MODELING THE LEVEL OF ENVIRONMENTALLY EFFICIENT CAR OWNERSHIP

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Abstract: This study attempts to develop a macro-level car ownership model using a bi-level optimization modeling approach. The upper level of the bi-level model deals with a maximum problem of zonal car ownership. Objective function is the total zonal car ownership and the constraints are the legalized standard of air quality and the frontier emissions estimated using a stochastic frontier analysis approach. The lower level is a user equilibrium assignment model. Pollutant concentrations are estimated using an artificial neural network model. The interdependencies of car ownership, traffic flow, and the emissions and pollutant concentrations are logically represented based on an iterated optimization process. The final optimized car ownership can be used as a benchmark of realizing environmentally sustainable transportation systems. Based on the data collected in Dalian, China and the Millennium Cities Database, the effectiveness of the proposed car ownership model was empirically confirmed.

Keywords: Zonal Car Ownership, Stochastic Frontier Analysis, Artificial Neutral Network

1. INTRODUCTION

Economic growth induces the increment of car ownership, which in turn makes trip convenient on one hand, intensifies urban spaces and induces various urban problems such as traffic congestion, the heavy energy consumption and environmental pollution. Pollutions by car traffic have been increasing continuously since the last decades. For example, In Britain, at least three-quarter of CO, a quarter of CO2 and more than a half of NOx comes from car traffic (Stead, 1999). The similar phenomena have also appeared in some main large cities in China, where about 60% of CO, 50% of NOx and 30% of HC are from automobile emissions (Li, 2001). Emissions from road traffic have worsened the human living conditions and ecosystems, and consequently the sustainable development.

Basically, environmental loads from transportation system are mainly influenced by engine emission level, vehicle ownership level, and road network performance, where the first factor
can be dramatically reduced with the progress of technological innovations. However, the number of vehicles directly influences on both the pollution level and travel demand in a city. The future is expected that environmental performance of road traffic might be further worsened with the rapid increase of car ownership. Accordingly, it is becoming a more and more important policy concern how to balance the environmental sustainability and economic development, especially in developing countries.

As well-known, vehicle population in a city is affected by not only consumers’ preferences, but also circumstantial factors such as available parking space, road capacity, and taxations. Therefore, increase of vehicle ownership is not unlimited. Before traffic environmental load reaches the environmental capacity, i.e., the maximum capacity to accommodate environment pollution, authorities are required to take some measures to improve urban environmental quality, such as control of both vehicle ownership and use behavior. Thus, environmental capacity should be taken into account in the design of transportation systems. However, to measure the environmental capacity is still an ill-solved problem because some of the influential factors are unobservable. Instead of that, standards of air quality in cities are often adopted as a threshold for evaluating pollution level. As air quality is expressed as the value of pollutant concentration, it can be easily applied to control the environmental load in any scale of spaces.

Besides the environmental control at link level, it is also necessary to alleviate the total amount of emissions in the whole city from the perspective of environment protection. The specification of required level of total emissions traditionally depends on experts’ experiences, but the decisions sometimes are arbitrary and lack of theoretical support. Under such circumstances, in this paper, it is suggested to apply the concept of frontier output, which has been widely applied for efficiency analysis in the field of econometrics. By using such an approach, it is possible to calculate the frontier emissions, namely the environmental capacity, assuming there is no inefficiency of transportation systems.

To realize sustainable urban development, it is becoming more and more important how to meet the traffic demand caused by the increasing car population conditional on the environmentally acceptable levels. This paper attempts to propose an integrated model for predicting the environmentally sustainable car ownership in city level. Here, two types of environmental restrictions are included, one is the pollutant concentration limit at link level and another is the emission limit at city level. Here, the pollutant concentration is estimated using an artificial neutral network (ANN) model, while acceptable levels of emissions are calculated based on a stochastic frontier analysis (SFA) approach. To represent the interactions between the growth of car ownership and corresponding environment levels as well as the optimal traffic assignment, a bi-level optimization model is used. The upper level is a car ownership model, in which objective function is to maximize the total zonal car ownership, and constraints are, 1) pollutant concentrations on links from car traffic should meet the national standard of air quality, and 2) the emissions in the whole city should not exceed the frontier emissions. The lower level is a fixed-demand user equilibrium (UE) assignment model. Moreover, to examine the performance of the proposed model, a sensitivity analysis based optimization algorithm is adopted. In this paper, as an initial analysis of this integrated model, only passenger cars are dealt with. Including trucks and other vehicles in the model is left as a future research issue.

