taxation levels in different scenarios

We calculate the optimal levels of car-related taxes and highway toll in this section. Results in 3 scenarios are shown in Table 2 and then we analysis the highway driving demand change, urban road driving demand change and car ownership demand changes respectively.

In scenario 1, car-related taxes and highway toll revenues meet the government and highway company's expenditure, and the government is the only social planner to manage both the taxes and toll rates, according to our calculation, the optimal highway toll is 1.7 cents/km, fuel tax is 166.6 cents/liter and the car ownership should be 443.0 dollars/year, the result compared to the initial taxes and toll rates are presented in Table 2.

Table 1 Optimal toll, fuel tax and car ownership tax (MCF=1.236)

Scenarios	Toll (cents/km)	Fuel tax (cents/liter)	Car ownership tax (dollars/year)
(1) Simultaneous optimization	1.7	166.6	443.0
(2) Separate budget	6.0	34.7	1657.1
(3) Only fuel tax, fixing others	7.4	114.8	498.3
Current level (2010)	7.4	41.4	498.3

* The currency rate in 2010 is set as 6.77 Yuan/Dollar.

The reason why a dropping highway toll and a small increase in car ownership tax can reduce congestion and air pollution in scenario 1 is that, compared to these two taxation items, the fuel tax is more effective to incentive people's behavior on traffic demand which leads directly to the emission and congestion. Compared to highway toll, fuel tax reduces both driving demands on urban roads and highway roads. In the research of (Feng, Fullerton, & Gan, 2013)[10], to abate the same amount of pollutants, the descending order for marginal cost of abatement is vehicle-based tax, gasoline tax, emission tax. Our results that fuel tax is more effective on abatement of emission than other taxes/tolls proved Feng's argument.

In scenario 2 we optimize the fuel tax and car ownership tax, leave the toll subject to highway companies' budget. In this scenario optimal highway toll rate is very close to the current rate. the optimal fuel tax is 34.7 cents/liter, and the car ownership tax is 1657.1 dollars/year. Compared to present level, the car ownership tax is surprisingly high in scenario 2. We can explain this by fiscal revenue reasons. In current Beijing, some of the toll on state-run highway roads are collected by governments, in scenario 2 highway toll are separated from government's control, then the other revenues should be higher to compensate for the toll revenue parts. Since the car ownership tax is inelastic on car-related demands, the government may rise car-ownership sharply. Compared to scenario 1, this result implies fiscal revenue consolidation is very important in optimization of car-related taxes.

The scenario 3 we optimize fuel tax only, leaving the car ownership tax and highway toll as current rates. Optimal fuel tax in this scenario is 114.8 cents / liter, we can use the results in scenario 3 to compare the former study of (Lin & Zeng, 2014)[7]. By their calculation, the optimized Pigouvian tax in Beijing is 247.6 cents/liters.. Comparing the results of 1st and scenario 3, we can draw the conclusion that the interactions of car-related taxes and toll make the outcome different, and we should consider multiple existed car-related taxes simultaneously.

Since we have already had the optimized taxes and toll rates as well as the demand functions, we can calculate highway traffic and urban road traffic demand change by substituting the optimal tax/toll results into the demand functions, and we get Table 3.

Table 2 Optimal demand of highway traffic, urban road traffic and car ownership

Demands	Highway traffic (km/car)	Urban road traffic (km/car)	Car ownership
(1) Simultaneous optimization	4,412	25,759	2,511,107
(2) Separate budget	4,324	12,629	4,892,647
(3) Only fuel tax, fixing others	68	21,686	3,316,347
Current level (2010)	3,872	17,288	4,809,000

* The currency rate in 2010 is set as 6.77 Yuan/Dollar.

Table 2 explains the demand change after the optimizations. In scenario 1, when optimized taxes and toll are imposed, the highway road traffic demand as well as the urban road traffic demand is higher, while car ownership is significantly decreased. the new tax system can strongly stimulate consumers to change their driving choice and car ownership choice. This result indicates that an optimal tax system will not restricting driving, but to expand the road usage to a maximal level by reallocate the social resource.

In scenario 2, the changed demand is relatively close to the current level compares to scenario 1, because there are no significant changes on the highway toll and fuel tax rates. These two taxes contribute more to the change of consumer's behavior compare to the car ownership tax, as the car ownership tax elasticity of car ownership demand is only -0.01, car ownership tax elasticity of driving demand is only -0.12, so that the rise of car ownership tax alone can hardly make significant change on people's driving behavior nor car ownership demand. Compare to the scenario 1, the result implies that it's important to consider the corresponding fiscal revenue when social planner optimize multiple taxes.

As for the scenario 3, the highway traffic demand per car becomes extremely low. Compares to the results in scenario 1, the toll rate is much higher (1.7 in scenario 1, 7.4 in scenario 3). This result reveals that the interaction between different taxes distortion is significant, and we shouldn't ignore this interaction effect on optimizing the tax/toll.

(2) Social welfare changes in different scenarios.

