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Abstract. This paper optimizes fuel tax, car ownership tax, highway tolls, and peak-time area pricing in Beijing with explicit consideration of marginal costs of public funds arising from these taxes and pricing. We establish two scenarios: scenario 1 optimizes the two taxes, tolls, and area pricing simultaneously; scenario 2 optimizes the two taxes and tolls without area pricing. Using Beijing's parameters obtained from previous studies, our calculation results show that 1) the optimal area pricing is 50 CNY/entry; 2) Scenario 1 reduces the number of cars in peak time by more than 50%, but scenario 2 reduces it by 10%; 3) regardless of area pricing, fuel tax should be higher and car ownership tax lower. We do some sensitivity analyses to demonstrate the possible ranges of the tax and pricing instruments.

Key words: Optimal taxation, Marginal cost of public funds, Externality, Area pricing
JEL Classification: H21; H23; R48

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1. Introduction

Heavy traffic congestion, which greatly increases travel time[1], arises in Beijing due to the land use pattern. First, separation between living and working areas is relatively clear. The inner city provides about 70% of the job opportunities, while about 40% of the population live in the suburbs.[2] Second, a U-shaped building height curve from the center to the suburb and an expansion of transportation networks have forced the city edge to expand, which leads to a further increase in car usage demand (Ding, 2013). However, it is difficult to change the land use pattern in the short term.

Currently, air pollution is very severe in Beijing. The air pollution level increases from the suburbs to the center with the volume of cars (Jiming et al., 2000). 74% of CO and 67% of NO_x in the atmosphere in Beijing come from vehicle exhaust (Hao and Wang, 2012), and about 30% of the variance in local $PM_{2.5}$ can be explained by traffic emissions (Zhang et al., 2016). It is, therefore, an urgent task to impose appropriate traffic policies to reduce traffic and car emissions.

Car-related taxes and pricing are useful to control traffic congestion in the short as well as long term. When we optimize the car-related taxes and pricing, however, we should take account of the financial constraint of the tax and pricing and the deadweight losses arising from them. Parry and Bento (2001) state that road toll revenues must be used to reduce the distortionary taxation. Similar analyses, which optimizes the rates of the revenue items, have been conducted by Bovenberg and de Mooij (1994), Parry (1997), Bento et al. (2014) and Kono et al. (2019).

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[1] According to the Beijing Traffic Development Annual Report (2014), the average congestion time is about 2 hours per day, and the average traffic speed on urban roads is only 23.2 km/h during the rush hours.

[2] Data from the Beijing Municipal Bureau of Statistics. See website http://www.bjstats.gov.cn/tjsj/sjjd/201511/t20151123_321580.html

Many countries levy car-related taxes, and some of them impose highway tolls. But the annual tax on car ownership differs greatly across countries. The annual car expenditure of tax/toll items is shown in Figure 1.[3] In France, Japan and China, highway users must pay tolls, while in some other countries they do not; in North European countries like Denmark and Finland, the car ownership tax is much higher than that in China and the US; while the fuel tax is similar across many countries. These large differences among countries may show that governments do not optimize the car-related tax items, and at least they show no world standards on their rates. Accordingly, in many countries, optimizing them may increase the welfare drastically.

Figure 1. here

As shown in Fig. 1, in China, the current fuel tax is relatively low. Since 1993, the volume of oil imports has increased by an enormous rate of 65% (He et al. 2005). At least in the short term, fuel tax can control the fuel consumption. Likewise, highway tolls can reduce the traffic on highways. In a relatively long term, car ownership tax affects car ownership, and therefore affects traffic demand. This implies that the revenue from the individual tax item depends on the other tax/toll rates through the change in traffic demand and car ownership. Accordingly, the government should optimize these tax/toll items simultaneously to increase the social welfare and to decrease the total tax distortions, given its fiscal constraint.

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[3] The data of the annual expenditure on fuel tax and the annual average tax on car ownership and acquisition except China in Figure 1 are estimated by Japan's Cabinet Office, and that on highway tolls comes from Kono et al. (2019) in yen. The data in China is calculated from the current highway toll, fuel tax and car ownership tax in 2010. For car identities, these data are based on the assumption that a consumer purchases a car of 2000 cc class for a unit price of $30,000, with mileage of 10,000 km annually for 6 years with annual fuel consumption of 1000 liters.

To take tax/toll distortions into account, we can use marginal cost of public funds (hereafter, 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).[4] According to the optimal tax theory, in order to optimize car-related taxes and highway tolls, the MCFs of these policy taxes/tolls should be at the same level as that of labor income tax.

Many papers have explored the optimization of car-related taxes. Parry & Small (2005) develop an analytical framework of assessing the second-best optimal level of fuel tax considering unpriced pollution, congestion, and accident externalities, and interactions with labor income tax. Lin & Zeng (2014) applied the same method to Chinese data to optimize fuel tax. However, these two studies considered only a single tax item. Anas et al. (2009) studied optimal congestion toll and fuel tax with a logit model and compared taxation efficiency with traffic-related externalities. However, they did not optimize the other tax/toll items. Fullerton & West (2010) considered multiple taxes for gasoline, engine size and vehicle age, to find the second-best policy for reducing the pollution in the U.S, but did not consider the government's fiscal constraint. Tikoudis et al. (2015) consider this point and examine congestion taxes in a monocentric city, focusing on the differentiation of road taxes over space, because the labor supply elasticity and the marginal utility of income vary across locations. Hirte and Tscharaktschiew (2020) discuss the role of endogeneity of labor supply in shaping optimal transportation taxes.

None of the previous studies, however, consider all the car-related pricing and tax instruments and the government fiscal constraint to find the optimal levels of them. To take

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[4] In the optimal tax system, MCF should be 1 for both lump-sum tax and distortionary tax as Jacobs (2018) certified. Due to the empirical research of Liu (2009), China faces a relatively high MCF of labor wage tax ranging from 1.207 to 1.236.

account of them simultaneously, Kono et al. (2019) extend the work of Parry and Small (2005) to include all the car-related tax instruments (fuel tax, car ownership tax, and highway tolls), distortions of which simultaneously change through a change in the number of car trips in Japan. In addition, they explore how consolidating different fiscal constraints of transportation agencies affects optimal car-related taxes and tolls.

This research is in the same vein as in the Japanese case by Kono et al. (2019). What is new, however, is that we introduce the area pricing, which has been successfully imposed in London, into Beijing to explore the optimal levels of the pricing and tax policies. We calculate the optimal rates in two scenarios. Scenario 1 simultaneously optimizes all taxes and congestion pricing; Scenario 2 optimizes fuel tax, car ownership tax, and highway tolls without area pricing.

Using Beijing's parameters, which we obtain from previous studies, our calculation results show that 1) the optimal area charge is 50 CNY/entry; 2) with the area charge, the number of cars in peak time is reduced by more than 50%, but without the charge, it is reduced by 10%; 3) regardless of the area pricing, higher fuel tax and lower car ownership tax should be imposed to reduce the marginal cost of public funds and air pollution and congestion externalities. Sensitivity analysis of the area charge elasticity of demand demonstrates that our assessment of multiple policy instruments falls within the practical range.

The remainder of this paper is organized as follows. Section 2 explains the model, Section 3 describes the related data in Beijing, and Section 4 demonstrates the results of the optimization and the sensitivity analyses. Section 5 concludes the paper.

2. Model and optimization of tolls and taxes

2.1 Individual behavior

To analyze the car-related system, we concentrate mainly on gasoline automobiles. The reason is that the private gasoline automobiles constitute the majority of the traffic in Beijing.[5]

Consumers are heterogeneous in our model. Consumer i can choose to own a car or not and choose to use the car for commuting in peak time or only for private purposes in off-peak time. Car ownership status is denoted by δ^i: if consumer i has a car and drives, then $\delta^i = 1$; on the other hand, if he/she does not have a car and uses public transport, then $\delta^i = 0$. In peak time, consumers commute to the center of Beijing by car or public transport. Car usage status is denoted by θ^i, if consumer i commutes by his/her own car, then $\theta^i = 1$; on the other hand, when he/she commutes by public transport, then $\theta^i = 0$. In off-peak time, consumers who have their own car drives for private purposes. We do not consider the consumers' choices regarding where to live and where to work; that is, the average travel distance to the workplace and the number of days in work are given.