This paper is organized as follows. Section 2 gives a brief review of existing literature. After that, Section 3 describes the model structure. A case study in Dalian City, China is conducted in Section 4. Finally the study is concluded and some future research issues are also
2. REVIEWS

In varieties of historical literatures, car ownership is originally thought to be influenced by the urban economy level which usually expressed as GDP and the S-type line can better illustrate their interrelations (Dargay and Gately, 1999; Dargay, 2001; Ortuzar et al., 1999). In most recent studies, many indicators affecting car ownership have been discussed. In general, as the multiple influence factors on car purchase and car use, lots of scientific literatures concern the car-related studies using disaggregate analysis approaches from the viewpoint of household or individual characteristics (Choo and Mokhtarian, 2004; Bhat and Puluguranto, 1998; Kuwano et al., 2005).

However, as the significant negative influence on environment and energy consumption by road traffic in cities, various policy studies relating to car-environment nexus such as the additional emission tax for car purchase, the willingness-to-pay for environmental economy, car sharing, etc., have been conducted in most recently literature. Mueller and Haan (2006) proposed a computer model to simulate purchases of passenger cars under future policies about fuel consumption which mainly consists of cash rewards as so-called “bonus-malus” scheme, including tax rebates for fuel-efficient cars and surplus sales tax on highly fuel consuming vehicles. A multi-agent system with 24 different agent types is used to forecast the response of individuals under future bonus-malus schemes. John (2006) reviewed the literature and activities related to automotive environmental information and reveals issues pertinent to strengthening programs that foster consumer interest in "greener" (less polluting and more fuel-efficient) vehicles. Barth et al. (2006) overviewed and analyzed the car sharing systems in Japan and Singapore compared with European and North American cities.

In analyzing the amount of pollutants by transport, the computation of emissions and pollutant concentration made the important part of transportation environment studies with numerical feature. As the significant disadvantages of the widely discussed Gauss model, a series of line source models based on it, such as HIWAY, CALINE, GM, CAL3QHC, etc., are developed, which greatly improved the limitation of the Gauss model, but still have many deficiencies in representing the actual influences on pollutant concentration based on traffic flow characteristics. Considering the restriction in realizing the model in real applications, Park et al. (2006) proposed a methodology using a vehicle-mapping table which can convert Vehicle Miles Traveled fractions from FHWA types to MOBILE types deserves to utilize readily available data sources. Jackson et al. (2006) verified the variability in onboard measurements of light-duty vehicle gas and particulate emissions by drivers and road types based on data surveyed on a 30-mile test route.

Recently, most of studies have been interested in the forecast of pollutant concentration with the technique of ANN. Since the ANN-based model, compared with the traditional models, do not need to know the concrete formulation between input and output and can be used for solving such problems with great flexibility. For example, Drozdowicz et al. (1997) developed an ANN-based model to forecast CO concentration in Rosario city. Moseholm et al. (1996) investigated the relationships between traffic and CO concentrations near an intersection, which is sheltered from the wind by multi-story buildings. Gardner and Dorling (1999) predicted the hourly average $NO_x$ and $NO_2$ concentration in London with neural network. Nagendra and Khare (2004) developed the ANN-based line source model to forecast CO concentration and carried out the numerical test with observed data in an intersection and...
a link.

For environment control and management target, specification of the control value, namely environmental capacity, becomes an important topic as the reason that governors or officers intend to control the pollution into a certain range. However, environment system is very complicated since it involves various activities and units which lead to the impossibility to measure the environmental capacity. Kyoto Protocol has specified that the emitted pollutants of six kinds of greenhouse gases from all developed countries in 2010 should be reduced by 5.2% compared with the emission level in 1990. Additionally, regarding the first pillar of the EU’s strategy, in 2003, the average specific CO₂ emission of the fleets are 163 g/km for ACEA (Europe manufactures), 172 g/km for JAMA (Japan) and 179 g/km for KAMA (Korean) (Mueller and Haan, 2006). Especially in the most recent G8 international conference hosted by Germany, the new strategies to alleviate carbon dioxide are discussing. All these regulated values provide a meaningful upper limit for environment capacity operationally.

