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Tradable Credits Scheme on Urban Travel Demand: A Linear Expenditure System Approach and Simulation in Beijing

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Abstract

Using a linear expenditure system (LES) approach, we investigate the influences of a new mobility management measure, a tradable credits scheme (TCS), on the pattern of daily trips measured in kilometres. Generally, we assume that an individual's travel consists of a car mode and a non-car mode. The effects of the TCS are discussed from a microeconomic perspective and using a scenario simulation study for the municipality of Beijing. Whilst other research has shown that travellers trade their credits and are generally inclined to non-car mode, the implementation of the tradable credits scheme demonstrated here is that travellers are likely to restrain their use of both car and non-car travel modes. Furthermore, both car and non-car mode trips are shown to be price inelastic, whilst the cross-price elasticity for different districts demonstrates a complementary relationship between car and bus modes.

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1. Introduction

Urban transport is a fast growing sector in the modern world, playing a major role in the quality of life for individuals and in regional development. However, the presence of negative externalities in the road transport sector such as congestion and vehicle emissions (Santos, et al. (2010)), have generated a series of social, economic and environmental challenges. A steady increase in urbanisation and motorisation can also be observed as a trend in many developing countries. As a result, policies and actions to solve or mitigate negative externalities that arise

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from fast urbanisation are urgently needed. In this paper, we consider how a tradable credits scheme could help a city or urban area to achieve a target for a reduction in travel using the private car mode.

In order to avoid a progression towards an increasingly car-oriented society, there is a need to address the perception in some cultures of the car as a status symbol which people should aspire towards. A further issue is how to influence the mode choice of travellers and how to restrain the growing demand for car related travel. There are some direct ‘push’ mechanisms, such as ‘command and control’ policies including controls on car ownership (e.g., a quota system for new vehicle plates in Singapore, Chin and Smith (1997)), the driving ban scheme in Mexico City (Davis, 2008)), road pricing (Yang and Bell, 1997; Yang and Huang, 2005), hybrid rationing and pricing policies (Daganzo, 1994) and taxation (Ribbink, Riel and Semeijn, 2006). There are also ‘pull’ mechanisms, such as prioritising the development of public transport and encouraging people to choose mass transit systems (Xu et al., 2010), reward measures (Ben-Elia and Ettema, 2011) and tradable credits schemes (Akamatsu, 2007; Yang and Wang, 2011; Grant-Muller and Xu, 2014).

The tradable credits scheme (TCS) is a ‘pull’ mechanism that has evolved over a relatively long period, particularly in relation to pollution control where it has been well studied and used in practice. In the transport sector, there are no wide-scale implementations of such a scheme in the world to date though, apart from the following four specific case studies (Fan and Jiang, 2013): credit-based congestion pricing (CBCP) in Austin (USA), a tradable driving day rights scheme (TDDR) in Mexico City (Mexico), the Genoa mobility rights trial (GMR) in Genoa (Italy), and a tradable driving rights trial (TDR) in Lyon (France). A recent, related hypothetical case study by Mamum et al. (2013) built on empirical data from Florida. It considered the regulation of vehicle miles travelled and compared socioeconomic impacts of three market-based measures including gasoline tax, mileage fee and tradable mobility credits.

There are many factors influencing travellers’ mode choice, e.g., travel cost, travel purpose, level of service of public transport, age, education, employment, etc., and there have been a number of studies in this field taking a disaggregate approach, e.g., Ben-Akiva and Lerman (1985), Dijst et al. (2002), Hensher and Rose (2007), Ho and Mulley (2013), Chidambaram et al. (2014), Habib and Weiss (2014)). From the perspective of transport authorities and decision makers, transport policy plays a crucial role in influencing travellers’ mode choice.

In this study, we investigate a fundamental transport policy question with a modelling approach, that is, how a tradable credits scheme is likely to affect travelers’ mode choice if it were implemented in practice. Different existing studies with TCS, e.g., the bottleneck model approach to travel choices in rush hour with TCS (Nie and Yin, 2013), and the bottleneck model approach to congestion management and modal split with heterogeneous users with TCS (Tian, Yang and Huang, 2013), we develop a modelling framework with LES to study the impacts of TCS on travelers’ mode choices. Specifically, we investigate how the number of vehicle kilometers travelled (VKT) may be influenced by implementing a tradable credits scheme. The study supposes that a regional authority is responsible for implementing the tradable credits scheme, the initial credit allocation is free and individuals receive a number of credits (representing vehicle-kilometers) based on a target to reduce the total VKT for the urban area. In maximizing their utility, individuals must consider their choice of travel mode in the light of their credit allocation. Each individual must consider the permitted number of kilometres and the credit price (p_e), then determine how many further credits they should purchase if they wish to travel additional kilometres using a car.

To investigate the influence of a TCS on car trips we present a simulated policy scenario based on a linear expenditure system (LES) approach to individuals’ mobility. Individuals’ travel choices are assumed to consist of car mode and non-car modes, which are assumed to be complementary relationship. The theoretical concept behind the proposed TCS and the state of art related to this measure are discussed in this paper. The number of VKT is compared before and after the introduction of the TCS. A fundamental difference with previous studies of tradable credits schemes, which are considered to be a comparative measure to road pricing, is that this study is based on influencing the number of VKT by individuals for the purpose of urban mobility management.

The paper is structured as follows. In Section 2, a literature review concerning TCS studies and the appropriateness of a LES approach for transport analysis are presented. In Section 3, a LES approach to individual trips both with and without a tradable credits scheme is proposed and a theoretical analysis based on price elasticities and cross-price elasticities is also presented. In Section 4, two simulated scenarios of individual daily trips (based on the LES model) with and without a tradable credits scheme are demonstrated. In Section 5, the approach is illustrated using 2010 census data for Beijing municipality, whilst the paper concludes in Section 6.

2. Literature Review

2.1 A TCS for mobility management

The state-of-the-art concerning the development of the TCS can be traced back to the economic theory of pollution permit markets on external costs. Later, Dales (1968) demonstrated that the introduction of tradable credits could promote water quality management at lower cost than other mechanisms. The credit allocation mechanism has been further applied in a variety of different contexts including controlling air pollution, the degradation of wetlands, agricultural pollution, water scarcity and fisheries depletion (OECD, 2004). Examples include an oligopolistic power market model with tradable NO_x permits (Chen and Hobbs, 2005), biodiversity conservation with tradable credits (Drechsler and Watzold, 2009), Nitrates control in groundwater (Morgan et al, 2000), regulation of an airline duopoly on a congested airport (Verhoef, 2010), emission reduction from air transport (Mendes and Santos, 2008), incorporating the transport sector into a carbon cap-and-trade program (Ellerman et al., 2006, Millard-Ball, 2008; Jochem, 2008), pollution permits to reduce car ownership in the UK (Walton, 1997) and land use management (Henger and Bizer, 2010). Further elaboration of some key issues in using tradable credit schemes for road traffic congestion management, (including general characteristics, implementation actors and processes, transaction costs, likely impacts and finally, interactions with other policies) is given in Grant-Muller and Xu (2014).