Consumer i drives on a highway for a distance of x^i_{Hr} (km) and drives on urban roads for a distance of x^i_r (km). Subscript *r* indicates the time differentiation between peak and off-peak periods: k and *o* represent the peak periods and off-peak periods, respectively. This makes the purpose of car usage elastic (that is, it is used for commuting or private purposes). Fuel efficiency on the highway is $\overline{l_H}$ (liter/km) while it is $\bar{l}$ (liter/km) on the urban roads.[6] Under this setting, the fuel consumption on the highway is $\sum_r x^i_{Hr} \cdot \overline{l_H}$ (liter), and that on the urban roads is

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[5] In the Beijing Traffic Development Annual Report (2011), the heavy-duty vehicles with higher emissions comprise only 7.3% of all the vehicle ownership, and they face restrictions in driving in the inner city, while the light diesel car also face restrictions in Beijing, see announcement Beijing Environment Development (2006), No 6. http://fgcx.bjcourt.gov.cn:4601/law?fn=lar541s118.txt.

[6] The symbol * denotes the optimal value in the model. A variable with an overline is a constant value.

$\sum_r x_r^i \cdot \bar{l}$ (liter). Regardless of car ownership, consumers can commute by public transport for a travel distance of $\bar{x}_{pk}^i$. In addition to $\bar{x}_{pk}^i$, consumers who do not have a car use public transport for a travel distance of x_p^i (km) for both commuting and private purposes. The existence of public transport makes the car ownership demand and car usage demand elastic.

The annual car ownership tax contains an annualized purchase tax and an annual vehicle and vessel tax in China. The car ownership tax is denoted as s (CNY/year). Fuel tax is set at a rate of f (CNY/liter). Other expenditures like insurance, maintenance fees, and parking fees are included in annualized car price $\bar{c}$ (CNY/year). The consumer has to pay the highway toll p (CNY/km) regardless of time periods if he/she drives on the highway. In peak time, a driver is charged on both highways and local roads on entering the central area of the city; thus, he/she have to pay the area charge p_a whenever he/she commutes. The fare on public transport is denoted as $\overline{p_p}$ (CNY). Table 1 summarizes the taxes and congestion pricing the consumer has to pay.

Table 1. **here**

The budget constraint of consumer i is,

$$\begin{aligned} z^i + \delta^i \Bigg\{ \theta^i \Bigg[p_a + p\sum_r x_{Hr}^i + \sum_r (f + \bar{f})(\bar{l}_H \cdot x_{Hr}^i + \bar{l} \cdot x_r^i) + s + \bar{c} \Bigg] \\ + \left(1 - \theta^i\right)\left[p_a + p x_{Ho}^i + (f + \bar{f})(\bar{l}_H \cdot x_{Ho}^i + \bar{l} \cdot x_o^i) + s + \bar{c} \right] + \bar{p}_p \bar{x}_{pk}^i \Big\} \\ + \left(1 - \delta^i\right) \bar{p}_p x_p^i = (\bar{w}^i - \tau) L^i, \end{aligned} \tag{1}$$

where z^i denotes the composite goods with the price normalized to 1, $\bar{f}$ is before-tax gasoline price (CNY/liter), $\overline{w^i}$ (CNY/hour) represents wage rate of consumer i, τ expresses 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.

To take congestion externality into account, we must consider consumer i's time spent on the road. The time constraint contains leisure time y^i, labor time L^i, time spent on highways $T_{Hr} \cdot x_{Hr}^i$ (hours) and on urban roads $T_r \cdot x_r^i$ (hours) in peak or off-peak time, and time spent on public transport for commuting $\overline{T_p}$ (hours/km). All the time spent should meet the budget of consumer i's available time $\overline{M}$. Eq. (2) represents consumer i's aggregate annual time spent.

$$y^i + L^i + \delta^i \left[\theta^i \sum_r (T_{Hr} x_{Hr}^i + T_r x_r^i) + (1-\theta^i)(T_{Ho} x_{Ho}^i + T_o x_o^i + \overline{T}_p \overline{x}_{pc}^i) \right] + (1-\delta^i) \overline{T}_p x_p^i = \overline{M}. \tag{2}$$

In this equation, travel time function on highways T_{Hr} (hours/km) and on urban roads T_r (hours/km) can measure the congestion level on the road in peak or off-peak time. Travel time per distance is determined by the total traffic demand on the respective road,

$$T_{Hr} = T_{Hr}(X_{Hr}), \qquad T_r = T(X_r), \tag{3}$$

where $X_{Hr} \equiv \sum_i \delta^i x_{Hr}^i$ is the total travel distance demand on highways in period *r* and $X_r \equiv \sum_i \delta^i x_r^i$ is the total travel distance demand on urban roads in period *r*. Meanwhile, these functions satisfy $dT_{Hr}/dX_{Hr} \geq 0$, $dT_r/dX_r \geq 0$ because the more people drive, the more congestion is produced.

The utility of each consumer is affected by not only monetary and time-related factors but also environmental quality. The air condition is poor in Beijing. We define the environmental damage caused by car use on highways as E_H and on urban roads as E. For a simple description of the real-life context, E_H and E contain air pollution costs, noise costs and the greenhouse effect. With technological development, tailpipe emissions now vary primarily with vehicle miles traveled (VMT) rather than total fuel consumption (Parry, et al., 2007). This implies that car-related environmental damage can be a function of total travel distance. Therefore, we can define the functions of E_H and E, respectively, as

$$E_H = E_H(X_H), \qquad E = E(X). \tag{4}$$

where $X_H = X_{Hk} + X_{Ho}$ and $X = X_k + X_o$. We have $dE_H/dX_H \geq 0$, $dE/dX \geq 0$ here, as higher traffic volume brings more air pollution.

The utility of consumer i is determined by driving demand x_{Hk}^i, x_{Ho}^i, x_k^i, x_o^i, leisure time y^i, and environment factors E_H and E, if he/she owns a car and drives in both peak and off-peak periods. The reason why total travel times T_{Hr} and T_r are not included is that drivers tend not to recognize the marginal increase in congestion they produce, since the individual travel demand can be negligible in relation to total traffic volume. Owing to a quasi-utility form, the utility can be measured in terms of monetary values. The utility function of consumer i can be expressed as

$$U^i = (x_{Hk}^i, x_{Ho}^i, x_k^i, x_o^i, y^i, E_H, E) + z^i \, , \tag{5}$$

where driving demands in peak time are replaced by public transport distance x_p^i if consumer i does not have a car. We assume that $\partial U^i/\partial\zeta \geq 0,\ \partial {U^i}^2/\partial^2\zeta < 0, \zeta \in \{x_{Hk}^i, x_{Ho}^i, x_k^i, x_o^i, y^i\}$.

A rational consumer will always pursue the maximization of individual utility. To do this with the utility function in our model, we can substitute Eqs. (1) and (2) into Eq. (5), which yields

$$\begin{aligned}U^i &= u^i\left(x^i_{Hk}, x^i_{Ho}, x^i_k, x^i_o, y^i, E_H, E\right)\\&+(\overline{w}^i-\tau)\left\{\overline{M}-y^i-\delta^i\left[\theta^i\sum_r(T_{Hr}x^i_{Hr}+T_rx^i_r)+(1-\theta^i)(T_{Ho}x^i_{Ho}+T_ox^i_o+\overline{T}_p\overline{x}^i_{pk})\right]-\left(1-\delta^i\right)\overline{T}_px^i_p\right\}\\&-\delta^i\left\{\theta^i\left[p_a+p\sum_r x^i_{Hr}+\sum_r(f+\overline{f})(\overline{l}_H\cdot x^i_{Hr}+\overline{l}\cdot x^i_r)+s+\overline{c}\right]\right.\\&\qquad\left.+\left(1-\theta^i\right)\left[px^i_{Ho}+(f+\overline{f})(\overline{l}_H\cdot x^i_{Ho}+\overline{l}\cdot x^i_o)+s+\overline{c}\right]+\overline{p}_p\overline{x}^i_{pk}\right\}-\left(1-\delta^i\right)\overline{p}_px^i_p.\end{aligned} \tag{6}$$

From the first order conditions with respect to x_{Hk}, x_{Ho}, x_k, x_o, and y, we can obtain x_{Hk}, x_{Ho}, x_k, x_o, and y as functions of p, p_a, f, and τ. Labor supply change caused by driving demand change is not as sensitive as travel demand and car ownership because travel time and travel distance can hardly affect one's labor time. We have $x^{i*}_{Hk} \equiv x^{i*}_{Hk}(p,f,p_a,\tau)$, $x^{i*}_{Ho} \equiv x^{i*}_{Ho}(p,f,\tau)$ $x^{i*}_k \equiv x^{i*}_r(p,f,p_a,\tau)$, $x^{i*}_o \equiv x^{i*}_o(p,f,\tau)$, and $L^{i*} \equiv L^{i*}(\overline{w}^i-\tau)$, excluding fixed variables for our analysis and external variables for consumers from the function such as ($T_{Hk}, T_k, T_{Ho}, T_o, E_H, E$). Superscript * represents the variables optimally chosen by consumers.