Analyzing from the systematic view, environment capacity in some extent can be substituted by the frontier environment level when the transportation system operates in the most efficient state. In this sense, the calculation of environment capacity moves to the environment efficiency analysis of transportation system. In details, the environmental frontier of transportation system, defined as the best environment level under current transportation condition, implies the potential environment threshold.

Actually, the technique of system efficiency analysis has been applied widely in varieties of fields (Chiang et al., 2004; Hu and McAleer, 2005; Herrero, 2005) besides the econometrics. For application in transportation, Costa and Markellos (1997) evaluated the public transport efficiency for the period 1970 to 1994, and Pels et al. (2003) analyzed the inefficiencies and scale economies of Europe airport operations. In most of the existing studies about efficiency or inefficiency, two approaches, SFA and DEA, are usually used for measuring system efficiencies, because of their inherent advantages and disadvantages.

In the procedure of transportation planning, it is necessary to combine planning or optimization problems with traffic assignment model for analyzing multiple decision makings in balance, thus the bi-level optimal problems are formed. Furthermore, to numerically obtain the level of sustainable car ownership under environmental consideration, the bi-level optimization model is adopted. Actually, bi-level optimization problem is a branch of multi-level problems, which reflects synchronously associated decision-making behaviors between upper and lower levels. Decision-makers in upper level and users in lower level usually have different objectives and interrelates each other.

Looking through the historical studies, bi-level programming has been used in transportation fields more and more widely. Yang and Yagar (1995) resolved the traffic assignment and signal control problems in saturated road networks. In their research, the lower-level problem represents a fixed demand user equilibrium assignment model involving queuing and congestion. The upper-level is an optimization problem about signal control, taking account of drivers’ route choice behavior in response to signal split changes. Shan and Gao (2004), based on bi-level programming theories, present the transit equilibrium network design problems, in which the upper model is a normal transit network design problem which minimizes total system impedance and total expenses caused by frequency settings. The lower level is a trip equilibrium assignment model, which present users’ route choice behavior. In addition, Yang (1995) predicted the O-D demand with bi-level optimization models. Tam and Lam (2000), based on bi-level programming models, presented the relationship between road capacity and
car ownership, in which the upper level is maximum car ownership model, and the lower level is an equilibrium trip distribution/assignment problem. Moreover, Tam and Lam (2004), from the view of both travel demand and road network provision, presented the conception of equilibrium car ownership, and gave some analysis on Hong Kong as an example. These studies are bases for the applications of bi-level programming in transportation fields.

At present, for solving the bi-level programming problems, various kinds of algorithms have been developed, but most of them are designed to concrete ones and lack generalizations. As the complexity of road network and the verboxity of data, the existed methods could not be used directly. Till the year 1988, Tobin and Friesz firstly applied the sensitivity analysis methods of variational inequalities on urban transportation network planning, and proposed the restricted sensitivity analysis method for urban transportation equilibrium network (Tobin and Friesz, 1988), and proved the consistency between the result from restricted equilibrium methods and original problems, which provide a base for the use of bi-level programming in transportation. In this paper, the sensitivity analysis based algorithm founded by Tobin and Friesz is used to figure out the bi-level problem. As the multiple modules comprised in the proposed framework, the estimation on each part is carried out and finally incorporated into an iterated calculation procedure.

3. MODEL DEVELOPMENT

Environmentally sustainable car ownership is modeled by incorporating an ANN model and a SFA model into a bi-level optimization model. The ANN model is used to estimate the pollutant concentration on links, and the SFA model is used to calculate the emission frontier at a city level, and the bi-level model deals with the simultaneous maximization of zonal car ownership and the corresponding traffic flow.