In this section we discuss the social welfare effect. Like the calculation by Parry and Small (2005) [13], we obtain the function of social welfare change as

$$\Delta W = \Phi(\Delta p + p, \Delta f + f, \Delta s + s) - \Phi(p, f, s)\ , \tag{4.1}$$

If we substitute the original and optimal values of highway toll, fuel tax and car ownership into the function 2.11, we can have the results in Table 4.

Table 4 Social welfare change in 3 scenarios

Scenarios	scenario 1	scenario 2	scenario 3
1. Welfare change (million $)	3,641	2,976	2,148
2. Proportion of GDP in Beijing, 2010	1.75%	1.43%	1.03%
3. Welfare gain per capita (dollars)	185.6	151.7	109.5

* The currency rate in 2010 is set as 6.77 Yuan/Dollar.

Obviously, the social welfare gain in scenario 1 is higher than the other 2 scenarios. This implies that simultaneously optimization is important.

(3) Sensitivity analyses of the optimal results

a) Efficient taxation levels with different MCF values

By the explanation in section 3. the Chinese MCF of labor wage tax range from 1.207 to 1.264 by the research of (Liu, 2009)[18]. The sensitivity analysis in this section verified our assumption that the optimal tax rates should be considered with different MCF standards. In our setting, if the MCF of labor wage tax is 1.264 in Beijing, compares to that with MCF as 1.207, the optimal toll and fuel tax should be lower, and the car ownership tax should be higher.

Table 5 Optimal toll, fuel tax and car ownership tax in scenario 1 with different MCF

MCF	Toll (cents/km)	Fuel tax (cents/liter)	Car ownership tax (dollars/year)
1.207	1.9	167.4	404.5
1.236	1.7	166.6	443.0
1.264	1.6	166.0	477
Current level (2010)	7.4	41.4	498.3

* The currency rate in 2010 is set as 6.77 Yuan/Dollar.

b) Sensitivity analysis of environmental damage and congestion effect

First, we simply set the environmental externalities $E_H(X_H)$ and $E(X)$ as zero to calculate the optimal taxes/toll in the scenario 1 to represent the difference.

Then, we simply set the traffic congestion externalities $T_H(X_H)$ and $T(X)$ as zero to calculate the optimal taxes/toll in the scenario 1 to represent the difference.

Table 6 Pollution and congestion effects on results in scenario 1

	Toll (cents/km)	Fuel tax (cents/liter)	Car ownership tax (dollars/year)
1. With both externalities	1.7	166.6	443.0
2. No pollution externality	1.4	156.4	443.0
3. No congestion externality	0.05	79.0	442.0

* The currency rate in 2010 is set as 6.77 Yuan/Dollar.

The result is clear, that if we do not consider the environmental externalities, the optimal toll on highway should drop from 1.7 to 1.4 cents/km, also the optimal fuel tax should drop from 166.6 to 156.4 cents/km, since the car ownership tax contributes less than fuel tax or highway toll to the abatement of emission, the optimal car ownership tax stays the same.

Compare a no congestion scenario to scenario 1, the optimal highway toll drops from 1.7 to 0.05 cents/km, fuel tax drops from 166.6 to 79 cents/km. The reason of highway toll is still imposed is the existence of environmental externality which is much lower than congestion externality. In this case, the car ownership still extremely close to the initial value.

5. CONCLUSION

To explore a more efficiency traffic related tax and toll system in Beijing, this study uses a method in (Kono, Mitsuhiro, Morisugi, & Yoshida, 2016)[11] focusing on highway toll, fuel tax and car ownership tax to reduce the environmental externality and congestion externality. We calculated the optimal taxes and toll with data in Beijing and find out the fuel tax should be 166.6 cents/liter, car ownershipta tax should be 443 dollars/year, highway toll should be 1.7 cents/km.

This study concentrates on a model without political interference, we assume the non-market policies in Beijing don’t exist, in reality the government should find out how to balance the marketing policies and non-marketing policies. Also, in our research, the traffic demands are average values of all consumers in one year. In future studies we can explore more possibilities with classified car models and consumer income levels, since the demand elasticity can vary between these classes, so does the optimized taxes and tolls. The sensitivity analyses in this study also show that the congestion level and air pollution level affect the optimal results, so in future more efforts should be put on geographical characteristics within different districts. Another crucial point is this research is limited within one city, we assume that no exotic fuel consumption in our study in Beijing case, this lead to a problem that even in areas with different congestion level, the fuel tax cannot vary too much due to the existence of an arbitrage chance. To solve this problem, the government should impose distance tax to control the congestion problem in a long term.

