A tradable credits scheme for VMT reduction and environmental effects: a simulation case study for Great Britain

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Abstract

We investigate the influence of a tradable credits scheme (TCS) on travel demand and vehicle emissions, based on the vehicle miles travelled (VMT). With a microeconomic quantitative analysis scheme, a constant elasticity of substitution (CES) function is used as an approach to model the annual mileage by different travel purposes. An illustration is given for the effects of a TCS on emission mitigation based on historical data for Great Britain. A scenario analysis demonstrates that a tradable credits scheme can achieve a target for reducing the number of private trips. Besides a movement of trips from the private car mode to public modes, there is also some trip restraint, with individuals choosing not to take some trips. Compared with past research on road pricing in London (Fowkes et al. (1995)), the research illustrates that a TCS can be designed to have similar effects to a road pricing scheme. We also demonstrate that a TCS could bring emission changes arising from the changes with respect to VMT.

**Keywords:** Tradable credits scheme; Emission; Mode choice; Vehicle miles travelled; Climate change assessment
1. Introduction

Urban transport has an overriding role in economic activity and growth and is also of major importance for the quality of life of individuals as well as regional productivity. However in many cities, traffic congestion, emissions, traffic noise, and increasing travel costs have led to a series of problems. Congestion results in travel time delays and unreliability, increases in fuel consumption and increased driver stress. In the European Union (EU), transport generates approximately 25 to 30 percent of total greenhouse gas (GHG) emissions (Ellerman, et al., 2010). In China, statistics have shown that more than three quarters of total air pollution comes from vehicle carbon monoxide and hydrocarbon emissions in large cities including Beijing, Shanghai and Guangzhou (China Business News, 2011). The World Energy Outlook (WEO) 2009 project pointed out that global demand for transport appears unlikely to decrease in the foreseeable future and transport will grow by 45% by 2030. From the International Energy Agency statistics for 2010, the transport sector represented 22% of global CO2 emissions in 2008, whilst CO2 emissions from transport were dominated by road modes. The transport sector is therefore considered one of the main sources of greenhouse gas emissions.

The Kyoto Protocol proposed use of a system of emission permits as an economic tool for climate change mitigation. However, the use of a TCS for transport emissions is a relatively new measure both in theory and in practice. The lack of practical application of this economic measure may be attributable to an undeveloped and incomplete theoretical foundation and particular practical issues that are yet to be resolved. However the tradable credits scheme is a promising policy tool for mobility management and has received increasing attention in recent years. Some reviews of tradable credits scheme in the transport sector include: the regulation of road transport externalities (Verhoef et al., 1997), a review and appraisal of roadway capacity allocation (Fan and Jiang, 2013) and road congestion management (Grant-Muller and Xu, 2014).

If a TCS were to be implemented in an urban transport system, the budget for credits will become an additional resource considered within individuals’ mode choice. The use of a private car will become subject to additional monetary costs if there is a wish to use it beyond the limit of the initial credit allocation. There are various options within the scope of the scheme: people may want to fully use their credits, buy additional credits (where their use of the car exceeds the initial allocation), or save and sell them for financial gain. As a result, people have to not only decide on the necessity of the trips they take, but also on how they want to manage their budget of allocated credits. Mode choice for a typical individual in each geographic area will be affected by the individuals’ transport budget, the travel cost according to different modes and the individuals’ attitudes.
Different conceptual forms of TCS have been developed within existing road transport studies and according to the potential application area. These may include tradable driving day rights, tradable vehicle-miles, tradable fuel permits and tradable parking rights for example. A TCS based on VMT provides an alternative to restricting vehicle miles, although there are some potential disadvantages in the political reality and policy ramification, and also limitations, as pointed by Verhoef et al. (1997). These include the difficulties in applying the system in a spatially differentiated manner and the possibility of providing insufficient incentives to improve on vehicle technology. Under this scheme, each individual could receive a certain number of personal vehicle-miles (the unit of credits), which could subsequently be traded so as to accomplish an eventual distribution where only the vehicle miles with the highest benefits would remain, and some vehicle trips will be stopped or rescheduled. Furthermore, the policy target, defined as total vehicle mileage, has also a close connection with vehicle emissions.

Like similar papers, the political reality and policy ramifications are not treated here, however the authors make note of these limitations.

To implement a TCS, a fundamental question is how to measure the effects of a TCS quantitatively with respect to the VMT and vehicle emissions. In this study, we examine how travelers’ mode choice preferences could be influenced by implementing a TCS. The study supposes that the 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-miles). Now, in order to reduce the VMT and vehicle emission in the given urban area, individuals (in maximizing their utility), must consider their travel mode choice based on the credits distributed. That is, the individual must consider the permitted number of vehicle miles and the credit price ($p_e$).