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

$$\begin{aligned}V^i &= \delta^i\left[\theta^i v^i_{1\mathrm{c}}(p,f,p_a,\tau,T_{Hk},T_k,T_{Ho},T_o,E_H,E)+(1-\theta^i)v^i_{1\mathrm{p}}(p,f,\tau,T_{Ho},T_o,E_H,E)\right]\\&+\left(1-\delta^i\right)v^i_0(\overline{p}_p,\tau,E_H,E)\end{aligned} \tag{7}$$

where $v^i{}_{1\mathrm{c}}$ is the utility of a car owner who commutes by car, $v^i{}_{1\mathrm{p}}$ is the utility of a car owner who commutes by public transport, and $v^i{}_0$ is the utility of a consumer who does not have a car. Thus, function V^i represents the utility of car owner when $\delta^i = 1$ plus the utility of a consumer using only public transport when $\delta^i = 0$.

The number of total cars is $N_1 = \sum_i \delta^i$, and total number of cars in peak time is $N_k = \sum_i \delta^i\theta^i$. Utility of driving a car is determined by highway toll p, fuel tax f, area charge p_a

as well as exogenous values like congestion level T_{Hr} and T_r, $r \in \{k, o\}$, the environmental damage E_H and E, as well as the labor wage tax τ. As for the utility of public transport, the explanatory values are constant transport fare, environmental damage and a constant labor wage tax τ. Regarding the value of δ^{i^*}, $\delta^{i^*} = 1$ when $v_{1\mathrm{p}}^{i^*} > v_0^{i^*}$; $\delta^{i^*} = 0$ when $v_{1\mathrm{p}}^{i^*} < v_0^{i^*}$. $\theta^{i^*} = 1$ when $\delta^{i^*} = 1$ and $v^i_{1\mathrm{c}} > v^i_{1\mathrm{p}}$; $\theta^{i^*} = 0$ when $\delta^{i^*} = 1$ and $v^i_{1\mathrm{c}} < v^i_{1\mathrm{p}}$. We assume that labor tax τ does not affect car ownership and car usage. δ^{i^*} is the function of fuel tax, car ownership tax, and highway toll as $\delta^{i^*} \equiv \delta^{i^*}(p, f, s)$. θ^{i^*} is the function of fuel tax, highway toll, and area charge as $\theta^{i^*} \equiv \theta^{i^*}(p, f, p_a)$. The change in the indirect utility level associated with toll p, fuel tax f, car ownership tax s, area charge p_a, and labor tax τ can be obtained by the envelope theorem as $\partial V^i/\partial p = -\delta^{i^*}(x_{Hk}^{i^*} + x_{Ho}^{i^*})$, $\partial V^i/\partial f = -\delta^{i^*} \sum_r (\overline{l_H} \cdot x_{Hr}^{i^*} + \bar{l} \cdot x_r^{i^*})$, $\partial V^i/\partial s = -\delta^{i^*}$, $\partial V^i/\partial p_a = -\delta^{i^*}\theta^{i^*}$, and $\partial V^i/\partial \tau = -L^{i^*}$.

Since we set a quasi-linear utility function, the marginal utility of generalized income is identical across consumers (the other choice variables for consumer—car ownership, transportation demand, car usage, and leisure time—are heterogeneous). Thus, the indirect utility function V^i represents a Gorman function. Hence, we can aggregate all consumers' heterogeneous indirect utility functions. Substituting the demand functions into the utility function and aggregating the indirect utility function yields

$$\sum_{i=1}^{N} V^i = \sum_{i=1}^{N} \Big\{ \delta^i \big[\theta^i v_{1\mathrm{c}}^i(p, f, p_a, \tau, T_{Hk}, T_k, T_{Ho}, T_o, E_H, E) + (1-\theta^i) v_{1\mathrm{p}}^i(p, f, \tau, T_{Ho}, T_o, E_H, E) \big] + \left(1-\delta^i\right) v_0^i(\overline{p}_p, \tau, E_H, E) \Big\}, \tag{8}$$

where N is the total population.

Applying the envelope theorem to the aggregated indirect utility function yields

$$-\frac{\partial \sum_i V^i}{\partial p} = \sum_i \sum_r \delta^{i^*} x_{Hr}^{i^*} = \sum_r X_{Hr}^{*} \text{ for all } r \in \{k, o\}, \tag{9}$$

$$-\frac{\partial \sum_i V^i}{\partial f} = \sum_i \sum_r \delta^{i*}\left(\bar{l}_H \cdot x^{i*}_{Hr} + \bar{l} \cdot x^{i*}_r\right) = \sum_r \left(\bar{l}_H \cdot X^*_{Hr} + \bar{l} \cdot X^*_r\right) , \qquad (10)$$

$$-\frac{\partial \sum_i V^i}{\partial s} = \sum_i \delta^{i*} = N_1^*, \qquad (11)$$

$$-\frac{\partial \sum_i V^i}{\partial p_a} = \sum_i \delta^{i*} \theta^{i*} = N_k^* , \qquad (12)$$

$$-\frac{\partial \sum_i V^i}{\partial \tau} = \sum_i L^{i*} . \qquad (13)$$

2.2 Transport-related agencies' budget constraints

In China, highways are constructed and maintained by highway companies. While some of these highway companies are independent and set their own tolling rates, most of the highway companies are owned by the government. All the car-related taxes and area charge are controlled by governments. In this study, we consider two transportation-related agencies: a highway company and the government.

Government expenditure (without highway tolls) meets the revenue budget:

$$\bar{G} = K \equiv \sum_{i=1}^{N} \delta^{i*} \left[\theta^{i*} p_a + \sum_r f\left(\bar{l}_H \cdot x^{i*}_{Hr} + \bar{l} \cdot x^{i*}_r\right) + s \right] + \sum_{i=1}^{N} \tau L^{i*} , \qquad (14)$$

where $\overline{G}$ is the expenditure of Beijing's government, and K represents the tax revenue. Total revenue is composed of area charge, fuel tax, car ownership tax, and labor wage tax revenue.

The highway company manages the highway system. This company applies a loan from the bank to construct the roads and imposes tolls on vehicle users by distance or entrance times at a certain rate. When the highway company has a budget of their tolling revenue,

$$\overline{H} = R \equiv \sum_{i=1}^{N} \delta^{i*} p(x^{i*}_{Hk} + x^{i*}_{Ho}) , \qquad (15)$$

where $\overline{H}$ denotes the expenditure on road construction and maintenance for independent highway companies, R is the revenue which is collected from tolling on highways.

2.3 Two optimization scenarios

We explore how to impose an area charge in the presence of existing distortionary taxes, and examine the impact of area pricing on car-related demands in Beijing through the numerical simulation. So we optimize multiple policy instruments in two scenarios. First, we explore the scenario where the government introduces area pricing and optimizes all car-related taxes and tolls; second, the government does not implement area pricing and optimize the other taxes and tolls that have already been imposed in Beijing. In other words, the second scenario optimizes the current taxes and tolls. To give a more specific view of these scenarios, we can exhibit the following mathematical definitions.

Scenario 1 simultaneously optimizes highway toll p, fuel tax f, car ownership tax s, area charge in peak periods p_a, and labor tax τ. The government uses tax revenues K and highway toll revenue R to meet the budget of highway expenditure $\overline{H}$ and other government expenditures $\overline{G}$.

$$\max_{\{p,f,s,p_a,\tau,i\in(1,2,\ldots N)\}} \sum_{i}^{N} V^i \quad s.t.\, \overline{G} + \overline{H} = K + R \tag{16.1}$$

Scenario 2 optimizes highway toll p, fuel tax f, car ownership tax s, and the labor tax τ simultaneously without area charge p_a.

$$\max_{\{p,f,s,\tau,i\in(1,2,\ldots N)\}} \sum_{i}^{N} V^i \quad s.t.\, \overline{G} + \overline{H} = K + R \tag{16.2}$$

2.4 Optimization of the social welfare

To give a direct explanation of how to optimize policy instruments, we choose Scenario 1 as an example. Maximizing Function (16.1), we have the following Lagrangian function.