Recent investigations of TCS for mobility management, for example Yang and Wang (2011), have discussed the management of road network mobility with TCS. They demonstrate that the most desirable network flow patterns (including socially optimum, Pareto-improving, revenue-neutral and side-constrained traffic flow patterns) can be arrived at with the appropriate distribution of credits among travellers and the correct selection of link specific rates. Wang et al. (2012) extend their work, considering heterogeneous travellers with different values of time and proposing a variational inequalities (VI) formulation with a tradable credit scheme, user equilibrium (UE) and market equilibrium (ME) conditions. They also discuss how to decentralise system optimal and Pareto-improving traffic flow patterns with appropriately designed TCS. Bulteau (2012) proposed a neo-classical microeconomics approach, with the constant elasticity of substitution (CES) utility function in microeconomic analysis to deal with the feasibility of a tradable emission permit system for urban motorists. The CES form of utility function allows several situations to be considered, which depends on the parameters. Wu et al. (2012) studied the mechanisms to achieve better equity under congestion-mitigation policies (i.e., congestion pricing and tradable credits scheme). They adopted a mathematical formulation with equilibrium constraints, considered income effect on travellers' choices of trip generation, mode and route on multimodal transportation networks, and explicitly captured the distributional impacts of congestion pricing and the tradable credits scheme on different income and geographic groups. For further recent studies on the TCS for travel behaviour analysis, see for example Nie and Yin (2013), Tian, Yang and Huang (2014), Bao et al. (2014), Wang et al. (2014), and Xu and Grant-Muller (2015).

2.2 The appropriateness of a LES approach

Whilst not often used in a transport context, the linear expenditure system (LES) is a system of demand functions originally suggested by Klein and Rubin (1947) and estimated/derived by Stone (1954), which usually possesses desirable properties from the standpoint of elementary economic theory, e.g., to consider traveller's responses to cost or price. The LES was first proposed as a system to investigate the pattern of demand for consumer goods (including transport) using annual data for the UK from 1920-1938 (Stone, 1954). The method has been widely applied to estimate the demand for municipal public services (Bergtrom and Goodman, 1973), consumer demand in environmental analysis (Aasness and Holtmark, 1993), estimating the costs of raising a child (Griffiths and Valenzuela, 2001), estimating elasticities of demand for various goods and services generated by domestic and foreign tourists in Australia (Divisekera, 2007), welfare analysis for Africa (Shimeles, 2010) and the expenditure income effects behind structural transformation (Herrendorf, Rogerson, and Valentinyi, 2011).

The ability of the model to allow for the joint presence of non-discretionary and discretionary elements in consumer behaviour lends this approach to transport demand modelling. Most households have a minimum (required) level of transport for essential activities such as access to education, employment and retail consumption. A further level of transport demand arises for discretionary activities, which may include leisure and social purposes. Moreover, within a fixed budget there may be trade-offs between travel and non-travel categories, with

the potential to reduce the number of trips taken. This rationale was the basis on which Gaudry and Dagenais (1979) adopted an LES-inspired approach to the development of the DOGIT model, an extension of a logit approach for transport demand. A direct application of LES to the demand for transport within household consumer demand, and specifically to represent the choices between alternative modes, was used by Aasness and Hollsmark (1993). They constructed a three-tier hierarchical consumer demand model that included an LES sub-model for public vs private transport modes. In this paper we similarly draw on the ability of the LES to represent an element of discretionary choice above a non-discretionary level of demand in the design of the TC scheme.

3. Methodology

3.1 Linear expenditure system (LES)

We consider two travel modes: the car mode, A , measured according to daily kilometres (unit: kilometre), and non-car modes, X , which represents the daily kilometres expenditure on all other non-car modes (km). Average car costs (per car and per kilometre travelled) consist of maintenance costs, fuel and insurance and are denoted as p_A . The average non-car mode cost (measured per kilometre) is p_X . The quantities A and X are arguments of a direct utility function, both yielding positive marginal utility:

$$U = U(A, X) \quad (1)$$

Assuming that for the car mode and non-car modes there exists a given external parameter, γ_i , (or subsistence consumption as it is referred to in economics (Steger, 2000)) and there is no utility generation below γ_i .

Utility maximization *per capita* for the car mode and non-car modes can therefore be formulated as

$$\text{Max } U(A, X) = \beta_1 \ln(A - \gamma_1) + \beta_2 \ln(X - \gamma_2) \quad (2)$$

s.t.

$$p_A A + p_X X = Y \quad (3)$$

$$A \geq \gamma_1, X \geq \gamma_2 \quad (4)$$

The associated Lagrangian function is then:

$$L = \beta_1 \ln(A - \gamma_1) + \beta_2 \ln(X - \gamma_2) - \lambda(p_A A + p_X X - Y) + \mu_A(A - \gamma_1) + \mu_X(X - \gamma_2)$$

The first order optimal conditions are given by:

$$\frac{\partial L}{\partial A} = \beta_1 \frac{1}{A - \gamma_1} - \lambda p_A + \mu_A \geq 0 \quad (5)$$

$$\frac{\partial L}{\partial X} = \beta_2 \frac{1}{X - \gamma_2} - \lambda p_X + \mu_X \geq 0 \quad (6)$$

$$A \left(\beta_1 \frac{1}{A - \gamma_1} - \lambda p_A + \mu_A \right) = 0 \quad (7)$$

$$X \left(\beta_2 \frac{1}{X - \gamma_2} - \lambda p_X + \mu_X \right) = 0 \quad (8)$$

$$\mu_A(A - \gamma_1) = 0 \quad (9)$$

$$\mu_X(X - \gamma_2) = 0 \quad (10)$$

$$p_A A + p_X X = Y \quad (11)$$

$$\lambda \geq 0; \mu_A \geq 0; \mu_X \geq 0 \quad (12)$$

$$A \geq 0; X \geq 0 \quad (13)$$

Therefore,

$$A = \gamma_1 + \frac{\beta_1 p_X}{\beta_2 p_A} (X - \gamma_2) \quad (14)$$

$$X = \gamma_2 + \frac{\beta_2 p_A}{\beta_1 p_X} (A - \gamma_1) \quad (15)$$

Furthermore, from $\beta_1 + \beta_2 = 1$, we have

$$p_A A = \beta_1 Y + \beta_2 p_A \gamma_1 - \beta_1 p_X \gamma_2 = \beta_2 p_A \gamma_1 + \beta_1 (Y - p_X \gamma_2) \quad (16)$$

$$p_X X = \beta_2 Y - \beta_2 p_A \gamma_1 + \beta_1 p_X \gamma_2 = \beta_1 p_X \gamma_2 + \beta_2 (Y - p_A \gamma_1) \quad (17)$$