To investigate the influence of a given TCS we present a microeconomic quantitative analysis framework to simulate policy scenarios. Travel patterns are compared before and after introduction of a tradable credits scheme. This is also extended to consider how a TCS should be designed so that it has similar impacts to a congestion pricing scheme. This is important in order that policy makers may understand how a TCS would need to look in order to act as a substitute scheme in the future, or in order to bring further improvement from road pricing. Furthermore, we discuss the effects of TCS on vehicle emissions based on VMT.

The simulation studies presented in this paper are based on Fowkes et al. (1998), which investigated the effects on mileage by public and private transport in 2006 of various measures that have been proposed to restrain the use of the private car. That study utilized a series of household survey data, including the 1985/6 National Travel Surveys (NTS), and selected tabulations from the 1991/3 hybrid data set provided by the Statistics Directorate of the Department of Transport (DOT). The NTS provided a
national data bank of personal travel information for Great Britain (DOT, 1993). As emphasized by Fowkes et al. (1998), the 2006 projection is by no means a forecast, as it merely attempts to project the 1985 to 1993 trends through to 2006.

The organization of the paper is as follows. In Section 2, we present an estimation model for individual average trips (based on a neo-classical microeconomic model) with and without a tradable credits scheme, including the determination of credit equilibrium price. In Section 3, the details of the simulation framework are given, involving journey data for Great Britain in 2006 and the London road pricing scheme. We also give the fundamental parameters and input settings based on data for Great Britain. In Section 4, we compare the effects of TCS arising from the simulation framework presented with those of the congestion pricing scheme in London, discussing differences in emissions with and without a TCS. The paper concludes in Section 5.

2. Methodology

Before introducing the simulation framework, we present the methodological approach as follows. Firstly we list the notation used in Section 2.1, followed by a presentation of the model formulation in Section 2.2 and determination of the travel pattern with a TCS in Section 2.3. The theoretical determination of the credit price is derived in Section 2.4.

2.1 Notation

Considering a given area $i$, $i = 1, \ldots, N$, then we adopt the following notation:

- $P_i$: population in area $i$, $i = 1, \ldots, N$
- $x_i^c$: individual trips via private mode in area $i$, unit: vehicle miles travelled (VMT), $x^c = \sum_{i=1}^{N} P_i x_i^c$
- $x_i^b$: individual trips via public mode in area $i$, unit: VMT, $x^b = \sum_{i=1}^{N} P_i x_i^b$
- $x_{i,k}^c$: individual trips with travel purpose $k$ via private mode in area $i$, unit: VMT
- $x_{i,k}^b$: individual trips with travel purpose $k$ via public mode in area $i$, unit: VMT
- $U_i(x_i^c, x_i^b)$ ($U_{i,k}(x_{i,k}^c, x_{i,k}^b)$): utility function for a representative individual in area $i$ (for travel purpose $k$)
- $I_i$: individual transport budget devoted to travel in area $i$
- $p_i^v (p_{i,k,v})$: price of private mode per mile travelled in area $i$ (for travel purpose $k$), including maintenance costs, fuel and insurance
- $p_i^b (p_{i,k,b})$: price of public mode per mile travelled in area $i$ (for travel purpose $k$)

Parameters:
- $a_i$: allocation parameter for private mode trips/the proportion of transport income spent on private mode use
\(a_{i,k}\) allocation parameter for private mode trips for travel purpose \(k\)/the proportion of transport income spent on private mode use

\(\rho_i\) (\(\rho_{i,k}\)) substitution elasticity in area \(i\) (for travel purpose \(k\))

\(\varepsilon_i\) (\(\varepsilon_{i,k}\)) elastic coefficient in area \(i\) (for travel purpose \(k\)), \(\varepsilon_i = \frac{1}{1-\rho_i} (\varepsilon_{i,k} = \frac{1}{1-\rho_{i,k}})\)

Tradable credits scheme

\(p_{i,c}\) price of tradable credits in area \(i\)

\(x_{i,c}^c\) credits received per individual in area \(i\), e.g., each credit/license entitles the holder to travel one mile by private mode.

\(\bar{x}\) total number of credits set according to the total VMT, \(\bar{x} = \sum_{i=1}^{N} p_i x_{i,c}^c\)

2.2 A constant elasticity of substitution (CES) model

Suppose for a particular area \(i\), the daily travel modes for travelers is split into public (\(c\)) and private (\(b\)). Considering environmental goals or other factors, the authority may wish to restrain the number of private trips for different travel purposes (\(k\)) with respect to the number of annual average mileage travelled (i.e. restraint private mileage by VMT) and it is supposed that the authority will approach this target with a tradable credit scheme. Before implementation of the TCS, it is assumed that each individual in area \(i\), with travel purpose \(k\), maximizes his/her utility by \(U1\):

\[
\begin{align*}
\text{Max } U_{i,k}(x_{i,k}^c, x_{i,k}^b) &= \left[ a_{i,k}(x_{i,k}^c)^{\rho_{i,k}} + (1 - a_{i,k})(x_{i,k}^b)^{\rho_{i,k}} \right]^{\frac{1}{\rho_{i,k}}} \\
\text{s.t. } & \\
\sum_{k=1}^{K} p_{i,k,b} x_{i,k}^c + \sum_{k=1}^{K} p_{i,k,b} x_{i,k}^b & \leq l_i \quad \forall i = 1, \ldots, N \quad (2a) \\
x_{i,k}^c & \geq 0 \quad \forall i = 1, \ldots, N, k = 1, \ldots, M \quad (3a) \\
x_{i,k}^b & \geq 0 \quad \forall i = 1, \ldots, N, k = 1, \ldots, M \quad (4a)
\end{align*}
\]