$$\begin{aligned}\Phi = \sum_{i=1}^{N} \delta^{i} \Big[& \theta^{i} v_{1\mathrm{c}}^{i}(p, f, p_a, \tau, T_{Hk}(X_{Hk}^{*}), T_k(X_k^{*}), T_{Ho}(X_{Ho}^{*}), T_o(X_o^{*}), E_H(X_H^{*}), E(X^{*})) \\ & + (1-\theta^{i}) v_{1\mathrm{p}}^{i}(p, f, \tau, T_{Ho}(X_{Ho}^{*}), T_o(X_o^{*}), E_H(X_H^{*}), E(X^{*})) \Big] \\ & + \sum_{i=1}^{N} \left(1-\delta^{i}\right) v_0^{i}\left(\bar{p}_p, \tau, E_H(X_H^{*}), E(X^{*})\right) \\ & + \varphi \left\{ \underbrace{\sum_{i=1}^{N} \delta^{i*} \left[\theta^{i*} p_a + p \sum_{r} x_{Hr}^{i} + \sum_{r} f(\bar{l}_H \cdot x_{Hr}^{i} + \bar{l} \cdot x_r^{i}) + s \right] + \sum_{i=1}^{N} \tau L^{i*}}_{\equiv K+R} - \bar{G} - \bar{H} \right\} \end{aligned} \tag{16}$$

The first order conditions of Function (16) are

$$\frac{d\Phi}{dQ} = \sum_{i=1}^{N} \frac{dV^{i}}{dQ} + \varphi \frac{dK + dR}{dQ} = 0 \;\; \Rightarrow \;\; -\varphi = \sum_{i=1}^{N} \frac{dV^{i}}{dQ} \Bigg/ \frac{dK + dR}{dQ}, \tag{17a}$$

where $Q = \{p, f, s, p_a\}$, and

$$\begin{aligned} & \frac{d\Phi}{d\tau} = \sum_{i=1}^{N} \frac{dV^{i}}{d\tau} + \varphi \frac{dK}{d\tau} = 0 \\ & \qquad \Rightarrow \;\; -\varphi = \sum_{i=1}^{N} \frac{dV^{i}}{d\tau} \Bigg/ \frac{dK}{d\tau} = \sum_{i=1}^{N} L^{i*} \Bigg/ \Big(\sum_{i=1}^{N} L^{i*} + \sum_{i=1}^{N} \tau(\bar{w}^{i}) \frac{\partial L^{i*}}{\partial \tau}\Big). \end{aligned} \tag{17b}$$

Applying the envelope theorem to the indirect utility function, we can represent $\sum_{i=1}^{N} \frac{dV^{i}}{dQ}$ and $\frac{dK + dR}{dQ}$ of Eq. (17a) as the functions of observable economic variables. Note that the left-hand side of these equations is *MCF* ($= -\varphi$). Hence, the right-hand sides of all the three equations should be equal.

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

$$MCF = \frac{\dfrac{\sum_{i=1}^{N} dV^i}{df}}{\dfrac{dK + dR}{df}}$$

$$= \frac{\overbrace{\sum_r \left(l_H X_{Hr}^* + l X_r^* \right)}^{\text{Consumer surplus in fuel market}} + \overbrace{\sum_r \left[e_H \frac{\partial X_{Hr}^*}{\partial f} + e \frac{\partial X_r^*}{\partial f} \right]}^{\text{Environmental externalities}} + \overbrace{w\left(N_k \cdot t_k^f + N_1 \cdot t_o^f \right)}^{\text{Congestion externalities}}}{\underbrace{p \sum_r \frac{\partial X_{Hr}^*}{\partial f}}_{\text{Toll revenue}} + \underbrace{[\sum_r \left(l_H X_{Hr}^* + l X_r^* \right) + f \frac{\partial \sum_r \left(l_H X_{Hr}^* + l X_r^* \right)}{\partial f}]}_{\text{Fuel tax revenue}} + \underbrace{s \frac{\partial N_1^*}{\partial f}}_{\text{Car ownership tax revenue}} + \underbrace{p_a \frac{\partial N_k^*}{\partial f}}_{\text{Area pricing revenue}}}, \tag{18}$$

where $e_H \equiv N \frac{\partial v}{\partial E_H} \frac{\partial E_H}{\partial X_H}$ and $e \equiv N \frac{\partial v}{\partial E} \frac{\partial E}{\partial X}$ are both environmental externalities for one unit of driving on highways and local roads, and $t_k^f \equiv \frac{\partial T_{Hk}}{\partial X_{Hk}} \frac{\partial X_{Hk}^*}{\partial f} + \frac{\partial T_k}{\partial X_k} \frac{\partial X_k^*}{\partial f}$ and $t_o^f \equiv \frac{\partial T_{Ho}}{\partial X_{Ho}} \frac{\partial X_{Ho}^*}{\partial f} + \frac{\partial T_o}{\partial X_o} \frac{\partial X_o^*}{\partial f}$ are the marginal change in peak time and off peak time congestion externalities with respect to fuel tax, respectively. $-\varphi$ represents MCF of fuel tax. The right-hand side of this equation is the ratio of social welfare change to the tax and toll revenue changes. The term $\sum_r \left(l_H X_{Hr}^* + l X_r^* \right)$ is the change in the consumer surplus. The term $\left[\sum_r \left(\bar{l}_H X_{Hr}^* + \bar{l} X_r^* \right) + \frac{\partial \sum_r \left(\bar{l}_H X_{Hr}^* + \bar{l} X_r^* \right)}{\partial f} f \right]$ denotes the fuel tax revenue change, and $p \sum_r \frac{\partial X_{Hr}^*}{\partial f} + s \frac{\partial N_1^*}{\partial f} + p_a \frac{\partial N_k^*}{\partial f}$ shows that these distortionary taxes and area charge can interact to determine the optimal policies.

3. Case study of Beijing

This research calculates the optimal rates of multiple taxes and congestion charge, using the real data in Beijing, including traffic demand elasticities, traffic externalities and current traffic condition data obtained from previous studies and our own estimation. The year is set at 2010, and the exchange rate is set as 6.77 CNY/USD in 2010.

3.1 Tax policy and highway tolls in Beijing

In 2010 in Beijing, the highway tolls are imposed on all the highways, although the toll rates are slightly different.[7] The average toll is 0.5 CNY/km. We set this average value as per-km toll. Fuel tax is 30-40% in the full gasoline price, and we set the fuel tax as 2.8 CNY/liter in our paper.[8] Since the car ownership tax in China contains both a one-time purchase tax and a so-called annual vehicle and vessel tax, this tax is set as 1686 CNY/year.[9,10]

3.2 Parameters related to travel demand and car ownership demand

3.2.1 The elasticities and the demand functions

As shown in Section 2.1, we have derived consumer *i*'s car ownership decision as $\delta^{i*}=\delta^{i*}(p,f,s)$, consumer *i*'s car usage decision for commuting as $\theta^{i*}=\theta^{i*}(p,f,p_a)$, and consumer *i*'s transport demands as $x_{Hk}^{i*}=x_{Hk}^{i*}(p,f,p_a)$, $x_{Ho}^{i*}=x_{Ho}^{i*}(p,f,p_a)$, $x_{k}^{i*}=x_{k}^{i*}(p,f,p_a)$, and $x_{o}^{i*}=x_{o}^{i*}(p,f,p_a)$. According to eqs. (9)–(13), the aggregated transportation demand and car ownership demand are $X_{Hk}^{*}=\sum_i \delta^{i*}\theta^{i*}x_{Hk}^{i*}=X_{Hk}^{*}(p,f,s,p_a)$, $X_{Ho}^{*}=\sum_i \delta^{i*}\theta^{i*}x_{Hk}^{i*}=X_{Ho}^{*}(p,f,s,p_a)$, $X_{k}^{*}=\sum_i \delta^{i*}\theta^{i*}x_{k}^{i*}=N_c^{i*}x_k^{i*}=X_{k}^{*}(p,f,s,p_a)$, $X_{o}^{*}=\sum_i \delta^{i*}\theta^{i*}x_{o}^{i*}=X_{o}^{*}(p,f,s,p_a)$, $N_1^{*}=\sum_i \delta^{i*}=N_1^{*}(p,f,s)$, $N_k^{*}=\sum_i \delta^{i*}\theta^{i*}=N_k^{*}(p,f,s,p_a)$, and the total labor supply is $\sum_i L^{i*}=L^{*}(\tau)$. Since we do not

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[7] The levy standard of highways in Beijing is posted on the official website of the Beijing Municipal Commission of Transport, http://jtw.beijing.gov.cn/xxgk/jtgf/.

[8] Fuel tax details can be checked on the official website of the Ministry of Finance of the People's Republic of China http://szs.mof.gov.cn/zhengwuxinxi/zhengcefabu/201412/t20141212_1166868.html . But, each one liter of product oil, other than the original price, a 22-cent consumption tax, a 17% value-added tax and additional taxes are contained, so there is around 38%-42% fuel tax in the retail price. In 2010, average gasoline price in Beijing is 1 dollar.