Therefore,

$$A = \beta_2 \gamma_1 + \frac{\beta_1}{p_A} (Y - p_X \gamma_2) \quad (18)$$

$$X = \beta_1 \gamma_2 + \frac{\beta_2}{p_X} (Y - p_A \gamma_1) \quad (19)$$

Here the parameter β_1 can be interpreted as the marginal budget used for the car mode, β_2 is the marginal budget

used for non-car modes. The parameter γ_1 represents the fundamental level of trips the individual requires using the car mode (km), whilst γ_2 is the minimum level of non-car mode trips. The quantity $[Y - (p_A\gamma_1 + p_X\gamma_2)]$ represents individual discretionary transport budget or individual supernumerary transport budget in this research and satisfies $Y \geq p_A\gamma_1 + p_X\gamma_2$.

Concerning the mode, in equations (2-4) we consider a simplified LES where an individuals' travel consists of either the car mode or a non-car mode. Under this framework a minimum level of travel by each mode (car mode and non-car modes) is assumed, irrespective of the price of the mode or the individual transport budget, Y . Therefore each traveller has a minimum level of use for each mode (given as γ_1 and γ_2). The individual transport budget Y , is then allocated according to a choice between β_1 and β_2 for the two available travel modes.

Before a discussion of the properties of the LES approach for an individuals' pattern of mode choice, we assume the marginal consumption for the car mode and non-car modes is active, i.e. $\beta_1 > 0$, $\beta_2 > 0$. Furthermore, we assume that both modes operate normally, that is, travellers consume both car travel and non-car travel as goods, and these two goods are normal goods in economics sense. This can be represented mathematically by $\frac{dA}{dY} > 0$ and $\frac{dX}{dY} > 0$.

In economics, elasticity is a convenient summary measure for the effect of one explanatory variable on quantity (for all else held constant). The price elasticity of demand, which is generally known as the price elasticity, measures the demand rate of response for a quantity or service resulting from a price change (Arnold, 2008). If the price elasticity is unit this implies that the demand is unit elastic, whilst if the price elasticity is greater than 1 then demand is price elastic (i.e., demand is sensitive to price changes). If the price elasticity is less than 1, then the demand is price inelastic (i.e., demand is not sensitive to price changes), whilst if the price elasticity is zero, it implies that price changes have no effect on the quantity demanded.

We then have the following properties according to the models (2-4):

Proposition 1. The price elasticity is always less than 1.

From Eqs. (14) and (15) we have

$$\frac{dA}{dp_A} = -\frac{\beta_1}{p_A^2}(Y - p_X\gamma_2) \quad (20)$$

$$\frac{dX}{dp_X} = -\frac{\beta_2}{p_X^2}(Y - p_A\gamma_1) \quad (21)$$

Combining Eqs. (16) and (17), we have the price elasticity for the car mode and non-car modes:

$$E_{AA} = -\frac{dA}{dp_A} \frac{p_A}{A} = \frac{\beta_1(Y - p_X\gamma_2)}{\beta_2 p_A \gamma_1 + \beta_1(Y - p_X\gamma_2)} < 1 \quad (22)$$

$$E_{XX} = -\frac{dX}{dp_X} \frac{p_X}{X} = \frac{\beta_2(Y - p_A\gamma_1)}{\beta_1 p_X \gamma_2 + \beta_2(Y - p_A\gamma_1)} < 1 \quad (23)$$

Therefore trips by both car and non-car modes are price inelastic.

Proposition 2. The travel modes (car mode and non-car modes) are complementary.

In economics the cross elasticity of demand (or cross-price elasticity of demand) measures the responsiveness of the demand for a good to a change in the price of another good (Bordley, 1985). Here, we define the cross-price elasticity for car trips with respect to the price of non-car modes as:

$$E_{AX} = \frac{dA}{dp_X} \frac{p_X}{A} = \frac{-\beta_1 p_X \gamma_2}{\beta_2 p_A \gamma_1 + \beta_1(Y - p_X \gamma_2)} < 0 \quad (24)$$

The cross-price elasticity measures the responsiveness of car trips to a change in the price of non-car modes. While travellers can take trips by the car mode and non-car modes, a negative cross elasticity in Eq. (24) means that the car mode and non-car modes are complements, that is, an increase (or decrease) in the demand for car trips is caused by an increase (or decrease) in the demand for non-car trips. The car mode and non-car modes are therefore not in a substitution relationship (generally, we can assume a substitution relationship if the trips by one mode decrease and the trips by another mode increase) and this should be noted in the following policy simulation and analysis.

Besides the modelling and initial investigation in this subsection, we have two notes as follows:

Note 1: Eqs (18) and (19) are valid only if both demands of car mode and non-car mode are strictly positive (both car mode and non-car mode are used). Theoretically, there are two corner solutions: (i) only car mode is used (with $X = 0$); (ii) only non-car mode is used with $A = 0$. Under case (i), the car trips can be determined by $A = \frac{Y}{p_A}$. Under case (ii), the non-car mode can be determined by $X = \frac{Y}{p_X}$.

3.2 The LES for a tradable credits scheme

At this point we consider a tradable credits scheme. Let p_e be the price of tradable credits and \bar{A} is the number of credits initially distributed. The total number of credits is equal to the total permitted number of kilometres. Therefore, the utility maximization problem with a tradable credits scheme becomes

$$\text{Max } U(A, X) = \beta_1 \ln(A - \gamma_1) + \beta_2 \ln(X - \gamma_2) \quad (25)$$

s.t.

$$p_A A + p_e(A - \bar{A}) + p_X X = Y \quad (26)$$

$$A \geq 0, X \geq 0 \quad (27)$$

From the utility maximization problem (25-27), we have

$$A = \beta_2 \gamma_1 + \frac{\beta_1}{p_A + p_e} (Y + p_e \bar{A} - p_X \gamma_2) \quad (28)$$

$$X = \beta_1 \gamma_2 + \frac{\beta_2}{p_X} [Y + p_e \bar{A} - (p_A + p_e) \gamma_1] \quad (29)$$

The price elasticity with respect to car mode and non-car modes is given by:

$$E1_{AA} = - \frac{dA}{d p_A} \frac{p_A}{A} = - \frac{\beta_1 p_A (Y + p_e \bar{A} - p_X \gamma_2)}{A (p_A + p_e)^2} \quad (30)$$

$$E1_{Ae} = - \frac{dA}{d p_e} \frac{p_e}{A} = - \frac{\beta_1 p_e (p_A \bar{A} + p_X \gamma_2 - Y)}{A (p_A + p_e)^2} \quad (31)$$