APPENDIX A AN INTEGRABILITY CONDITION

To set the utility function which can generate the demand functions, the parameters in the demand functions must follow an integrability condition due to a so-called symmetry of second derivatives. To express this condition, we have

$$\begin{cases}\dfrac{\partial^2 V^i}{\partial p\partial f}=\dfrac{\partial^2 V^i}{\partial f\partial p}\\ \dfrac{\partial^2 V^i}{\partial f\partial s}=\dfrac{\partial^2 V^i}{\partial s\partial f}\\ \dfrac{\partial^2 V^i}{\partial p\partial s}=\dfrac{\partial^2 V^i}{\partial s\partial p}\end{cases}\Rightarrow\begin{cases}\dfrac{\partial X_H}{\partial f}=\dfrac{\partial(l_H\cdot X_H+l\cdot X)}{\partial p}\\ \dfrac{\partial X_H}{\partial s}=\dfrac{\partial N_1}{\partial p}\\ \dfrac{\partial(l_H\cdot X_H+l\cdot X)}{\partial s}=\dfrac{\partial N_1}{\partial f}\end{cases}\qquad(A1)$$

Also, we should have $\frac{\partial^2(K+R)^i}{\partial p\partial f}$, $\frac{\partial^2(K+R)^{\mathrm{i}}}{\partial \mathrm{f}\partial s}$ and $\frac{\partial^2(K+R)^{\mathrm{i}}}{\partial \mathrm{p}\,\partial s}$ satisfy the same condition, with (A6) stand it will hold as well.

APPENDIX B ESTIMATING ELASTICITIES IN OUR MODEL

To evaluate the linear function of highway traffic demand, urban road traffic demand and car ownership demand in Beijing, we use the tax/toll elasticity of demands to calculate the parameters in the demand functions. Table 7 exhibit all the elasticities used in this research.

The source of our estimation come from some previous studies. In the study of (Lin & Zeng, 2013)[19], the price elasticity of gasoline demand in China is estimated with a mean value as -0.3465, since the fuel tax is approximately 40% of the full gasoline price in Beijing, so that the fuel tax elasticity of fuel demand can be set at -0.1386. Fu & Gu (2017)[13] estimate the highway toll elasticity of air pollution in China with a value of -0.15, by their evaluation, approximately half of the air pollution is caused by traffic, so that we can roughly set the highway toll of total traffic demand is -0.3. Lee & Kang (2015)[14] made an estimation on the gasoline price elasticity on vehicle demand as -0.437, multiplied by 40% we have the fuel tax elasticity of vehicle demand as -0.17. By the analysis of (Qiu & He, 2017)[20], fuel price elasticity of VMT is -0.4105 in China, thus we have the fuel tax elasticity of VMT as -0.1642. As the integrability conditions hold, we can calculate the fuel tax elasticity of both highway traffic demand and urban road traffic demand $E_f^{X_H}$ and E_f^X by

$$\begin{cases}l_H\cdot E_f^{X_H}\cdot\dfrac{X_H}{f}+l\cdot E_f^X\cdot\dfrac{X}{f}=E_f^F\cdot\dfrac{F}{f}\\ E_f^{X_H}\cdot\dfrac{X_H}{f}+E_f^X\cdot\dfrac{X}{f}=E_f^{VMT}\cdot\dfrac{X_H+X}{f}\end{cases};\qquad(A2)$$

And the highway toll elasticity of both highway traffic demand and urban road traffic demand $E_p^{X_H}$ and E_p^X by

$$\begin{cases}l_H\cdot E_p^{X_H}\cdot\dfrac{X_H}{p}+l\cdot E_p^X\cdot\dfrac{X}{p}=E_f^{X_H}\cdot\dfrac{X_H}{f}\\ E_p^{X_H}\cdot\dfrac{X_H}{p}+E_p^X\cdot\dfrac{X}{p}=E_p^{VMT}\cdot\dfrac{X_H+X}{p}\end{cases};\qquad(A3)$$

If we assume that when the car ownership tax increases, the proportion of traffic growth rate on highway and urban road is X_H/X since the change on both roads are indiscriminate, and we can calculate the car ownership tax elasticity of highway traffic demand $E_s^{X_H}$ and urban road traffic demand E_s^X respectively with (A6)

$$E_s^{X_H}=E_s^X=E_f^{N_1}\cdot\frac{N_1}{f}\cdot\frac{s}{F}\qquad(A4)$$

To estimate the car ownership tax elasticity of car ownership demand, we assume a function of car ownership demand in China include variables GDP per capita and car price index and consumer mind index. All the data come from (Statistics, Beijing Statistical Yearbook, 2002-2012)[21]. The function is

$$\begin{aligned}&ln(\,number\ of\ cars\ per\ capita\,)=\\ &1.41+0.35\,ln(\,real\ GDP\ per\ capita)\\ &\quad-0.73\,ln(\,car\ price\ index\,)\\ &\quad-0.37\,ln(consumer\ mind\ index)\end{aligned}\qquad(A5)$$

So, we can have the car ownership tax elasticity of car ownership demand as -0.01 under the assumption that the annual car ownership tax in Beijing is 498.2 dollars a year and the car with a price of 30000 dollars.

Table 7 All the elasticities parameters in Beijing's case

Elasticities	Highway demand X_H	Urban road demand X	Car ownership demand N_1
Highway toll p	-1.66	0.006	-0.07

Fuel tax f	-0.56	-0.076	-0.17
Car ownership tax s	-0.11	-0.11	-0.01

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