3.1 A bi-level optimization model

Here, the optimization problem is divided into two levels, where the upper level is to maximize total zonal car ownership and the lower level solves user equilibrium traffic assignment problem. The domain constraints are traffic environmental requirements from the perspective of sustainability. The model structure at upper level is shown as follows:

Max: \[ \sum_{i \in I} u_i \]  
\[ s.t. \quad D(E_a) \leq E_0, \quad a \in A \]  
\[ \sum_a E_a \leq y_0, \quad a \in A \]  
\[ E_b = g_b(v_b) \]  
\[ E_c = g_c(v_c) \]  
\[ E_a = E_c + E_b \]  
\[ u_i \geq 0, \quad i \in I \]

where, \( u_i \) - car ownership of zone \( i \),
\( D(\cdot) \) - diffusion function along links,
\( E_a \) - total traffic emissions on link \( a \),
\( E_0 \) - ceiling permitted pollutants concentration of link \( a \), here means the control level of air quality,
$y_0$ - total permitted emissions in the whole city, here means the environmental emission of efficient transportation system,

$E_b$ - bus emissions on links,

$E_c$ - car emissions on links,

$I$ - the set of zones,

$A$ - the set of links,

$v_b$ - car flow (pcu/h) on link $a$,

$v_c$ - bus flow (pcu/h) on link $a$,

$g_b(v_b)$ - function of bus emission on link $a$, and

$g_c(v_c)$ - function of car emission on link $a$.

Here, $y_0$ is calculated reflecting the environmental efficiency of transportation systems, which is obtained using the stochastic frontier model described later. $E_b$ and $E_c$, emission levels of bus and car, can be calculated by functions $g_b(v_b)$ and $g_c(v_c)$ respectively which consider the factors of traffic flow, link length and emission factors corresponding to different vehicle types and travel speed. The calculation equation of emissions can be formulated as follows:

\[ g_b(v_b) = v_b \times L_a \times \alpha_b \]  

\[ g_c(v_c) = v_c \times L_a \times \alpha_c \]

where, $L_a$ - the length of link $a$, and

$\alpha_b$, $\alpha_c$ - the emission factors of bus and car respectively.

It is assumed that only car and bus modes are available. Such modal split structure can be observed in most of Chinese cities, which are targeted in this paper. As road traffic environmental load is determined by not only physical structure of road, but also traffic volume and flow characteristics etc., it is necessary to represent car ownership level and traffic assignment in the same modeling framework. Here, this is realized by applying a bi-level optimization modeling approach, which deals with the above optimization problem of car ownership as an upper level and the following user equilibrium traffic assignment problem as a lower level.

\[ \text{Min: } \sum_a \int_0^{v_a} C_a(x)dx \]  

\[ s.t. \sum_r f_r = t_{ij}, \quad i \in I, \quad j \in J \]

\[ v_a = \sum_{r \in R} f_r \delta_{ar}, \quad a \in A \]

\[ f_r, t_{ij} \geq 0, \quad r \in R, \quad i \in I, \quad j \in J \]

where, $C_a$ - travel time of link $a \in A$,

$f_r$ - the flow on path $r$,

$t_{ij}$ - trips between O-D pair $(i, j)$, and

$\delta$ - the associated matrix of link and path.

Based on the above-described bi-level optimization model, the interdependencies existing in car ownership level, traffic flow and environmental load are incorporated simultaneously. As a result, environmentally sustainable car ownership level can be obtained.

3.2 Modal Split Model with Spill-over Effect

To represent the modal split between car and bus, we use the following equations (14) and
Here, $t'_{ij}$ - car trips between O-D pair $(i,j)$, $t^b_{ij}$ - bus trips between O-D pair $(i,j)$, $T_{ij}$ - traveler numbers between O-D pair $(i,j)$, $P_{cij}$ - probability of choosing car mode from zone $i$ to $j$, $P_{bij}$ - probability of choosing bus mode from zone $i$ to $j$, $\beta_c$ - occupancy rate of a car, $\beta_b$ - occupancy rate of a bus and $\omega_i$ - $u_i / \text{population of zone } i$.

One of the features of the above modal split model is to incorporate the spill-over effect caused by the unsatisfied car demand into the bus choice model. Concretely speaking, in case that current car ownership rate $\omega_i$ is less than actual choice probability $P_{cij}$, latent car users have to use bus because they do not have available cars. Such effect is called spill-over effect in this study.

### 3.3 Pollutant concentration model

The pollutant concentration is calculated using an ANN model. Considering the availability of data needed for network training and the data requirement in current study, a feedback neural network model developed in our previous studies (Feng et al., 2006) is adopted.

The network structure composed of nine input vectors (temperature, humidity, wind speed, wind direction, traffic volume, travel speed, flow composition, source strength and height level), three hidden neurons in a single hidden layer and single output vector (carbon monoxide). Model structure is shown in Figure 1.
When the developed model is introduced into the bi-level model, values of all the input variables and the estimated weight parameters, except for traffic volume and travel speed, are fixed during the optimization calculation process. Such treatment reflects the fact that only changing traffic conditions lead to a variety of pollutant concentrations, even though only one of the pollutants are dealt with here.