Comparing Eqs. (30-31) (the presence of a tradable credits scheme), and Eqs. (22-23) (the absence of a tradable credits scheme), the price elasticity will be variant if a tradable credits scheme applies.

$$E1_{XX} = - \frac{dX}{d p_X} \frac{p_X}{X} = \frac{\beta_2 [Y + p_e \bar{A} - (p_A + p_e) \gamma_1]}{\beta_1 p_X \gamma_2 + \beta_2 (Y - p_A \gamma_1)} = 1 + \frac{p_e (\beta_2 \bar{A} - \gamma_1) - \beta_1 p_X \gamma_2}{\beta_1 p_X \gamma_2 + \beta_2 (Y - p_A \gamma_1)} \quad (32)$$

Furthermore, it is clear that the implementation of the tradable credits scheme does change the complementarity relationship between the car mode and non-car modes, as shown in Proposition 2. This can be derived from the following Eq. (33):

$$E1_{AX} = \frac{dA}{d p_X} \frac{p_X}{A} = \frac{-\beta_1 p_X \gamma_2}{\beta_2 (p_A + p_e) \gamma_1 + \beta_1 (Y + p_e \bar{A} - p_X \gamma_2)} < 0 \quad (33)$$

From Eqs (30-32), it can be seen that the tradable credits scheme affects the price elasticities of car mode and non-car modes. However, it still retains a complementary relationship between car mode and non-car modes, seen by the negative cross elasticity in Eq. (33).

3.3 Further derivation

To estimate the daily trips by car mode and non-car modes with and a without tradable credits scheme, theoretically these can be calculated based on Eqs. (18-19) (without a tradable credits scheme) and Eqs. (28-29) (with a tradable credits scheme). However, these equations are dependent on a series of parameters, i.e., the subsistence consumption for the car mode γ_1 , the subsistence consumption for the non-car modes γ_2 , the price for the car mode p_A , the price for the non-car modes p_X , the marginal budget used for car mode β_1 , the marginal budget used for non-car modes β_2 and the individuals' transport budget Y . The exact estimation of these parameters is difficult, as in most cases the required data are unavailable or incomplete.

The subsistence consumption for the car mode γ_1 and the non-car use modes γ_2 are difficult to calibrate directly. However these directly affect the daily trips by car mode and non-car modes. Without a loss of generality, we assume that

$$\gamma_1 = f_1(A, X, \beta_1, p_A, Y, \varphi) \quad (34)$$

$$\gamma_2 = f_2(A, X, \beta_2, p_X, Y, \omega) \quad (35)$$

where φ and ω are exogenous parameters and are estimated from case studies.

Under the case of not introducing a tradable credits scheme, we can combine Eqs. (18-19) and Eqs. (34-35),

$$A = \beta_2 f_1(A, X, \beta_1, p_A, Y, \varphi) + \frac{\beta_1}{p_A} [Y - p_X f_2(A, X, \beta_2, p_X, Y, \omega)] \quad (36)$$

$$X = \beta_1 f_2(A, X, \beta_2, p_X, Y, \omega) + \frac{\beta_2}{p_X} [Y - p_A f_1(A, X, \beta_1, p_A, Y, \varphi)] \quad (37)$$

Under the case of introducing a tradable credits scheme, then combining Eqs. (28-29) and Eqs. (34-35) we have

$$A = \beta_2 f_1(A, X, \beta_1, p_A, Y, \varphi) + \frac{\beta_1}{p_A + p_e} (Y + p_e \bar{A} - p_X f_2(A, X, \beta_2, p_X, Y, \omega)) \quad (38)$$

$$X = \beta_1 f_2(A, X, \beta_2, p_X, Y, \omega) + \frac{\beta_2}{p_X} [Y + p_e \bar{A} - (p_A + p_e) f_1(A, X, \beta_1, p_A, Y, \varphi)] \tag{39}$$

The existence of an equilibrium solution to the Eqs. (36-37) and Eqs. (38-39) can be guaranteed by Brouwer’s fixed-point theorem and a solution can be calculated iteratively using Newton’s method for complex cases (Karamadian, 1977).

4. Scenario simulations

Based on the models in Section 2, there are two possible approaches for the simulation of policy scenarios. If the subsistence consumption for the car mode γ_1 and non-car modes γ_2 can be calibrated directly, we can use Eqs.(18-19) and (28-29) for a comparative analysis i.e. between the case with and without a tradable credit scheme. When the estimation of γ_1 and γ_2 through survey data becomes difficult, we can estimate daily trips for the car mode and non-car modes based on Eqs. (36-39). The two scenario simulation processes are presented in Figure 1.