It is noted that we assume all travel activities (for all travel purposes) are within the given transport budget \(l_i\).

Alternative, if we do not consider the travel purpose \(k\), the utility model can be written as \(U1'\) for each area \(i\),

\[
\begin{align*}
\text{Max } U_{i}'(x_{i,c}^c, x_{i,b}^b) &= \left[ a_i(x_{i}^c)^{\rho_i} + (1 - a_i)(x_{i}^b)^{\rho_i} \right]^{\frac{1}{\rho_i}} \\
\text{s.t. } & \\
p_{i,c} x_{i,c}^c + p_{i,b} x_{i,b}^b & \leq l_i \quad \forall i = 1, \ldots, N \quad (2b) \\
x_{i,c}^c & \geq 0 \quad \forall i = 1, \ldots, N \quad (3b) \\
x_{i,b}^b & \geq 0 \quad \forall i = 1, \ldots, N \quad (4b)
\end{align*}
\]

The target utility function in \(U1, U1'\), and also the following \(U2, \ U2'\), is called the constant elasticity of substitution (CES) utility function in microeconomic analysis.
The CES form of the utility function allows several situations to be considered, which depend on the value of the parameter $\rho$ (Bulteau, 2012). In this study, when the parameter $\rho = 0$, the utility function is, in fact, in the form of a Cob-Douglas utility function, which shows the private mode and public mode as not being substitutable. When parameter $\rho = 1$, it indicates the private mode and public mode to be perfect substitutes; when the parameter $\rho = -\infty$, it indicates that the private mode and public mode are complementary. A similar model has been used as an approach to individual utility in related areas such as: economics (Santos et al., 2010), an individual tradable emission permit scheme for urban motorists (Bulteau, 2012) and the influence of urban form on energy consumption according to individual consumption behaviour (Yin et al., 2013).

2.3 A CES model considering a TCS

Suppose the regulatory authority then implements a tradable credits scheme. The initial credit distribution is free and each individual in each area receives a number of credits that permits private trips: $\bar{x}_i^c$. The individual then needs to consider the amount of miles that are allowed by a private mode e.g., car and the price of a credit if they wish to travel further miles by a private mode. Under the TCS, the utility maximization problem for each representative individual in area $i$ with respect to different travel purposes can then be formulated as the following:

$$U2: \quad \text{Max } U_{i,k}(x_{i,k}^c, x_{i,k}^b) = \left[ a_{i,k}(x_{i,k}^c)^{\rho_{i,k}} + (1 - a_{i,k})(x_{i,k}^b)^{\rho_{i,k}} \right]^{1\over \rho_{i,k}}$$

s.t.

$$\sum_{k=1}^{K} p_{i,k,v} x_{i,k}^c + \left( \sum_{k=1}^{K} p_{i,e} x_{i,k}^c - \bar{x}_i^c \right) + \sum_{k=1}^{K} p_{i,k,b} x_{i,k}^b \leq l_i, \ \forall i = 1, \ldots, N \quad (6a)$$

$$x_{i,k}^c \geq 0, \ \forall i = 1, \ldots, N, k = 1, \ldots, M \quad (7a)$$

$$x_{i,k}^b \geq 0, \ \forall i = 1, \ldots, N, k = 1, \ldots, M \quad (8a)$$

Similar to $U1$ above, if we do not consider the travel purpose $k$, the utility model (5a-8a) can be written as $U2'$

$$U2': \quad \text{Max } U_i(x_i^c, x_i^b) = \left[ a_i(x_i^c)^{\rho_i} + (1 - a_i)(x_i^b)^{\rho_i} \right]^{1\over \rho_i}$$

s.t.