[9] The car ownership tax in China contains the one-time car purchase tax and a vehicle and vessel tax, see the official site of Beijing Local Taxation Bureau, http://shiju.tax861.gov.cn/bjds/swcx/ssfgcx/index.asp. As in our assumption, for a car of 2000 cc class for a unit price of $30,000, the annual car ownership tax can be calculated on the website http://auto.sina.com.cn/calculator/.

[10] In China, the average lifespan of cars is 14.5 as the research of Hao, Wang, Ouyang and Cheng (2011) revealed. See the details in Science China Press, volume 41, 2011.

consider the endogeneity of where to live and where to work, the average distance of one-day commuting and the number of working days per year are both constant. So, the following relationship is satisfied: $N_k^* = (X_{Hk} + X_k)/\bar{m}$, where $\bar{m}$ represents the total trip length for commuting per year.

We set the aggregated indirect utility function as the following quadratic form:

$$\begin{aligned}\sum\nolimits_i^N V^i = &-[\alpha_{Hk} p + \alpha_{Ho} p + f \sum_r (\bar{l}_H \alpha_{Hr} + \bar{l}\,\alpha_r) + \alpha_{N1} s + \alpha_{Nk} p_a \\ &+ (\beta_{Hk}/2) p^2 + (\beta_{Ho}/2) p^2 + f^2 \sum_r ((\bar{l}_H \gamma_{Hr} + \bar{l}\,\gamma_r)/2) + (\eta_{N1}/2) s^2 \\ &+ (\varsigma_{Nk}/2) {p_a}^2 + pf \sum_r \gamma_{Hr} + fs \sum_r (\bar{l}_H \eta_{Hr} + \bar{l}\,\eta_r) + sp \sum_r \eta_{Hr} + p_a p \sum_r \varsigma_{Hr} \\ &+ p_a f \sum_r (\bar{l}_H \varsigma_{Hr} + \bar{l}\,\varsigma_r) + \alpha_L \tau + (\beta_L/2) \tau^2] \\ &- e_H \sum_r X_{Hr}^* - e \sum_r X_k^* - \sum_r T_{Hr}(X_{Hr}^*) X_{Hr}^* - \sum_r T_r(X_r^*) X_r^*,\end{aligned} \tag{19}$$

where e_H and e are parameters representing the welfare effect of environmental externalities including air pollution, noise, and global warming for highway and urban roads.

Equation (19) yields a linear form of transportation demand functions, the car ownership function, and total labor supply function: $X_{Hk} = \alpha_{Hk} + \beta_{Hk} p + \gamma_{Hk} f + \eta_{Hk} s + \varsigma_{Hk} p_a$ for highway in peak periods, $X_{Ho} = \alpha_{Ho} + \beta_{Ho} p + \gamma_{Ho} f + \eta_{Ho} s + \varsigma_{Ho} p_a$ for highways in off peak periods, $X_k = \alpha_k + \beta_k p + \gamma_k f + \eta_k s + \varsigma_k p_a$ for local roads in peak periods, $X_o = \alpha_o + \beta_o p + \gamma_o f + \eta_o s + \varsigma_o p_a$ for local roads in off-peak periods, $N_1 = \alpha_{N1} + \beta_{N1} p + \gamma_{N1} f + \eta_{N1} s$ for total number of cars, and $\sum\nolimits_i L^i = \alpha_L + \beta_L \tau$.[11] In this process, we have to take account of so-called integrability conditions from the demand and supply

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[11] Other forms can be assumed. Nevertheless, constant elasticity demand function is not appropriate for our model because one distortion cannot be treated properly, as shown in Morisugi and Kono (2012). In the current paper, deadweight losses arising from tax play an important role in determining the tax rates. In the linear demand function, the deadweight losses can be calculated by triangles. Actually, triangles can approximate the area of deadweight losses shaped by some nonlinear demand functions. Therefore, we use the linear form demand function. The linear form of demand can be derived from a quadratic form of utility function such as in Ottaviano et al. (2002).

functions to the aggregated indirect utility function. That is, it is necessary for us to set the parameters of the demand and supply functions which have the utility function generating the demand functions.

We calibrate the parameters in these demand functions by evaluating the price elasticities of car-related demands. For example, if we know the total highway driving demand in peak periods and highway toll rate, the gradient of highway toll in highway road driving demand function β_{Hk} can be obtained by the highway toll elasticity of highway driving distance demand. By the same mechanism, we can obtain the rest of the parameters in demand functions of X_{Hr}, X_r, and N_1. The demand function of N_k can be obtained from $N_k^* = (X_{Hk} + X_k)/\overline{m}$. We set $\overline{m}$ as Beijing's average one-day commuting distance, 19.2 km, multiplied by 245 work days (Engelfriet and Koomen, 2018). Meanwhile, because the demand functions are generated by the utility function, so an integrability condition (or the symmetry of second derivatives) must be satisfied, the parameters in these demand functions must follow certain rules as shown in Appendix D.

The number of vehicles in Beijing in 2010 is 4.809 million, and the average driving demand is evaluated as 21,161 kilometers/car per year,[12] and it is assumed that the traffic demand on highways is 18.3% of total traffic demand.[13] Based on these data, we can obtain the total traffic demand on highways in Beijing of 18,622,674,567 kilometers, and the total traffic demand on urban roads of 83,140,574,433 kilometers in 2010.

Using the integrability condition (or the symmetry of second derivative) of well-behaved utility functions (as shown in Appendix C) and the assumption that the elasticity in peak time is

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[12] See the Beijing Traffic Development Annual Report (2011).

[13] The source of this proportion is the Chinese Highway Road Trip Report by Gaode Map (in Chinese), see http://report.amap.com/download_city.do.

40% lower than that in off-peak time, we can evaluate some elasticities. We need to calibrate the parameters in the demand functions. We set the toll elasticity of the highway traffic demand in peak time and in off-peak time as -0.32 and -0.53, respectively; the toll elasticity of the urban road traffic demand in peak time and off-peak time is 0.19 and 0.32, respectively; the toll elasticity of car ownership demand is -0.06. We do not obtain the area charge elasticity of demand in Beijing because there is no area charge for vehicles entering the central area of Beijing. There are some cities, however, that do impose area charge for them, such as London, Stockholm, and Singapore. We use Singapore's area charge elasticity of travel demand in peak periods estimated by Olszewski and Xie (2005), and we set that in off-peak periods (cross elasticity of demand) as 0.01 for both highways and urban roads.

As a result, we can obtain the parameters of highway tols, fuel tax, car ownership tax, area pricing as $\beta_{\mathrm{Hk}} = -1311036290$, $\gamma_{\mathrm{Hk}} = -20484942$, $\eta_{Hk} = -63075$, and $\zeta_{Hk} = -128790$, respectively. Applying the same technique, we can calculate the remaining parameters. The demand functions by our estimation are shown in Table 2.

Table 2 here

3.2.2 Parameters of environmental externalities

It is well-known that in Beijing air pollution has become a major problem especially since car ownership began to grow in 2000. To study the social environmental externality caused by traffic, two aspects of gasoline-related pollution should be studied, one being urban air pollution, and the other being global air pollution.

The local air pollution includes particulate matter like $PM_{2.5}$ and PM_{10}, as well as carbon monoxide (CO), nitrogen oxide ($\mathrm{NO_X}$) and hydrocarbons (HC). Carbon monoxide (CO) has the effect of reducing oxygen in the bloodstream causing breathing difficulties and cardiovascular problems; nitrogen oxide ($\mathrm{NO_X}$) and hydrocarbons (HC) react in sunlight to form ozone, affecting pulmonary function in children and asthmatics and reducing visibility. Particulate matter ($PM_{2.5}$) is small enough to reach lung tissue, and studies have documented a causal relation between particle exposure and mortality (Dockery et al., 1993). The local air pollution externality $\frac{\partial v_1^{i^*}}{\partial E}\frac{\partial E}{\partial X}$ is calculated by Tong et al. (2014) with the willingness to pay method and the human capital resource method, considering mainly the human health effect. The cost of traffic-related air pollution in 2011 in Beijing is around 1516 billion CNY, equal to 0.65% of the Beijing GDP in 2011. According to Tong et al., the traffic-related local pollution externality is set as 0.078 CNY/km per car, and traffic noise externality is 9.4×10^{-4} CNY/km.[14]

The marginal cost of greenhouse gas is calculated by the cost of carbon per ton, as marginal damage from additional global warming rises with temperature level (Parry et al., 2007). An analysis by Tol (2005) suggests a current upper bound cost of $340 per ton. If we assume that a gallon of gasoline contains 0.0024 tons of carbon (National Research Council, 2002), the marginal cost of global air pollution is 0.16 CNY/liter of gasoline. We assume the fuel efficiency of an automobile on urban roads $\bar{l}$ is 10.87 km/liter, and the fuel efficiency on highways $\overline{l_H}$ is 1.5 times that on urban roads.[15] Thus, the marginal cost of global warming can be set as 0.015 CNY/km.