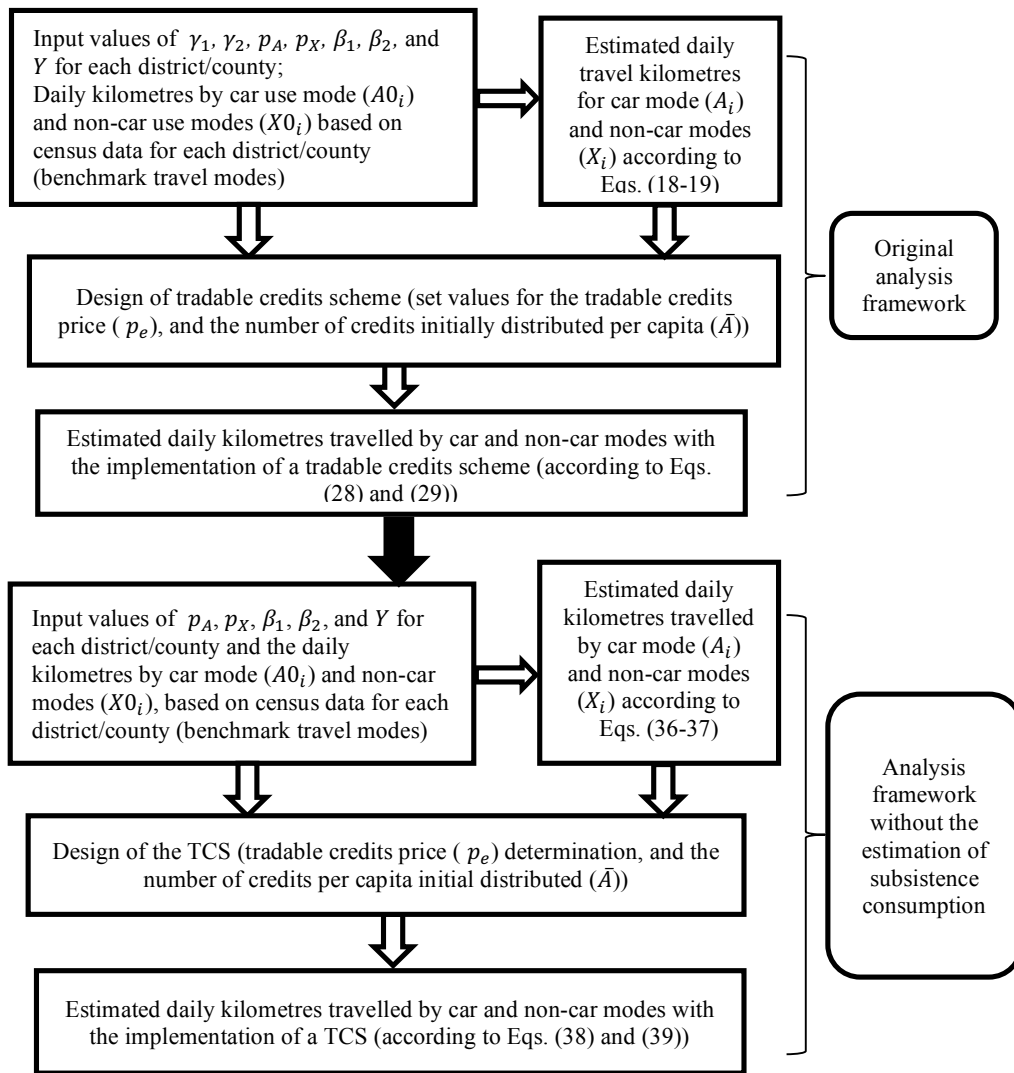


Figure1 Daily travel scenarios simulation with respect to travel modes

Supposing the city/region studied can be separated into N districts/counties, and each district is represented by the

suffix i , $i = 1, \dots, N$. We can firstly estimate the daily travel distance per person and per district centroid for the car mode (A_i) and non-car mode (X_i) based on the parameters in each district and according to Eqs. (18-19). Then, we set the benchmark travel by each mode (daily distance travelled by car and non-car modes) per person in each zone using, for example, historical census data. The daily kilometres by car and non-car modes are represented as $A0_i$ and $X0_i$ ($i = 1, \dots, N$) respectively.

In general, the estimated daily distance travelled by modes (A_i and X_i) are dependent on the parameters γ_1 , γ_2 , p_A , p_X , β_1 , β_2 and Y , as shown in Eqs. (18-19). Alternative methodologies exist in public economics to calibrate the parameters based on the availability of data (see for example, Binet (2013) for an application to municipal public expenditure). We can compare the estimated daily average distance travelled by A_i and X_i with the benchmark figure, i.e. $A0_i$ and $X0_i$ for each district/county. The calibrated parameters (i.e., γ_1 , γ_2 , p_A , p_X , β_1 , β_2 , and Y) can be retained with the updated daily average travel distance from the introduction of the tradable credits scheme. The determination of the benchmark daily travel distance for the modes studied is therefore critical for the evaluation of the tradable credits scheme, given it directly affects the parameters γ_1 , γ_2 , p_A , p_X , β_1 , β_2 , and Y . When a direct estimation of the parameters, γ_1 and γ_2 , become difficult, we can also estimate A_i and X_i by indirectly setting the levels of subsistence consumption, as shown in Eqs. (34-35). In this case, we need only to calibrate the parameters p_A , p_X , β_1 , β_2 , and Y .

For convenience, the design of the TCS in this illustration will focus on the setting of the tradable credits price (p_e) and the number of credits initially distributed per capita (\bar{A}). Other scheme design issues e.g., transaction cost, price setting are omitted, although it is acknowledged that these design features are important in practice (see Grant-Muller and Xu (2014) for more detail). Here, the investigation of a TCS will be based on Eqs. (28-29) or Eqs. (38-39). The impacts of introducing the TCS can be found by comparing the difference between the benchmark daily travel distance by mode and the updated travel distance by mode, as demonstrated in Figure 1. In Section 4 a scenario simulation is provided for the specific case of Beijing, China.

5. Scenario studies for Beijing

Beijing is the major political, commercial and financial centre of China with a high population density, rapidly developing transport infrastructures and increasing travel demand (Xu, et al., 2015). As shown in Figure 2, the municipality covers a total area of 16,807.8 km² with 14 districts and 2 counties under its jurisdiction ($N = 16$). Alongside fast economic development, Beijing is facing the serious traffic congestion and air pollution problems that accompany a rapid growth in car and bus mode trips. To investigate the potential to reduce car trips using policy, we conducted an analysis of the effects of a tradable credits scheme using scenario simulation and 2010 census data for Beijing. In the light of data availability, we used the bus survey data (including tramcar) instead of the non-car mode X outlined above.

The simulation used the 2010 Beijing Urban Household Survey data. An OD matrix between districts/counties was constructed based on the census of travel patterns of 46900 households from across the whole municipality of Beijing. The resulting 16x16 OD matrix represents the daily OD travel demand (journeys per person per day) between districts/counties. In the census, daily travel records are collected using one-day trip diaries (12th Sept, 2010) for all members of the selected households. The information provided includes travel purpose, travel time and travel modes. It is noted that to apply the policy simulation analysis framework in practice, the model would need to be carefully calibrated using a detailed survey or statistical data (Paris, Perali, and Piccoli, 2004). To provide an accurate and true calibration of each parameter in the model for the large city of Beijing is beyond the scope of this particular paper, which aims instead to illustrate the principles of the method. For the analysis we follow the assumptions given in Section 2 and leave further calibration efforts for future research.

5.1 Estimating daily vehicle kilometres by car mode and bus mode for each district/county: using census data ($A0_i$ and $X0_i$)

Theoretically there are different ways to estimate car mode $A0$ (km) and bus mode $X0$ (km) in each district/county based on survey data if it cannot be given/derived directly. According to the 2010 census data for Beijing and travel mode statistics, the daily total number of trips (excluding walking) was 29.04million person trips,

where daily car trips represented 9.93 million person-trips (TA in Eqs. (42-43)) and daily bus trips (including tramcar trips) amounted to 8.18 million person-trips. The ratio of travel modes from this data is therefore 34.2% for the car (RA in Eqs. (42-43)) and 28.2% for the bus (RX in Eqs. (42-43)).