$$p_{i,v} x_i^c + p_{i,e} (x_i^c - \bar{x}_i^c) + p_{i,b} x_i^b \leq l_i, \ \forall i = 1, \ldots, N \quad (6b)$$

$$x_i^c \geq 0, \ \forall i = 1, \ldots, N \quad (7b)$$

$$x_i^b \geq 0, \ \forall i = 1, \ldots, N \quad (8b)$$

Comparing Eq. (2a)/(2b) and Eq. (6a)/(6b), we find that there exists a balance with the credits scheme from the perspective of individuals as follows. Firstly, it brings an increased cost for private mode use ($p_{i,v}$) and secondly, it brings an increase in the individuals’ transport budget ($l_i + p_{i,b} \bar{x}_i^c$) for area $i$. This term $p_{i,b} \bar{x}_i^c$ could be treated as a transport saving if an individual chose to sell credits. According to the associated Lagrangian, we can derive the following solution for $U2$ when two modes
are used:

\[
\begin{align*}
\bar{x}^c_{i,k} &= \left( \frac{a_i}{p_{i,v} + p_{i,e}} \right)^{\epsilon_{i,k}} \frac{l_i + p_{i,e}x^c_{i,j} - \sum_{j=1}^{K} l_{i,j} x^c_{i,j}}{a_i^{\epsilon_{i,k}}(p_{i,v} + p_{i,e})^{1-\epsilon_{i,k}} + (1-a_i)^{\epsilon_{i,k}} p_{i,e}^{1-\epsilon_{i,k}}} , \forall i = 1, \ldots, N, k = 1, \ldots, M \quad (9a) \\
\bar{x}^b_{i} &= \left( \frac{1-a_i}{p_{i,b}} \right)^{\epsilon_{i}} \frac{l_i + p_{i,e}x^c_i - \sum_{j=1}^{K} \sum_{j=k}^{N} l_{i,j} x^c_{i,j}}{a_i^{\epsilon_{i}}(p_{i,v} + p_{i,e})^{1-\epsilon_{i}} + (1-a_i)^{\epsilon_{i}} p_{i,b}^{1-\epsilon_{i}}} , \forall i = 1, \ldots, N \quad (10a)
\end{align*}
\]

where \( \epsilon_{i,k} \) is the elastic coefficient in area \( i \) for travel purpose \( k \), \( \epsilon_{i,k} = \frac{1}{1-\rho_{i,k}} \).

The solution of \( U2' \):

\[
\begin{align*}
\bar{x}^c_{i} &= \left( \frac{a_i}{p_{i,v} + p_{i,e}} \right)^{\epsilon_{i}} \frac{l_i + p_{i,e}x^c_i}{a_i^{\epsilon_{i}}(p_{i,v} + p_{i,e})^{1-\epsilon_{i}} + (1-a_i)^{\epsilon_{i}} p_{i,e}^{1-\epsilon_{i}}} , \forall i = 1, \ldots, N \quad (9b) \\
\bar{x}^b_{i} &= \left( \frac{1-a_i}{p_{i,b}} \right)^{\epsilon_{i}} \frac{l_i + p_{i,e}x^c_i}{a_i^{\epsilon_{i}}(p_{i,v} + p_{i,e})^{1-\epsilon_{i}} + (1-a_i)^{\epsilon_{i}} p_{i,b}^{1-\epsilon_{i}}} , \forall i = 1, \ldots, N \quad (10b)
\end{align*}
\]

where \( \epsilon_{i} \) is the elastic coefficient in area \( i \), \( \epsilon_{i} = \frac{1}{1-\rho_{i}} \). Solutions for models \( U1 \) and \( U1' \) can included in Eqs. (9a-10a) and Eqs. (9b-10b) by setting \( p_{i,e} = 0 \), and \( \bar{x}^c_i = 0 \), \( \forall i = 1, \ldots, N \), separately.

### 2.4 Determination of the credit price

We can further determine the credit price in Section 3.3 and discuss how this will affect the traveler’s mode choice. In order for the market to be balanced and consistent with the target for private mode use (as set by the regulatory authority), the credit price, which is based on the VMT, can be set as

\[
x^c = \sum_{i=1}^{N} \sum_{k=1}^{K} p_i x^c_{i,k} = \bar{x} = \sum_{i=1}^{N} \bar{x}^c_i
\]

Or, if we do not consider the travel purpose,

\[
x^c = \sum_{i=1}^{N} p_i x^c_i = \bar{x} = \sum_{i=1}^{N} p_i \bar{x}^c_i
\]

From Equation (11),

\[
\sum_{i=1}^{N} \sum_{k=1}^{K} p_i \left( x^c_{i,k} - \bar{x}^c_i \right) = 0
\]

Similarly, from Equation (12)

\[
\sum_{i=1}^{N} p_i \left( x^c_i - \bar{x}^c_i \right) = 0
\]