3.4 Environmental Efficiency Model

In system efficiency analysis, SFA (Stochastic Frontier Analysis) and DEA (Data Envelopment Analysis) are the two dominating approaches. DEA do not impose a specific function relationship between production output and input, but estimates the efficiency via an optimization formulation. One of the advantages of DEA approach is that it can calculate the efficiency even in case of very small sample size, but its disadvantages are that the calculation results are very sensitive to the set of input variables. However, SFA approach has an advantage of allowing for random shocks and measurement errors. It also assumes the specific statistical distribution of both random shocks and error terms. Since the significant statistical characteristics of SFA approach as well as the sufficient sample size at hand for parameter estimation and validation, SFA approach is chosen to calculate the environmental efficiency in this study.

Generally speaking, producers expect the minimum inputs bundles required to produce various outputs, or the maximum output producible with various input bundles, and a given technology, where it is called production frontier (Kumbhakar and Lovell, 2000). When analyzing the transportation system from environmental viewpoint, the decrease of pollutant level which can be regarded as the productive output. Furthermore, the environmental efficiency measurement of transportation system is considered as the cost efficiency, regardless of the price information needed in the production procedure. Thus, the environmental efficiency analysis model based on Monte-Carlo equation can be expressed as follows:

\[ \ln y_i = \beta_0 + \sum \beta_n \ln x_{i \alpha} + \varepsilon_i \]  
\[ \varepsilon_i = \nu_i + \mu_i \]

where, 
- \( y_i \) - output variable of firm \( i \), and here means the total amount of car emissions in city \( i \), regardless of the different travel modes,
- \( x_{i \alpha} \) - the \( \alpha^{th} \) input variable of sample \( i \),
- \( \mu_i \) - non-negative cost inefficiency component,
- \( \nu_i \) - two-sided random-noise component,
- \( \varepsilon_i \) - a composite error term, and
- \( \beta_0, \beta_n \) - the unknown parameters needed to be estimated.

Then, the measure of environment efficiency \( CE_i \) is provided by

\[ CE_i = \exp(-\mu_i) \]

Here, \( CE_i \) reflects the degree of environmental inefficiency. The lower of the value means the shorter distance from the actual value to the emission frontier. That is to say, high \( CE_i \) values are identical to the high emission level when the transportation system is efficiently operating.
3.5 Calculation Algorithm
For the standard UE model at lower level, the convex combination methods can be used to get link flow, path flow, and running speeds on each link. Then we calculate the pollutants with emission factors and the traffic characteristics to determine whether it is satisfied with the constraints or not. In addition, with sensitivity analysis based optimization algorithm we get the derivatives of the equilibrium link flows and path flows with respect to zonal car ownership, and feedback the derivative value and transportation environment load data into the upper model. Through solving the upper-level linear optimization problem, zonal car ownership with environmental capacity as a restraint can be obtained. Furthermore, new OD pairs can be calculated by car ownership data and are reassigned on the road network. This process will be iterated until convergence. Then the maximal car ownership level accommodated in a city conditional on environmental capacity is obtained.

During the iteration process, calculation of derivation of the upper level decision variable (zonal car ownership) to lower level decision variable (link flow) is the key problem, which could be calculated by variational inequality sensitivity analysis based algorithm. Sensitivity analysis reflects the fact that the solution changes with value of input variables. The purpose to analyze urban transportation network equilibrium problems with sensitivity analysis method is to find changes of equilibrium link flow in response to perturbation parameters. Therefore, it is necessary to calculate the derivatives of equilibrium link flow with respect to perturbation parameters. As road network equilibrium problem can be formulated as a form of variational inequality, the variational inequality based sensitivity analysis method helps the calculation of derivatives. But because of the network complexity and data volume, traditional sensitivity analysis method could not apply directly here. Tobin and Friesz (1988) proposed a sensitivity analysis based method for equilibrium flows in the restricted road network, which provides a foundation to calculate the derivatives of equilibrium link flow with respect to perturbation parameters. As the calculation complexity and consideration on paper length, the algorithm would not be discussed here.