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[14] Meanwhile, the marginal local air pollution cost in Los Angeles is evaluated as 2.3 cents/mile (1.43 cents/km) for the year 2000 (Small & Kazimi, 1995); the marginal cost of local air pollution of Japan is set as 1.8 cents/km with a range of 1.1-2.6 cents/km by Kono, et al. (2016).

[15] This value is evaluated from the data in Kang, et al. (2015) (in Chinese) by Innovation Center for Energy and Transportation.

3.2.3 Traffic congestion externality

Each car drives on the road, which slows down the other cars. This is external cost of congestion that is not paid by the individual road user, as illustrated by Creutzig and He (2009). We apply their calculation method for congestion.

Each driver pays a constant amount for each km, reflecting fuel and other operating costs I_{fix}. Each driver values the time spent on the road. With increased road density q that is interpreted as cars per road capacity, the speed $s(q)$ decreases. The individual cost function is $I(q) = I_{\text{fix}} + n_p \text{VOT}/s(q)$, where VOT is the value of time (CNY/hour) and n_p is the average number of passengers per car. The speed is assumed to be a linear function of road density: $s(q) = \alpha - \beta q$. The higher q is, the more each additional car slows down other cars. The marginal external cost with respect to q is obtained by differentiating $I(q)$ with respect to q times q: $q dI(q)/dq = q\beta n_p \text{VOT}\left(1/s(q)\right)^2$. We calculate the marginal cost of congestion in each road type and time period. Our parameters are obtained from Creutzig and He (2009): VOT = 40.0 (CNY/hour), $n_p = 1.13$, $\alpha = 60$ for highway, $\alpha = 30$ for local roads, and the speed in the reference situation is 25 km/hour for highway in peak time, 50 km/hour for highway in off-peak time, 15 km/hour for local road in peak time, and 22 km/hour for highway in off-peak time, respectively.

3.2.4 Marginal cost of public funds in China

The marginal cost of public funds is the measurement of the deadweight loss. Liu (2009) builts a general equilibrium model to evaluate the MCF in China. By increasing major tax rates by 1%, and checking the consumer's utility and government revenue changes, MCF can be calculated. When the saving elasticity is in the range of 0-0.4, and labor supply elasticity ranges from 0 to 0.15, the MCF of labor wage tax ranges from 1.207 to 1.264. From this, for the base dataset of the current study, we choose the mean value of 1.24.[16] We set the parameters on the labor supply function so that MCF is equal to the current MCF in China by using the current average labor tax. The estimated labor supply function is determined as $\sum_i L^i = 16265.3\times10^6 - 62413.9\times10^4\tau$.

3.3 Summary of all the parameters in this study

Table 3 summarizes the parameters we use in our calculation. This includes the price/tax elasticities of car-related demands, air pollution externalities, and the value of time in Beijing.

Table 3. here

4. Optimal levels of tolls and car-related taxes in Beijing

4.1 Efficient taxation levels in different scenarios

In this section, we calculate the optimal levels of highway toll, fuel tax, car ownership tax, and area charge on vehicles entering the city center.[17] Table 4 shows the optimal values for two scenarios. Table 5 shows the impact of optimization on travel demand, external costs, and welfare.

Table 4. here

Table 5. here

In Scenario 1, we can obtain that the optimal highway toll is 0.39 CNY/km, fuel tax is 6.9 CNY/liter, car ownership should be 722 CNY/year, and area charge should be 50 CNY per car.

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[16] Compared to other forms of taxation, the labor wage tax in China is relatively high, for example, the MCF of transportation and postal service business tax is 1.184, and the MCF of light-industry add-value tax is 1.099. It means that compared to labor wage tax, the light-industry add-value tax or transportation and postal service business tax should be at higher rates to balance the tax system and reduce the tax distortion.

[17] Let $|H|$ be a bordered Hessian matrix and in the numerical simulation the Hessian is negative definite because the determinants of the bordered presenting principal minor matrices $|H_2| > 0$, $|H_3| < 0$ and $|H_4| > 0$. So, in the numerical simulation, the second order of the optimization is satisfied, and optimal solution is globally unique.

Comparing scenario 1 with the reference situation, we find that fuel tax should be more than twice as high as the reference level but car ownership tax should be lower than the reference level. In Scenario 2, to reduce the marginal cost of public funds, car ownership tax should be set at 148 CNY/year, which is substantially smaller than the reference situation. Instead, the higher highway toll and fuel tax should be set. Consequently, in both scenarios, higher fuel tax and lower car ownership tax are effective. According to Lin and Zeng (2014), who consider the MCF of labor wage tax, the optimal fuel tax in Beijing is 16.8 CNY/liter without considering multiple taxes. As we must maintain the highway traffic volume at a level high enough to prevent highway companies' revenue from falling too much, we cannot impose fuel tax at the rate estimated by Lin and Zeng (2014).

With regard to the change in travel demand, the smaller highway toll in Scenario 1 makes off-peak highway demand increase by 11%. However, because of the area pricing, highway and local road demands in peak time decrease by 28 % and 63 %, respectively. In addition, the number of cars in peak time is reduced by 56 % in Scenario 1, but it is reduced by 10 % in Scenario 2 where there is no area pricing. This means that many people commute by public transport. A different situation appears in Scenario 2, in which the peak time highway demand increases by 7.1 % and peak time local road demand decreases by 10 %. This is because there is no area pricing and car ownership tax is much less than the current rate. In the two scenarios, total number of cars is reduced by more than 20 %. As shown in Table 2, the marginal change in demand with respect to fuel tax, which is coming from the fuel tax elasticity of demand, is much larger than that with respect to the car ownership tax. Thus, the total number of cars is reduced even though the car ownership tax is reduced.

With regard to the external costs, the total external costs are reduced by 61 % in Scenario 1 and 44 % in Scenario 2. The welfare gain per car is 11400 CNY for Scenario 1 and 8300 CNY for Scenario 2. Comparing the two scenarios, welfare gain per car increases by 3000 CNY by introducing area pricing. These gains are large, so area pricing should be introduced, while simultaneously optimizing multiple policy instruments.

4.2 Sensitivity analysis

Since Beijing does not use area pricing on vehicles entering the city center, we use Singapore's area charge elasticity of both highway and local road demand in peak time. In Figure 2, we vary the elasticity, holding all other parameters at their values shown in Table 1. "X" denotes the benchmark optimal level of each instrument, which indicates the results of Scenario 1 in Table 4.

In the cases where the parameter is more than - 0.1, the optimal level of highway toll, fuel tax, and car ownership tax varies by less than 10 % from the benchmark optimal level. In all parameter values, the optimal fuel tax is between 6.7 and 6.9 CNY/liter, and the highway toll is between 0.35 and 0.4 CNY/km. This implies that the value of these instruments is robust. It is natural that area charge is the most sensitive to the parameter. The value varies between 30 and 130 CNY/entry as we cover the range of the parameter. The real values in several cities are 116 CNY/day in London (£11.5), 9.5 to 35 CNY/entry in Stockholm (10 to 35 SBK), and 0 to 14.9 CNY (0 to 3.0 SGD) in Singapore.[18] Comparing our assessment of area pricing with the real value, this value is valid.

Figure 2. here

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[18] The congestion charge levels in London, Stockholm, and Singapore are obtained from the Tristate Transportation Campaign, 2017. "Road pricing in London, Stockholm and Singapore. A way forward for New York City". We use 10.12 CNY/GBP, 0.95 CNY/SEK, and 4.97CNY/SGD in 2010.

5. Conclusions

We explored an efficient level of area pricing, considering pre-existing distortionary taxes such as highway toll, fuel tax, car ownership tax, and labor tax in Beijing; we also explored the effects of introducing the optimized area pricing on the travel demand. The importance of considering the marginal cost of public funds arising from labor wage tax is discussed by Parry & Small (2005), Bento et al. (2014), and Kono et al. (2019), among others.