Combining equations (13) and (9a), we have the following

\[
\begin{align*}
\frac{\sum_{i=1}^{N} \sum_{k=1}^{K} a_i^{\epsilon_{i,k}}(l_i + p_{i,e}x^c_i) - \sum_{i=1}^{N} \sum_{k=1}^{K} l_{i,j} x^c_{i,j}}{a_i^{\epsilon_{i,k}}(p_{i,v} + p_{i,e})^{1-\epsilon_{i,k}} + (1-a_i)^{\epsilon_{i,k}} p_{i,e}^{1-\epsilon_{i,k}}} \left[ \frac{1}{\sum_{i=1}^{N} p_i \bar{x}^c_i} \right] p_{i,e} &= \left[ \frac{\sum_{i=1}^{N} \sum_{k=1}^{K} a_i^{\epsilon_{i,k}}(l_i + p_{i,e}x^c_i) - \sum_{i=1}^{N} \sum_{k=1}^{K} l_{i,j} x^c_{i,j}}{a_i^{\epsilon_{i,k}}(p_{i,v} + p_{i,e})^{1-\epsilon_{i,k}} + (1-a_i)^{\epsilon_{i,k}} p_{i,e}^{1-\epsilon_{i,k}}} \right] - p_{i,v} , \forall i = 1, \ldots, N
\end{align*}
\]

Combining equations (14) and (9b), we have the following
\[ p_{i,e} = \left[ \frac{\sum_{i=1}^{N} a_i^e (I_i + p_{i,e} x_i^e)}{\sum_{i=1}^{N} x_i^e} \right] - p_{i,v}, \forall i = 1, \ldots, N \]  

Eq. (15) or (16) give an implicit solution for the credit price, which could be solved using an iterative approach given the car costs per kilometer travelled \( p_{i,v} \), the price of mass transit per kilometer travelled \( p_{i,b} \), the individual transportation budget in zone \( i \), \( I_i \), the total number of credits sets by the authority \( \bar{x} \), and related coefficients.

3. Case study for Great Britain

3.1 Simulation framework

To carry out a scenario study based on the available data for Great Britain in 2006, we firstly present here a simulation framework for the analysis of a TCS. This is based on the methodology developed and presented in Section 2. A case study for Great Britain is presented in Section 3.2 and employs a scenario based approach, as summarized in Figure 1 below.

According to the methodology developed and presented in Section 2, the simulation framework actually provides an implicit assumption that land use remains unchanged, which is consistent with the empirical studies of road congestion given in Fowkes et
al. (1995). The assumption that land use remains unchanged and therefore firm and residential location are treated as predetermined is not new, and has been widely used in existing studies, e.g., Keeler and Small (1977). Therefore, the proposed modelling approach is only a partial equilibrium model, and what is analyzed based on this simulation framework is a short-term response to changes in the cost of travel. As shown in this paper, this modelling could partially answer the question of how a TCS should be designed so that it has similar impacts to a congestion pricing scheme. This might be of interest to policy makers who may wish to understand how a TCS would need to look in order to act as a substitute scheme but have similar impacts. If it were possible to do this in principle, then from a social research perspective it would be interesting to hear the views of policy makers as to why they would not wish to implement the credit scheme. It may also indicate whether it is possible to design a scheme that would have advantages over the congestion pricing scheme, either in terms of the size of the impacts or the distribution of the impacts.

By applying a TCS, there are undoubtedly long-term effects on firms and residential location decisions, which would need further consideration of land use changes. For this kind of approach, a general equilibrium modeling methodology would be necessary. Whilst this goes significantly beyond the scope of this paper, it could however go some way to answering more interesting questions, such as how far would households move from work if a VMT-based TCS is implemented? How would their long-term travel patterns change as a consequence of an increase in VMT-based TCS? From the general equilibrium approach, interested readers can refer to related studies on congestion, land use and management policies, e.g., Anas and Kim (1996), Anas and Xu (1999), Anas and Rhee (2006, 2007), Safirova et al. (2006), Gupta et al. (2006), and Zhang (2010).

### 3.2 Annual journey average mileages in Great Britain in 2006

In Fowkes et al. (1995), the daily travel mode disregarded walking and cycling and was split into public and private. The public mode was defined to be all rail and bus modes plus taxi and domestic air, whilst the private mode incorporated private cars, plus vans, lorries and motorcycles. Travel purposes included work, business and leisure. Also based on that study, a hierarchy of urbanisation can be used with Great Britain typically divided four ways: London, the conurbations, urban and rural. London is taken as the first area type. Secondly, all the built up areas of the English Metropolitan Counties and Glasgow are combined and coded as conurbations. The third category, coded urban, is all other built-up areas which together have a total population of over 25,000. All other locations have been coded rural, including any towns of less than 25,000 persons.

As shown in Table 1, case I shows the annual average miles given by a base 2006 projection for Great Britain with respect to the four categories. The base 2006 projection is not a forecast as it attempts to project the 1985 to 1993 trip trends of
private and public modes through to 2006. Case II reflects the reduction in annual average vehicles miles with an £8 all day charge to travel into central London. It takes the effects to be a London-wide reduction for private mode mileage of 7% for work, 2% for business and 7% for leisure, which is equal to an overall reduction of about 6.5%. As demonstrated in Table 1, annual average vehicles miles in the other areas (including conurbations, urban, and rural), remain constant in case I and case II.