To calculate the derivatives of link flow with respect to zonal car ownership, rewrite the lower level problem as the form of variational inequality, namely find the equilibrium link flow \( v^* \in \Omega \), for each \( v \in \Omega \), there is:

\[
\begin{align*}
  c(v^*)^T (v - v^*) & \geq 0 \\
  \Omega &= \{v \mid v = A^f, A^f = q, f \geq 0\}
\end{align*}
\]

(19) \hspace{1cm} (20)

\( c(v) \) is a link impedance vector, \( f \) is path flow, \( q \) is O-D matrix, \( A \) is link/path incidence matrix. The sufficient and necessary condition that variational inequality has solutions is:

\[
\begin{align*}
  c'(v^*) - \pi - A^T \mu &= 0 \\
  \pi_i f_i^v &= 0, \quad i \in I, \quad j \in J, \quad k \in K_{ij} \\
  A^f - q &= 0 \\
  \pi &\geq 0
\end{align*}
\]

(21) \hspace{1cm} (22) \hspace{1cm} (23) \hspace{1cm} (24)

Obviously, perturbation urban traffic equilibrium network problem can be changed to a variational inequality problem, namely find the equilibrium link flow \( v^* \in \Omega \), for each \( v \in \Omega \),
there is:
\[
c(\nu^*, \epsilon)^T (\nu - \nu^*) \geq 0
\]
\[
\Omega(\epsilon) = \{ \nu | \nu = \Delta f, \Lambda f = q(\epsilon), f \geq 0 \}
\]
(25)
(26)

In the restricted transportation equilibrium network, path flow has to be positive, namely just paths with flows are considered. Because the derivatives of equilibrium link flow with respect to perturbation parameters is completely same as the result of origin problems [28], the nonbinding constraints in matrix should be ridded in actual calculation process. Then, the form of simplified equations is given by:
\[
c^0(f^*, 0) - \Lambda^{0T} \mu = 0
\]
\[
\Lambda^0 f^{0*} - q(0) = 0
\]
(27)
(28)

Here 0 represents the corresponding vectors or matrices with decreased columns or rows. Meanwhile, the Jacobin Matrix of equation group with respect to \((f^0, \mu)\) could be formulated:
\[
J_{f^0, \mu} = \begin{bmatrix}
\nabla_{f^0} c^0(f^*, 0) & -\Lambda^{0T} \\
\Lambda^0 & 0
\end{bmatrix}
\]
(29)

Here, assume that
\[
[J_{f^0, \mu}]^{-1} = \begin{bmatrix}
B_{11} & B_{12} \\
B_{21} & B_{22}
\end{bmatrix}
\]
(30)

The following equation can be easily obtained
\[
B_{22} = [\Lambda^0 \nabla_{f^0} c^0(f^*, 0)^{-1} \Lambda^{0T}]^{-1}
\]
(31)
\[
B_{12} = \nabla_{f^0} c^0(f^*, 0)^{-1} \Lambda^{0T} [\Lambda^0 \nabla_{f^0} c^0(f^*, 0)^{-1} \Lambda^{0T}]^{-1} = \nabla_{f^0} c^0(f^*, 0)^{-1} \Lambda^{0T} B_{22}
\]
(32)
\[
B_{21} = -[\Lambda^0 \nabla_{f^0} c^0(f^*, 0)^{-1} \Lambda^{0T}]^{-1} \Lambda^0 \nabla_{f^0} c^0(f^*, 0)^{-1} = -B_{22} \Lambda^0 \nabla_{f^0} c^0(f^*, 0)^{-1}
\]
(33)
\[
B_{11} = \nabla_{f^0} c^0(f^*, 0)^{-1} [I - \Lambda^{0T} [\Lambda^0 \nabla_{f^0} c^0(f^*, 0)^{-1} \Lambda^{0T}]^{-1} \Lambda^0 \nabla_{f^0} c^0(f^*, 0)^{-1}]^{-1} = \nabla_{f^0} c^0(f^*, 0)^{-1} [I + \Lambda^{0T} B_{21}]
\]
(34)

In addition,
\[
\begin{bmatrix}
\nabla_{\epsilon} f^0 \\
\nabla_{\epsilon} \mu
\end{bmatrix} = \begin{bmatrix}
B_{11} & B_{12} \\
B_{21} & B_{22}
\end{bmatrix} \begin{bmatrix}
-\nabla_{\epsilon} c^0(f^*, 0) \\
\nabla_{\epsilon} q(0)
\end{bmatrix}
\]
(35)