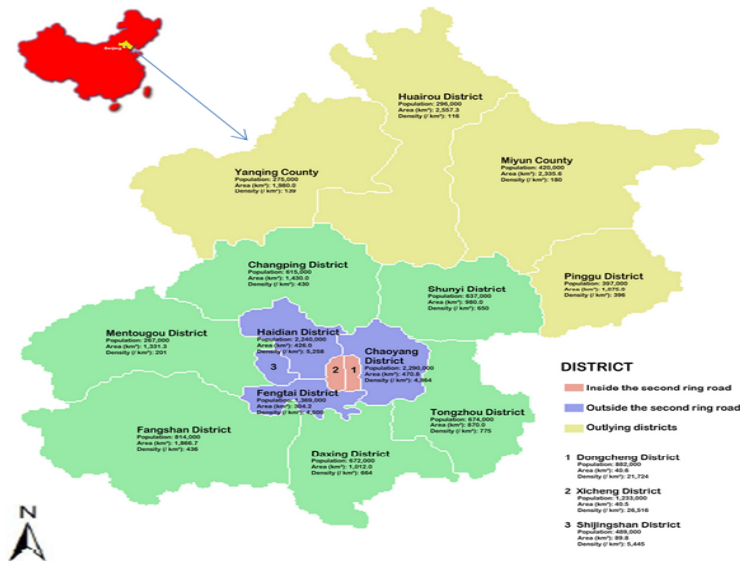


Figure 2 Districts/counties and population density for Beijing Municipality (Source: <http://beijingconflict.wordpress.com/maps/>)

Table 1. Median statistics for the 16 districts/counties of Beijing

District/county	Population (Pop_i)	Trip ratio (RT_i)	Daily total car trips (TTA_i)	Daily total bus trips (TTX_i)
Dongcheng	91.9	0.114	1128976.336	930012.732
Xicheng	124.3	0.110	1096333.732	903122.8528
Chaoyang	354.5	0.162	1608642.78	1325145.814
Haidian	328.1	0.135	1341452.985	1105043.849
Fengtai	211.2	0.115	1137477.582	937015.7723
Shijingshan	61.1	0.046	457050.95	376503.1995
Fangshan	94.5	0.046	455906.5515	375560.4825
Daxing	136.5	0.030	299178.4566	246453.1495
Tongzhou	118.4	0.035	342829.0838	282411.0681
Mentougou	29	0.0455	451001.9866	371520.2669
Changping	166.1	0.076	752687.2208	620038.4155
Shunyi	87.7	0.029	286644.5686	236128.1542
Pinggu	41.6	0.014	143376.7795	118108.9684
Yanqing	31.7	0.010	101905.9588	83946.7012
Huirou	37.3	0.016	160052.3	131845.7013
Miyun	46.8	0.017	166482.7295	137142.8728
Total	1960.7	1	9.93*10 ⁶	8.18*10 ⁶

Key: Population (Pop_i) (unit: 10000 persons); daily total car trips (TTA_i) and daily total bus trips (TTX_i) (unit: journeys per person per day).

From the 16x16 OD matrix (representing daily OD travel demand in person-trips between districts/counties), we can thus derive the ratio of person-trips (RT_i in Eqs. (42-43)) for each district/county from the total trips (TA in Eqs. (42-43)) and according to the travel pattern of the 46900 households in the census. This gives an estimate of the total daily trips for each district. The daily car trips $A0_i$ and bus trips $X0_i$ for each district/county therefore can be estimated as

$$A0_i = \frac{TTA_i * ADA}{Pop_i}, \quad i = 1, \dots, 16 \quad (40)$$

$$X0_i = \frac{TTX_i * ADX}{Pop_i}, \quad i = 1, \dots, 16 \quad (41)$$

$$TTA_i = RT_i * TA * RA, \quad i = 1, \dots, 16 \quad (42)$$

$$TTX_i = RT_i * TA * RX, \quad i = 1, \dots, 16 \quad (43)$$

where TTA_i and TTX_i represent the daily total car trips and bus trips (journeys per day) in district/county i , ADA represents the daily average car travel distance and we set $ADA = 30km$ based on the census. ADX represents the daily average bus distance travelled and we set $ADX = 7.86km$ based on the census, while Pop_i is the population in district/county i . The variables RT_i , TTA_i , TTX_i and Pop_i for the 16 districts/counties according to the census are shown in Table 1, and RA and RX is the ratio of travel mode by car and by bus as pointed in the beginning of this section.

We can therefore give a rough estimate of individual daily average car kilometres and bus kilometres based on the daily OD matrix of total trips and related statistics from the 2010 survey. The estimated car mode $A0_i$ and bus mode $X0_i$ for the 16 districts/counties are shown in Table 3 (column I1).

5.2 Estimating daily vehicle kilometres by car mode and bus mode for each district/county: using Eqs. (36-37) (A_i and X_i)

As seen from the survey data for Beijing, the demand for both car trips and bus trips increases quickly. This is different to an increase/decrease in just one mode. We will use the LES (Eqs. (18-19)) as an approach to the demand for car mode A_i and bus mode X_i in each district/county under the assumption of complementarity. Estimation of A_i and X_i are dependent on effective parameter setting for γ_1 , γ_2 , p_A , p_X , β_1 , β_2 , and Y however. As already mentioned, the determination of these parameters is difficult unless detailed survey data is available, and some professional data analysis methods are required during the process of practical transport policy evaluation. The accurate calibration of each parameter in the model for the large city of Beijing is beyond the scope of this paper. Instead, for the purposes of demonstrating the proposed models, we estimate these parameters using the 2010 census data for Beijing and the GDP per capita for each district/county, as shown in Table 2. The estimation of the price for car use mode p_A , price of bus mode p_X , marginal budget used for car mode β_1 , marginal budget used for bus mode β_2 and individual transport budget Y can be carried out based on the data available directly. However, the data required data to estimate subsistence consumption of the car mode γ_1 and subsistence consumption of the bus mode γ_2 are difficult to obtain. Here we use the Frisch method (1959) with the Frisch parameters. The estimation of γ_1 and γ_2 for each district/county is based on the following Eqs. (44) and (45)

$$\gamma_{1i} = A1_i + \frac{\beta_{1i} Y_i}{p_{A_i} \varphi_i}, \quad i = 1, \dots, 16. \quad (44)$$

$$\gamma_{2i} = X1_i + \frac{\beta_{2i} Y_i}{p_{X_i} \varphi_i}, \quad i = 1, \dots, 16. \quad (45)$$

where φ_i is the Frisch parameter, which can be used as a proxy for the marginal utility of transport budget. A higher Frisch parameter helps produce a lower own price elasticity and indicates a higher marginal utility of total expenditure. It is expected that a higher Frisch parameter exists in poorer countries. According to Frisch (1959), the Frisch parameter $\varphi = -0.7$ is a benchmark value for the ‘wealthy’ level and $\varphi = -10$ is a benchmark value for the ‘poor’ level. We set the value for each district/county based on the estimated GDP per capita and as shown in the last column of Table 2.

The estimated car mode A_i and bus mode X_i travel in the 16 districts/counties is shown in Table 3 (column I2). From the simulation outcomes, it is clear that A_i and X_i estimated from the model (Eqs. (36-37)) and the benchmark daily trips ($A0_i$ and $X0_i$) from survey data match well with the parameters used.