Table 1 2006 base mileage and road pricing in London (Unit: annual average miles)

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<td></td>
<td>Business</td>
<td>949</td>
<td>384</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Leisure</td>
<td>6861</td>
<td>7239</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Subtotal</td>
<td>15343</td>
<td>10439</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


3.3 Input determination
Firstly we determine the model inputs used here, which include the price of the private mode \( p_{i,v} \), the price of the public mode \( p_{i,b} \) and the individuals’ transport budget \( I_i \) for each area \( i \). The determination of these inputs depends on the data available from Siu et al. (1994), Fowkes et al. (1995) and Fowkes et al. (1998).

**Price of private mode** \( p_{i,v} \) The price of the private mode is determined by the average running fee with respect to the definition of the private mode in Fowkes et al. (1995), and then transferred to the unit of £ per mile.

**Price of public mode** \( p_{i,b} \) The price of the public mode is determined by the average fare of different public modes (£ per mile) according to Fowkes et al. (1995).

**Individuals’ transport budget** \( I_i \) It is difficult to obtain an accurate budget for travel for individuals in each geographic area. Here we estimate it according to the income statistics given by Siu et al. (1994) (See Table 6, page 21), which presented mean household incomes by person type and area type based on the NTS dataset. Generally,
we assume that no more than 20% of an individuals’ income is used as the transport budget.

According to the data available, the inputs ($p_{l,v}$, $p_{l,k,v}$, $p_{l,b}$, $p_{l,k,b}$ and $l_l$) are as shown in Table 2, which are used in the scenario simulation for the TCS. According to the 2006 base mileages presented for case I in Table 1, we can determine the parameters ($a_i$, $a_{i,k}$, $p_i$, $p_{l,k}$) for each area and for different travel purposes, also as shown in Table 2. These parameters are used in the analysis in Section 5.

Table 2 Inputs and calibrated parameters according to 2006 base mileage

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Purpose</th>
<th>London</th>
<th>Conurbations</th>
<th>Urban</th>
<th>Rural</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_{l,v}$ ($p_{l,k,v}$)</td>
<td>Work</td>
<td>$p_{1,1,v} = 0.1481$</td>
<td>$p_{2,1,v} = 0.0934$</td>
<td>$p_{3,v} = 0.0088$</td>
<td>$p_{4,v} = 0.0097$</td>
</tr>
<tr>
<td></td>
<td>Business</td>
<td>$p_{1,2,v} = 0.7976$</td>
<td>$p_{2,2,v} = 0.2896$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Leisure</td>
<td>$p_{1,3,v} = 0.1174$</td>
<td>$p_{2,3,v} = 0.0461$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_{l,b}$ ($p_{l,k,b}$)</td>
<td>Work</td>
<td>$p_{1,1,b} = 0.1284$</td>
<td>$p_{2,1,b} = 0.0114$</td>
<td>$p_{3,b} = 0.0022$</td>
<td>$p_{4,b} = 0.0025$</td>
</tr>
<tr>
<td></td>
<td>Business</td>
<td>$p_{1,2,b} = 0.4028$</td>
<td>$p_{2,2,b} = 0.0631$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Leisure</td>
<td>$p_{1,3,b} = 0.0056$</td>
<td>$p_{2,3,b} = 0.0075$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a_i$ ($a_{i,k}$)</td>
<td>Work</td>
<td>$a_{i,1} = 0.61$</td>
<td>$a_{i,2} = 0.96$</td>
<td>$a_{i,3} = 0.96$</td>
<td>$a_{i,4} = 0.97$</td>
</tr>
<tr>
<td></td>
<td>Business</td>
<td>$a_{i,2} = 0.81$</td>
<td>$a_{i,2} = 0.98$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Leisure</td>
<td>$a_{i,3} = 0.98$</td>
<td>$a_{i,4} = 0.95$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_i$ ($p_{l,k}$)</td>
<td>Work</td>
<td>$p_{i,1} = 0.14$</td>
<td>$p_{i,2} = 0.41$</td>
<td>$p_{i,3} = 0.24$</td>
<td>$p_{i,4} = 0.21$</td>
</tr>
<tr>
<td></td>
<td>Business</td>
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<td>$p_{i,2} = 0.12$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Leisure</td>
<td>$p_{i,3} = 0.23$</td>
<td>$p_{i,4} = 0.28$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$l_l$</td>
<td>--</td>
<td>2367.2</td>
<td>1663.6</td>
<td>1875.6</td>
<td>1990.2</td>
</tr>
</tbody>
</table>

4. Simulation and discussion

4.1 Comparing the effects of a TCS and congestion pricing scheme for London: a modelling approach

Although road congestion pricing is regarded as an efficient pricing strategy, it also brings some debates regarding, e.g., social equity (Giuliano, 1994) and economic efficiency (Banister, 1994; Viegas, 2001). Some people may also feel that paying for congestion is inappropriate, because they may prefer to pay for things they wish to acquire rather than for things they wish to avoid (i.e., traffic congestion) (Kahneman and Tversky, 1984; Geller, 1989). In fact recent studies have demonstrated that some alternative schemes can be designed to have the same impacts as road congestion pricing schemes. For example, Tillema et al. (2013) compared two congestion management schemes (road pricing and peak avoidance rewarding) and their impact on commuter behaviour, based on two studies that were conducted in the Netherlands. They concluded that the reward measure appears to be somewhat more effective in persuading people to travel outside peak hours, which would suggest that rewarding them may be more effective than charging (i.e., punishing) them. The behavioural rationale of many demand-based strategies aimed at managing traffic congestion, is
often based on negative incentives that associate the act of driving with punishment (in the form of tolls or increased parking costs).