Using the available parameters in Beijing, our best assessment is that the optimal level of area charge is 50 CNY/year, fuel tax is more than double and the car ownership tax is less than half its current rate, and highway toll depends on whether area pricing is implemented or not. Our model considers the interaction between the multiple policy instruments through car usage demand. According to the price elasticity of demand and the parameter estimation of demand functions, the marginal change in demand with respect to fuel tax is much larger than that with respect to the car ownership tax. This means that to control the heavy traffic congestion in Beijing and the tax distortion, higher fuel tax and the lower car ownership tax is better. Area pricing is substantially effective because the number of cars in peak time is reduced by 56 % with area pricing, but it is reduced by only 10 % without area pricing.

This study does not consider redistribution policies. Governments should consider how to balance efficient policies and redistribution 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 different categories of cars and consumer income levels, since the demand elasticity can vary between these categories, as do the optimized taxes and tolls. In the future, focus should be put on geographical characteristics within different districts. Another crucial point is that this research is limited to one city. We assume no variance in fuel consumption in our Beijing study. This leads to the problem that even in areas with different congestion levels, the fuel tax cannot vary too much due to the possibilities of arbitrage. To solve this problem, the government should impose a distance tax to control the congestion problem in the long term.

Appendix A. Car-related regulations in Beijing

In Beijing, several regulations have been implemented to restrict the growing demand for car use. Such policies include, first, driving restriction policy in 2008.[19] On each weekday, whether a vehicle may be driven or not depends on the last digit of the license plate. Driving restriction is not as effective as was intended in controlling car trips, as rule-breaking behavior is constant and pervasive (Wang, et al., 2014). Second, a diversified parking fee policy was introduced in 2011. This policy aimed to restrict parking in old districts of the city, forcing vehicles to drive outside the CBD. Some companies in the inner city offer parking subsidies to offset this restriction, which makes parking control ineffective, too. Third, purchase restriction policy[20] was implemented in 2011. Citizens must enter a lottery to win to buy a vehicle. According to Yang et al. (2014), the purchasing lottery policy cannot significantly decrease fuel consumption in Beijing.

Appendix B. Problems with constant elasticity demand functions

If we assume constant elastic demand functions, our model encounters a problem. We explain the problem using highway demand. To simplify the explanation, we suppose there are no congestion or environmental externalities (i.e., $\partial T_{Hr}/\partial X_{Hr} = 0$, $\partial T_r/\partial X_r = 0$, $\partial E_H/\partial X_H = 0$

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[19] See the details on the website of Beijing's government: http://www.beijing.gov.cn/bmfw/jtcx/zcwj/t1513910.htm (in Chinese).

[20] See the details on the website of the Chinese government: http://www.gov.cn/gzdt/2010-12/24/content_1771918.htm (in Chinese).

and $\partial E/\partial X = 0$） and no fuel tax (i.e. $f = 0$). The optimal toll condition is reduced to $-X/(X + p\, dX/dp = MCF$. If we apply a constant elastic demand (e.g.$\ln(X) = \alpha + \varepsilon_X \ln(P)$) to this condition, $-1/(1+\varepsilon_X) = MCF$. However, ε_X is constant while MCF is also exogenously constant, which implies that this optimal condition does not hold generally. Therefore, we cannot use constant elastic demand functions in our model.

Appendix C. Integrability conditions and calibration of the parameters of demand functions

To satisfy integrability conditions (i.e., in order to set the utility function which can generate the demand functions), we have

$$\frac{\partial^2 \sum_i V^i}{\partial p \partial f} = \frac{\partial^2 \sum_i V^i}{\partial f \partial p}, \text{ or } \frac{\partial \sum_r X_{Hr}}{\partial f} = \frac{\partial \sum_r (\bar{l}_H X_{Hr} + \bar{l} X_r)}{\partial p}, \text{ or } \sum_r \gamma_{Hr} = \sum_r (\bar{l}_H \beta_{Hr} + \bar{l}\beta_r), \tag{A2}$$

$$\frac{\partial^2 \sum_i V^i}{\partial f \partial s} = \frac{\partial^2 \sum_i V^i}{\partial s \partial f}, \text{ or } \frac{\partial \sum_r (\bar{l}_H X_{Hr} + \bar{l} X_r)}{\partial s} = \frac{\partial N_1}{\partial f}, \text{ or} \sum_r (\bar{l}_H \eta_{Hr} + \bar{l}\eta_r) = \gamma_{N1}, \tag{A3}$$

$$\frac{\partial^2 \sum_i V^i}{\partial p \partial s} = \frac{\partial^2 \sum_i V^i}{\partial s \partial p} \text{or } \frac{\partial \sum_r X_{Hr}}{\partial s} = \frac{\partial N_1}{\partial p}, \text{ or } \sum_r \eta_{Hr} = \beta_{N1}, \tag{A4}$$

$$\frac{\partial^2 \sum_i V^i}{\partial p \partial p_a} = \frac{\partial^2 \sum_i V^i}{\partial p_a \partial p}, \text{ or } \frac{\partial \sum_r X_{Hr}}{\partial p_a} = \frac{\partial N_c}{\partial p}, \text{ or } \sum_r \varsigma_{Hr} = \beta_{Nc}, \tag{A5}$$

$$\frac{\partial^2 \sum_i V^i}{\partial f \partial p_a} = \frac{\partial^2 \sum_i V^i}{\partial p_a \partial f}, \text{ or } \frac{\partial \sum_r (\bar{l}_H X_{Hr} + \bar{l} X_r)}{\partial p_a} = \frac{\partial N_c}{\partial f}, \text{ or} \sum_r (\bar{l}_H \varsigma_{Hr} + \bar{l}\varsigma_r) = \gamma_{Nc}, \tag{A6}$$

where $r \in \{k, o\}$.The other parameters of the demand functions are derived by using eqs. (A7)–(A9).

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

$$\begin{cases} l_H \cdot E_f^{X_H} \cdot \frac{X_H}{f} + l \cdot E_f^{X} \cdot \frac{X}{f} = E_f^{F} \cdot \frac{F}{f} \\ E_f^{X_H} \cdot \frac{X_H}{f} + E_f^{X} \cdot \frac{X}{f} = E_f^{VMT} \cdot \frac{X_H + X'}{f} \end{cases} \qquad (A7)$$

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

$$\begin{cases} l_H \cdot E_p^{X_H} \cdot \frac{X_H}{p} + l \cdot E_p^{X} \cdot \frac{X}{p} = E_f^{X_H} \cdot \frac{X_H}{f} \\ E_p^{X_H} \cdot \frac{X_H}{p} + E_p^{X} \cdot \frac{X}{p} = E_p^{VMT} \cdot \frac{X_H + X}{p} \end{cases} \cdot \qquad (A8)$$

We assume that the ratio of traffic growth rate on highways and urban roads, X_H/X, is fixed mainly because we cannot sufficiently forecast the growth rates separately. As a result, we can calculate the car ownership tax elasticity of highway traffic demand $E_s^{X_H}$ and urban road traffic demand E_s^{X} based on (A7).

$$\mathrm{E_s^{X_H}} = \mathrm{E_s^{X}} = \mathrm{E_f^{N_1}} \cdot \frac{\mathrm{N_1}}{\mathrm{f}} \cdot \frac{\mathrm{s}}{\mathrm{F}}. \qquad \text{(A9)}$$

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

$$\begin{aligned} &ln(\,number\ of\ cars\ per\ capita\,) = \alpha + \beta\, ln(\,real\ GDP\ per\ capita) \\ &\eta\, ln(\,car\ price\ index\,) + \lambda\, ln(consumer\ mind\ index). \end{aligned} \qquad (A10)$$

Table A2 Estimation of car price elasticity of car demand

	Coefficients	Standard Error	t-value	P-value
Intercept	1.4146268	4.69	0.304	0.770
$real\ GDP\ per\ capita$	0.35821941	0.155	2.32	0.0536
$car\ price\ index$	-0.732729	0.413	-1.774	0.119
$consumer\ mind\ index$	-0.3661433	0.629	-0.582	0.579

Regression Statistics	
Adjusted R Square	0.971
Observations	11

Car ownership tax elasticity of car ownership demand is -0.006 under the assumption that the annual car ownership tax in Beijing is 249 dollars a year and the price of a car is 30,000 dollars.