Table 2. Parameter settings for each district/county

District/county	γ_1	γ_2	p_A	p_X	β_1	β_2	Y	φ_i
Dongcheng	15.8487	6.3731	3.8	1	0.93	0.07	145.9112	-1.7
Xicheng	11.0995	4.9023	6.6	1	0.95	0.05	181.4181	-1.7
Chaoyang	9.9122	2.5269	6.2	1	0.9	0.1	86.6882	-3.4
Haidian	9.8878	2.3831	7.3	1	0.9	0.1	92.5742	-4.8
Fengtai	13.5853	3.0333	2.1	1	0.85	0.15	38.1271	-6
Shijingshan	19.1678	4.2658	2.1	1	0.85	0.15	52.5655	-6.5
Fangshan	12.6489	2.7501	2.8	1	0.83	0.17	43.0795	-7
Daxing	5.7804	1.2204	3.6	1	0.8	0.2	25.0411	-7
Tongzhou	7.7632	1.6439	3.5	1	0.8	0.2	31.9123	-7.9
Mentougou	14.4866	0.6868	2.6	1	0.85	0.15	32.6597	-8
Changping	11.8210	2.4907	1.7	1	0.8	0.2	26.3825	-7
Shunyi	7.7062	2.0059	5.8	1	0.95	0.05	38.4482	-3
Pinggu	9.0715	1.9145	2.8	1	0.8	0.2	31.0718	-7
Yanqing	8.9352	1.6089	2.2	1	0.6	0.4	23.3939	-9
Huairou	11.5143	2.3255	3.2	1	0.75	0.25	43.4718	-7.5
Miyun	9.4536	1.99871	2.9	1	0.8	0.2	33.1244	-7.5

5.3 Estimating daily vehicle kilometres by car mode and bus mode for each district/county under the TCS: using Eqs. (38-39) ($A1_i$ and $X1_i$)

From the benchmark daily car travel in Beijing shown in Table 3, i.e. the total daily distance travelled by private car is $2.9 \times 10^8 \text{ km}$, we therefore set the total number of credits as $TA = 2.9 \times 10^8 \text{ km}$. We then consider the case where the authority decides to reduce the total daily private car kilometres by 15% using a tradable credits scheme. That is, the total daily distance travelled by private car will be reduced to $2.46 \times 10^8 \text{ km}$. To achieve this target, we assume that credits are initially distributed to each person equally (in principle there may be different designs for the initial allocation of credits rather than this equal distribution), i.e., we set $\bar{A} = 7 \text{ km}$ for each person. We set the price of credits $p_e = 2 \text{ Yuan}$ (1 Chinese Yuan equals about 0.12 Euro). From eqs. (38-39) the effects of the tradable credits scheme can be demonstrated by articulating the scheme within the modelling framework, as shown in Table 3 (column I3, estimated daily distance travelled in district i by car mode $A1_i$ and bus mode $X1_i$ under the tradable credits scheme). With the implementation of a tradable credits scheme the total daily distance travelled by private car is now approximately $2.38 \times 10^8 \text{ km}$, which reaches the target reduction in car trips of 15%. It can also be seen that the proportionate reduction for each district is not constant, but varies as expected. The reduction of car kilometres also brings a decrease in bus kilometres, which is determined by the complementary relationship between the car mode and bus mode in the LES and given in Section 2.

5.4 Factors analysis

Based on the simulation in Section 3, we can investigate further according to the following facets.

The effects of the individual transport budget Y . With the LES approach, it is possible to simulate the effects of the individual transport budget Y on daily trips by car mode and bus modes. According to Eqs. (14-15) and Eqs. (18-19), daily trips in the 16 districts/counties of Beijing increase with a growth in the individual transport budget. Figure 3 illustrates the characteristics of daily trips by car mode and non-car modes. For each district/county, there is a fundamental and required amount of trips by the car mode, γ_{1i} , where there is no utility for car trips below γ_{1i} . Utility is only generated on the upper part of γ_{1i} , that is, $A_i - \gamma_{1i}$. Therefore with an increase in the individual transport budget, people are inclined to use the car mode more. This characteristic is similar to the Engel curve in

economics (Leser, 1963). From the Figure 3, we also see that the districts of Dongcheng and Xicheng have the strongest preference for the car mode with a steeper slope.

Table 3. Total daily average kilometres travelled by modes for each district/county with/without a TCS

District/ county	I1		I2		I3		$A0_i - A_i$	$\frac{A0_i}{A1_i}$
	$A0_i$	$X0_i$	A_i	X_i	$A1_i$	$X1_i$		
Dongcheng	36.8545	7.9542	36.3430	7.8079	26.4383	6.5691	0.5115	1.3939
Xicheng	26.4602	5.7108	26.6142	5.7643	22.1004	5.35435	-0.1540	1.1972
Chaoyang	13.6133	2.9381	13.5186	2.8729	11.9997	2.2904	0.0947	1.1345
Haidian	12.2656	2.6473	12.3134	2.6861	11.2329	2.1085	-0.0478	1.0919
Fengtai	16.1574	3.4872	16.4445	3.5936	12.3193	1.6180	-0.2871	1.3116
Shijingshan	22.4411	4.8434	22.6822	4.9328	15.9227	1.2824	-0.2412	1.4094
Fangshan	14.4732	3.1237	14.3045	3.0269	11.6611	1.1063	0.1687	1.2412
Daxing	6.5754	1.4191	6.5644	1.4092	6.6329	0.8970	0.0110	0.9913
Tongzhou	8.6865	1.8748	8.6030	1.8018	8.0756	1.4965	0.0835	1.0756
Mentougou	16.6554	10.0695	16.6781	1.8107	13.0819	0.4352	-0.0227	1.2732
Changping	13.5946	2.9341	13.7535	3.0016	10.6241	1.0732	-0.1589	1.2796
Shunyi	9.8054	2.1163	9.6412	1.0893	6.5935	1.0187	0.1642	1.4871
Pinggu	10.3397	2.2316	10.3080	2.2094	9.1023	1.3808	0.0317	1.1359
Yanqing	9.6441	2.0815	9.67010	2.1197	8.7672	0.5715	-0.0260	1.1000
Huairou	12.8728	2.7783	12.7557	2.6534	10.9761	0.3963	0.1171	1.1728
Miyun	10.6720	2.3033	10.6368	2.2778	9.3527	1.2963	0.0352	1.1411
Total trips	2.9×10^8	-	2.9×10^8	-	2.38×10^8	-	-	-

Key: I1 represents the benchmark total daily vehicle kilometres; I2 represents total daily vehicle kilometres estimated from Eqs. (18-19) without the TCS; I3 represents total daily vehicle kilometres estimated from Eqs. (38-39) with the TCS.