With the parameters and inputs given in Table 2, we can estimate the annual mileage for each area and by different travel purpose. Scenario I in Table 3 presents the estimated annual mileage of Great Britain according to the data available, given in Section 4.2. Comparing Scenario I in Table 3 and Case I in Table 1, we find that the model $U_1$ and $U_1'$ can approach the 2006 base mileage given by Fowkes et al. (1998) well.

We are naturally interested in further considering the question of how should a TCS be designed so that it has similar impacts to congestion pricing? This is important in order that policy makers may understand how it would need to look in order to act as a substitute scheme whilst having similar impacts. If it were possible to do this in principle, then it would be interesting to evaluate the reactions of policy makers and also to bring further views from the social research perspective.

Instead of the £8 all day charge to travel into central London (as mentioned in Section 3.2), we now investigate the implementation of a TCS in London only. The model with a TCS was presented in Section 3. According to the simulation framework (as shown in Figure 1), we can derive the annual average miles. With the parameter settings as in Table 2, we further consider the following two scenarios:

- **TCS1**: $p_{1,e} = £1$, $\bar{x} = 16139$, credits are distributed equivalently initially;
- **TCS2**: $p_{1,e} = £0.5$, $\bar{x} = 16139$, credits are distributed equivalently initially.

For the scenarios TCS1 and TCS2 we assume that a TCS will be implemented in the London area, with each individual in London receiving the number of credits $\bar{x} = 16139$ at the beginning, which entitles the holder to travel 16139 miles within one year. As shown in Scenario II of Table 3, the annual mileage estimated from the model is similar to case II of Table 2, which are the results based on the road congestion pricing scheme given by Fowkes et al. (1995). It is also noted that the annual mileage did not change in other three areas (conurbations, urban and rural) as we only consider the TCS for the London area.

To identify the effects of the credit price, we implement a simulation with $p_{1,e} = £0.5$, as shown in TCS2, which halves the credits price whilst keeping other settings the same as in TCS1. As shown in Scenario III of Table 3, the annual mileage for the private mode will decrease whilst the annual mileage for the public mode will increase in the London area, compared with Scenario I without TCS. The difference between the annual mileage for the two modes demonstrate that the effects of the credit price. The credit price given in TCS1, $p_{1,e} = £1$, is the equilibrium price calculated according to Eqs (15) in Section 2.4. Furthermore, comparing the annual mileage differences for the private mode and public mode in the London area (Comparing Scenario II and Scenario III in London area), we find that the reduction in annual mileage for the private mode, (i.e. $30954.1 - 30152.6 = 801.5$ miles), is not
equal to the increase in annual mileage for the public mode, (i.e. $15373.7 - 15068.2 = 305.2$ miles). This demonstrates that in addition to individuals changing from the use of the private mode to the public mode, individuals choose not to take some trips.

Table 3 Annual mileages with a TCS in London under different scenarios (Unit: annual average miles)

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Mode</th>
<th>Purpose</th>
<th>London</th>
<th>Conurbations</th>
<th>Urban</th>
<th>Rural</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Private</td>
<td>Work</td>
<td>9937.6</td>
<td>17467</td>
<td>208209.6</td>
<td>201626.1</td>
<td>500148.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Business</td>
<td>2496.2</td>
<td>5660.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Leisure</td>
<td>19849.2</td>
<td>34902.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Subtotal</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Public</td>
<td>Work</td>
<td>6973.9</td>
<td>2825.4</td>
<td>19706.9</td>
<td>13770.6</td>
<td>58464.8</td>
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<tr>
<td></td>
<td></td>
<td>Business</td>
<td>933.9</td>
<td>383.9</td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Leisure</td>
<td>6590.1</td>
<td>7280.2</td>
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<td>Subtotal</td>
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<td></td>
<td></td>
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<td>58029.9</td>
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<tr>
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<td>7543.5</td>
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<td></td>
<td></td>
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<td>6878.4</td>
<td>7280.2</td>
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<td>Subtotal</td>
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</tr>
<tr>
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<td>201626.1</td>
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<td>5660.8</td>
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<td>19055.4</td>
<td>34902.1</td>
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<td></td>
</tr>
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<td>58029.9</td>
<td></td>
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<td></td>
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<td></td>
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<td>Work</td>
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<td>2825.4</td>
<td>19706.9</td>
<td>13770.62</td>
<td>59035.2</td>
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<td></td>
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<td>943.3</td>
<td>383.9</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Leisure</td>
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<td>7280.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Subtotal</td>
<td>15068.2</td>
<td>10489.4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Key: scenario I: Estimated annual mileage based on models $U_1$ and $U_1'$ (without TCS); scenario II: Estimated annual mileage with $U_2$ and $U_2'$ (with TCS1) scenario III: Estimated annual mileage with $U_2$ and $U_2'$ (with TCS2)