From the incidence relations between link and path, we obtained:
\[
\nu^0 = \Delta^0 f^0
\]
(36)
\[
c^0(f^*, 0) = \Delta^{0T} c^0(\nu^*, 0)
\]
(37)
\[
\nabla_{\epsilon} \nu^0 = \Delta^0 \nabla_{\epsilon} f^0
\]
(38)
\[
\nabla_{\epsilon} c^0(f^*, 0) = \Delta^{0T} \nabla_{\epsilon} c^0(\nu^*, 0)
\]
(39)
\[
\nabla_{f^0} c^0(f^*, 0) = \Delta^{0T} \nabla_{f^0} c^0(\nu^*, 0) \Delta^0
\]
(40)

\(c^0(\nu^*, 0)\) is the vector of restricted link impedance function, \(\Delta^0\) is the corresponding matrix \(\Delta\), which cut the columns or rows. Thus it can be seen that the derivatives of equilibrium link
flow with respect to perturbation parameters can be calculated from formula \( B_{11}, B_{12}, (35) \sim (39) \) and (34). Here the perturbation parameter in upper level problem means car ownership. More detailed explanation about the optimized calculation could be found in any of the literatures (Tobin and Friesz, 1988; Yang, 1995; Gao and Sun, 2004). Here, we just simply formulate the realization steps of sensitivity analysis based algorithm as follow:

Step 0: Determine a set of initial car ownership \( u^{(k)} \), modal splits \( P_b^{(k)}, P_c^{(k)} \), occupancy ratio \( \beta_b, \beta_c \), number of travelers between zones \( T_{ij} \), etc, and set \( k = 0 \);

Step 1: Calculate travel demand \( t_b^{(k)}, t_c^{(k)} \) of car and bus respectively between zone \( i, j \);

Step 2: Solve user equilibrium assignment problem in lower level to get link flow \( v^{(k)} \), and calculate the corresponding environment load;

Step 3: Calculate \( \nabla u v^{(k)} \), the derivatives of link flow with respect to car ownership by the sensitivity analysis based algorithm;

Step 4: Take derivatives information and traffic environment load into upper model to solve upper linear programming problem to obtain a group of new car ownership \( u^{(k+1)} \);

Step 5: If \( |u_i^{(k+1)} - u_i^{(k)}| \leq \omega \) (\( \forall i \in I \)) stop calculation, otherwise, let \( k = k + 1 \), return to step 2.

4. CASE STUDY

Taking Dalian city as an example, we tested the integrated model. Dalian is a mountainous city, where the main travel modes are car and bus, and there is almost no bicycle in use. Figure 2 shows Dalian’s road network and zonal central IDs.

The topological data are obtained from the PT survey in 2000, and already has been compiled into the GIS database. The network which has been simplified for the purpose of calculation totally includes 33 zones, 895 links and 544 nodes. The traffic assignment link impedance function of traffic assignment is composed an ordinal BPR function with the following form.

\[
c_a \left( v_a \right) = C_a \left\{ 1.0 + 0.15 \left( \frac{v_a}{S_a} \right)^4 \right\}
\]

(41)

Although there are many pollutants emitted from road traffic, here only CO is dealt with considering its big share in urban environment pollutions. Emission factor of CO from existing study is used as follows (Yang, 2003):

\[
R_a = 11.14272 \frac{e^{0.047772 h_a}}{3280.8 h_a}
\]

(42)

where, \( R_a \) = emission factor on links (g/vehicle \cdot m), \( h_a \) = average speed on link \( a \) (km/h).
The emission result is taken as the input for concentration model which are constructed with ANN technique. Here, to obtain the ANN model, we used the actual data set surveyed based on five road segments in Dalian city for network training. When verifying the accuracy of training and testing procedure, the trained model is directly introduced into bi-level model. A three-layer network structure, with single hidden layer, is specified finally and the reflection functions in hidden layer and output layer are Sigmoid function and linear function respectively. More details on procedure of concentration prediction can be indexed from the paper by Feng et al. (2006).