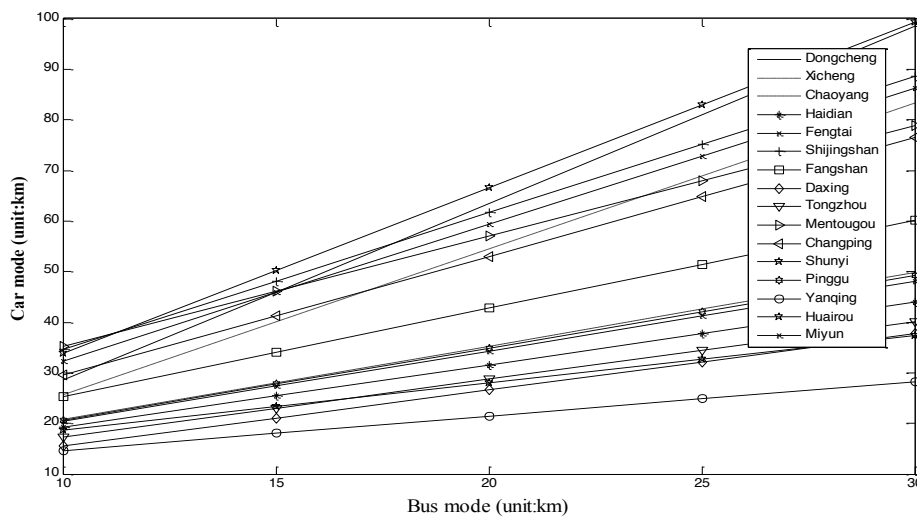


Figure 3 Daily vehicle kilometres by car and bus modes increasing with a growth in the individual transport budget for the 16 districts/counties of Beijing

The effects of the tradable credits scheme. The introduction of a tradable credits scheme can reduce car mode kilometres as expected. In Section 4.3, we assumed a target reduction in car kilometres of 15% with a tradable credits scheme and that the initial credits were distributed to each person equally. In fact there are other ways to distribute the credits initially, for example, to distribute credits in proportion to the number of car trips made without a tradable credits scheme or auction (Grant-Muller and Xu, 2014). It is likely that a different distribution of initial credits will bring different effects, therefore, it is important to determine how to distribute credits to people in practice.

A related problem is how to determine the price of credits. Theoretically, the credit price, which is based on the daily VKT and is determined by the market, should be set so as to be consistent with the target for car use set by the regulatory authority and to satisfy

$$\sum_{i=1}^{16} Pop_i A_i = \sum_{i=1}^{16} Pop_i \left[\beta_{2i} \gamma_{1i} + \frac{\beta_{1i}}{p_{A_i} + p_e} (Y_i + p_e \bar{A}_i - p_{X_i} \gamma_{2i}) \right] \quad (46)$$

or

$$\sum_{i=1}^{16} Pop_i A_i = \sum_{i=1}^{16} Pop_i \left[\beta_{2i} f_{1i}(A_i, X_i, \beta_{1i}, p_{A_i}, Y_i, \varphi) + \frac{\beta_{1i}}{p_{A_i} + p_e} (Y_i + p_e \bar{A}_i - p_{X_i} f_{2i}(A_i, X_i, \beta_{2i}, p_{X_i}, Y_i, \omega)) \right] \quad (47)$$

Eqs. (46) and (47) give an implicit solution for the credit price which could be solved using an iterative approach given estimates of the price of car use p_A , price of bus use p_X , marginal budget used for car travel β_1 , marginal budget used for bus travel β_2 , the individual transport budget Y and the Frisch parameters. As expected, if the number of credits initially distributed is fixed, an increase in the credit price, p_e , will result in a decrease in the daily car kilometres A_i . The districts with high Frisch parameters, e.g., Dongcheng, Xicheng, Shunyi, decrease car trips slowly compared with other districts, e.g., Yanqing, Mentougou.

From Eqs. (28-29), the effects of implementing a tradable credits scheme are twofold: firstly it increases the cost of travelling by the car mode and secondly, selling the credits will increase an individuals' transport budget, which can be treated as a compensation paid for giving up travel by car. This is consistent with some existing studies, e.g., Bulteau (2012) with the CES approach and Wu et al. (2012) with the social benefit measure approach; However, travellers in each district are inclined to restraint their car trips and there is no clear intention demonstrated that they will trade their credits. this is different outcome to indicate that individuals with a high individual transport budget (Y) are inclined to buy credits to support more car trips, whilst individuals with a low individual transport budget are inclined to sell credits to move to non-car modes (see the ratio $\frac{A0_i}{A1_i}$ in Table 3). Actually, this is because the number of initially distributed credits is much less than the amount consumed, as can be seen in Table 3, where $A1_i > 7$ holds for most districts, and 7 is the amount of credits assigned to travellers. Instead of trading, most of travellers need to buy credits from the government. As rich people in Dongcheng and Xicheng (shown in Table 2) will consume much more credits, i.e., their $A1_i$ is much larger than 7 as shown in Table 3.

6. Conclusions

To demonstrate the effectiveness of the model presented, we have undertaken a series of simulations using survey data for the municipality of Beijing from 2010. From the survey data, travel by car and bus modes increases quickly with rapid economic development, which led to an approach the car and bus modes in this analysis within the LES. Comparing with the existing literature related to TCS, this paper aims to study the impacts of TCS adopting the LES. As subsistence consumption parameters are difficult to estimate directly in the LES approach, we have presented an approach based on the Frisch method. Using simulation, we have investigated the effects of TCS and found that a TCS can achieve the car kilometre reduction target set.

A quantitative analysis of the relationship between transport policy and car trips has been carried out, with a case study based on Beijing municipality which was separated into 16 districts/counties. Firstly, a LES model was developed to estimate daily travel by car and non-car modes, which are also dependent on effective parameters settings. Secondly, a TCS with a given car trip reduction target was introduced to the LES model. It has been shown that the LES model used with a TCS can allow an estimation of the changes in daily travel by car and non-car use

modes. The LES model presented can allow an analysis of the effects of transport policy with different parameter settings.

With the simulation, we found that the effect of the individual transport budget on car trips is clear. With a growth in transport budget, travellers are more inclined to use the car mode. The districts of Dongcheng and Xicheng have the strongest preference for the car mode and a higher slope to the demand curve. A TCS can reduce the amount of travel by car, but this depends on the credit price determined by the market. Trips by both car and non-car modes are price inelastic. However, the districts/countries have different results, with the price elasticity of car in the districts Dongcheng, Xichang and Shunyi close to 1. The cross-price elasticity for different districts/counties demonstrates the complementary relationship between car and bus modes.

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