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Table 1. **Policy instruments**

		Highway		Local road	
	taxes for all car users	Peak	Off-peak	Peak	Off-peak
Peak time area pricing		p_a	-	p_a	-
Highway toll		p	p	-	-
Fuel tax	F				
Car ownership tax	S				

Table 2. Parameters in linear demand functions

	Toll p	Fuel tax f	Car owner tax S	Area charge p_a	Intercept
X_{Hk} (Highways, peak)	-13110.4×10^5	-20484.9×10^3	-63075	-128790	30848.6×10^5
X_{Ho} (Highways, off-peak)	-17568.6×10^6	-27229.0×10^4	-510338	98305	26815.6×10^6
X_k (Local roads, peak)	34752.8×10^5	-39194.8×10^4	-281599	-574981	89800.6×10^5
X_o (Local roads, off-peak)	47356.9×10^6	-52853.7×10^5	-22784.0×10^2	438879	68217.1×10^6
N_1 (Total number of cars)	-573413	-270678	-29	-	59017.0×10^2

Table 3. Summary of parameters

Parameters	Value	Source
Local air pollution externalities (CNY/km)	0.078	Tong et al. (2014)
Global air pollution externalities (CNY/km)	0.015	Tol. (2015)
Average fuel efficiency on highways (km/liter)	16.35	Kang et al. (2015)
Average fuel efficiency on urban roads (km/liter)	10.87	Kang et al. (2015)
MCF of labor wage tax	1.207-1.26	Liu (2009)
Average driving demand per car (km)	21,161	Annual report 2011
Car ownership in Beijing (million)	4.809	Annual report 2011
Value of time (CNY/hour)	40.0	Creutzig & He (2009)
Average labor wage tax (cents/hour)	62.4	Estimated from Beijing Local Taxation Bureau.[21]
Fuel tax elasticity of fuel consumption	-0.172	Lin & Zeng (2014)
Fuel tax elasticity of car ownership	-0.158	Lee & Kang (2015)
Fuel tax elasticity of total traffic distance	-0.164	Lee & Kang (2015)
Car ownership tax elasticity of car ownership	-0.01	Our estimation
Highway toll elasticity of total traffic distance	-0.30	Fu & Gu (2017)
Area charge elasticity of peak time highway demand	-0.106	Olszewski & Xie (2005)
Area charge elasticity of off-peak time highway demand	0.01	Our assumption
Area charge elasticity of peak time urban road demand	-0.106	Olszewski & Xie (2005)
Area charge elasticity of off-peak time urban road demand	0.01	Our assumption

* The exchange rate is set as 6.77 CNY/USD in 2010.

Table 4. Optimal level of multiple policy instruments

	Reference (Present level)	1) Simultaneous optimization	2) Without area Pricing
Marginal cost of public funds		1.24	1.24
Highway toll (CNY/km)	0.5	0.39	0.55
Fuel tax (CNY /liter)	2.8	6.9	7.7
Car ownership tax (CNY/year)	1686	722	148
Area charge (CNY/entry)	-	50	-

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[21] The average annual working time in Beijing is 2318.95 hours, working population is 5,876,526 in 2010, and the total labor wage revenue is 8.51 billion dollars in 2010.

Table 5. The impact of optimization on travel demand, external costs, and welfare

	Reference (Present level)	1) Simultaneous optimization	2) Without area pricing
Marginal cost of public funds		1.24	1.24
Travel demand (km/car/year)		Percentage change w.r.t. reference level	
Peak highway	426	- 28 %	7.1 %
Off-peak highway	3446	11 %	- 9.9 %
Peak local road	1902	- 63 %	- 14 %
Off-peak local road	15387	- 30 %	- 28 %
Number of total cars (millions)	4.8	- 21 %	- 27 %
Number of cars in peak periods (millions)	2.6	- 56 %	- 10 %
External costs (10^6 CNY/year): air pollution + greenhouse gas emissions + noise + congestion			
Peak highway	5377	- 71 %	40 %
Off-peak highway	4554	- 9.0 %	- 30 %
Peak local road	28417	- 94 %	- 43 %
Off-peak local road	62233	- 50 %	- 53 %
Total	100582	- 61 %	- 44 %
Speed (km/h)			
Peak highway	25	35	23
Off-peak highway	50	52	53
Peak local road	15	24	17
Off-peak local road	22	24	24
Welfare gain (10^3 CNY/car/year)		11.4	8.3

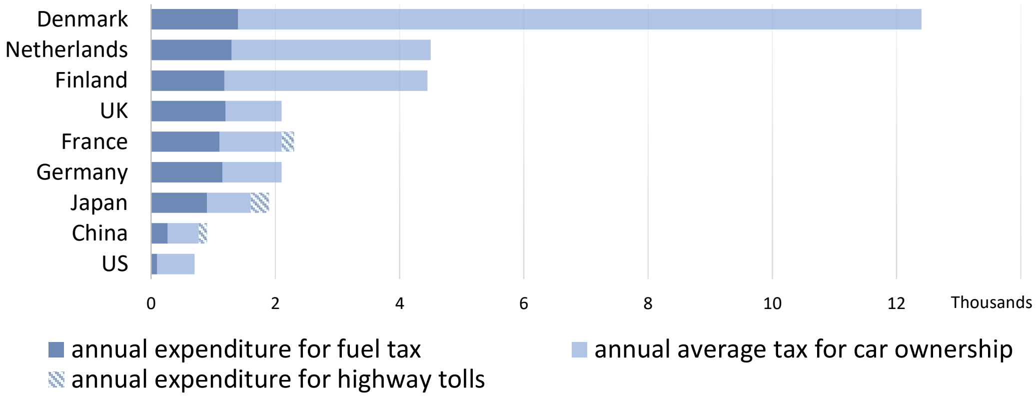

Figure 1. Annual car expenditure on taxes and tolls ($/year) (Ministry of Finance, Japan, 2011; data on China and highway tolls added by the authors)

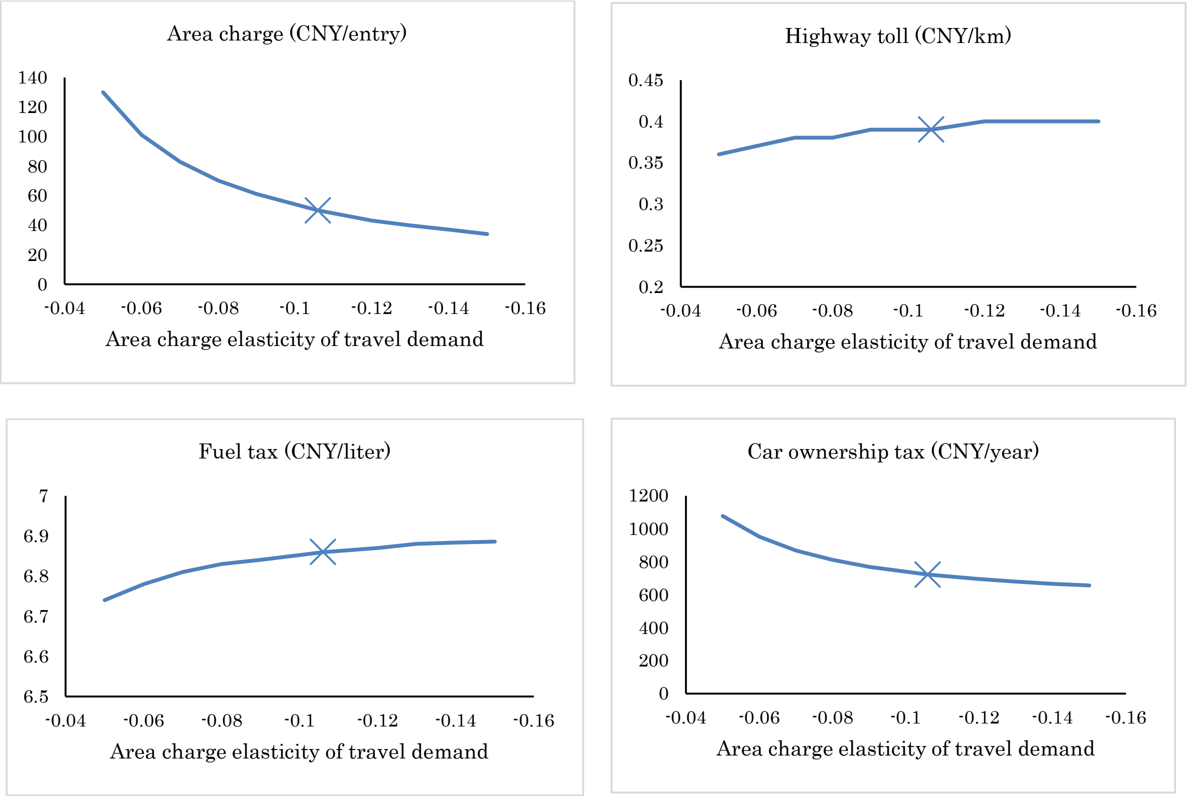

Figure 2. Sensitivity of optimal policy instruments to parameter variation