4.2 Emissions impact

We can further estimate the emissions impacts based on the simulations outlined in Table 3. According to the statistics (Naei.defra.gov.uk, 2014), the UK emissions data is $133.7$gCO2/km (82.89gCO2/mile) for a petrol car, $133.3$ gCO2/km (82.65gCO2/mile) for a diesel car and $1195.56$gCO2/km (741.25CO2/mile) for a bus. Without loss of generality, we assume all vehicles are petrol cars with the higher emissions factor. From Scenarios I-III given in Table 2, we can then roughly estimate
the emission differences as given in Table 4.

Furthermore, considering the increase in annual mileage for the public mode is small (fewer than 3 miles per day for Scenario II and even less for scenario III), we assume that the increase in miles for the public mode did not change the operational aspects of that mode (e.g., bus operations) and therefore does not increase public mode emissions.

We further assume a load factor for the private mode of 1, i.e., one car corresponds to one person travelling in the TCS. Based on Scenarios I, II and III given in Table 3, we can therefore calculate the annual CO2 emissions for the private mode according to the emission factors. As shown in Table 4, comparing Scenario I without a TCS and Scenarios II and III with TCS1 and TCS2, the CO2 emissions for the private mode decrease with the reduction in VMT. Therefore, we can aim to achieve both journey mileage and vehicle emission reduction targets with the implementation of a TCS, and further research will explore this more.

Table 4 Emissions differences with a TCS in London under different scenarios

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Mode</th>
<th>Mileage (unit:miles)</th>
<th>Emission (unit:gCO2)</th>
<th>Variance (unit:gCO2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Private</td>
<td>32283.0</td>
<td>2675937.87</td>
<td>-</td>
</tr>
<tr>
<td>II</td>
<td>Private</td>
<td>30152.6</td>
<td>2499349.014</td>
<td>176588.9(−)</td>
</tr>
<tr>
<td>III</td>
<td>Private</td>
<td>30954.1</td>
<td>2565785.349</td>
<td>110152.5(−)</td>
</tr>
</tbody>
</table>

5. Conclusions

The TCS has become familiar to environmental economists as a pollution control measure. This is in contrast to the case for many transport economists and transport management practitioners, for whom it is yet a new and unfamiliar approach. Despite that, researchers in transport economics can see the potential of a TCS for road traffic mobility management, although it is clear that many theoretical and application related issues remain undeveloped. In this paper, we have discussed how a TCS affects travelers’ mode choice using a simulation framework and measured the effects with respect to VMT and CO2 emissions.

A simulation study in Great Britain has been carried out to illustrate the working of the proposed model. We conclude that a TCS provides a promising policy option in reducing use of the private mode with respect to VMT. A cap-and-trade measure can achieve a target for trip reductions by private mode (as reflected by VMT) by changing travel mode-choices. The design of a tradable credits scheme (including the setting of a credit price) has been discussed. We emphasize that a TCS can clearly affect travelers’ mode choice under different credit prices, people can move from private mode to public mode and even restraint their total trips under a TCS. From another perspective, the presence of a TCS and a reduction in private mode use can
bring a reduction in total emissions.

The tradable credit scheme studied in this paper discourages use of the private mode by imposing quantitative restraints and encouraging a switch to PT travel, which could result in further emissions reductions. The TCS could be considered as an alternative to road congestion pricing and improve the transport system by restraining the growth of private mode trips and encouraging people to choose the public mode. This could also bring benefits from vehicle emission reductions. We assumed the increase in miles for the public mode did not change the operational aspects and therefore does not result in an increase in public mode emissions. This could be realized in practice with the development of the clean bus with low or zero emissions, which is an issue for future research. Some other key issues for further study are:

- An in-depth disaggregated analysis of the effects of the TCS on mode choice is necessary in order to explore how this type of scheme can deal with different mode choices from different perspectives;
- Further development of the model is needed to integrate route choice behavior under a macroscopic transport network equilibrium analysis;
- From general equilibrium approach to discuss the relationship of congestion, land use and management policies;

Policy packages are now favoured by many policy makers as an effective means to introduce behavioural change. Packages can be defined as any combination of one or more economic measures with one or more other types of measures (regulatory, physical, technology). Further research is needed to investigate how a tradable credits scheme could interact with these other types of measures within such a package.

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**References**


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