The calculation of environmental control value in the whole city level is formulated using SFA technique. For simplifying the calculation of environmental efficiency, only one input variable, car ownership, is taken into account, and also single output variable, carbon monoxide. The dataset used for validation is selected from the Millennium Cities Database which is compiled by UITP, in collaboration with Murdoch University. The database includes the data covering 100 cities worldwide concerning demographics, economics, urban structure and a large number of transport related data. Although varieties of factors influencing the emissions of transportation system, for matching the requirement of current paper, the single indicator, car numbers of each 1000 person, is taken into account. For this case, it is assumed the car ownership absolutely determines the emission levels in a city.

The final formula of environment efficiency analysis is obtained based on the data of 59 cities which are selected from the database as the reason of data absence. For Dalian case, the efficient emissions, here named the environmental capacity, can be computed by this model.
only need to change the value of car ownership. The result of parameter validation is shown in Table 1.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Std. Error</th>
<th>t-ratio</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>1.546</td>
<td>0.396</td>
<td>3.909</td>
</tr>
<tr>
<td>Car numbers per 10,000 persons</td>
<td>0.751</td>
<td>0.054</td>
<td>13.944</td>
</tr>
<tr>
<td>Std. deviation of composite error term</td>
<td>0.464</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model Log likelihood</td>
<td>-28.24</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Thus, the environmental frontier could be calculated by the following equation:

$$\ln(y_{CO}) = 1.546 + 0.751\ln(x_{car})$$

(43)

where, $y_{CO}$ and $x_{car}$ are the amount of carbon monoxide emission and car numbers per 1000 persons respectively.

For controlling the pollutant concentration at link level, the environment standard of atmosphere quality in China (shown in Table 2) is adopted. Because there are not so many heavy industries existed in Dalian which answer for much in environmental load, the pollution share by transportation contribute most ratio on CO pollutions. Therefore, the day-average concentration limit is directly used as the restriction value ignoring the pollution shares by transportation system and the level II of air quality for environmental control is used in this study.

<table>
<thead>
<tr>
<th>Pollutants</th>
<th>Concentration Limits (mg / m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Period</td>
</tr>
<tr>
<td>TSP</td>
<td>Day-average</td>
</tr>
<tr>
<td></td>
<td>Each time</td>
</tr>
<tr>
<td>PM10</td>
<td>Day-average</td>
</tr>
<tr>
<td></td>
<td>Each time</td>
</tr>
<tr>
<td>SO2</td>
<td>Day-average</td>
</tr>
<tr>
<td></td>
<td>Each time</td>
</tr>
<tr>
<td>NOx</td>
<td>Day-average</td>
</tr>
<tr>
<td></td>
<td>Each time</td>
</tr>
<tr>
<td>CO</td>
<td>Day-average</td>
</tr>
<tr>
<td></td>
<td>Each time</td>
</tr>
<tr>
<td>O₃</td>
<td>Hour-average</td>
</tr>
</tbody>
</table>

We input all data of road network and zones into a MapInfo system, and match zonal central IDs with a node layer in road network. These data are essential for traffic assignment with Frank-Wolfe method. OD demand is assumed to be fixed person trips between each pairs and modal split changes according to the vector of zonal car ownership.

To calculate the derivative of link flow with respect to car ownership, it needs to deal with lots of links, nodes and zones data. Here, we represent the data with matrix style and integrate Visual Basic with Matlab to carry out matrix calculation. At last, with the technique of MapBasic, we illustrate the calculated results in GIS platform (MapInfo). During the calculation, it is found that after 2337 time iterations, output got to convergence. Table 3 shows a part of the calculated results.
Here, the $P(i)$ in Table 3 means the mode share of cars in zone $i$. This variable is increasingly changed with the increment of car ownership in zone level. From above results, it also can be seen that with the increment of trip demands, urban car ownership increase gradually, which lead to the aggravation of environment pollution by road traffic. Although the micro change is not always increased, the main trend is upward. When the iterated calculations get convergence under the constraints of limited concentration and environmental efficiency, car ownership in a city reaches the optimum. With reference to this information, authority may take some management measures to control car numbers in a sustainable level, to improve urban environment and to optimize travel distributions.

### 5. SUMMARY

This study attempts to estimate environmentally sustainable car ownership level in a city by integrating ANN and SFA approaches into a bi-level optimization modeling framework, where the upper level deals with car ownership and the lower level does traffic assignment. The car ownership model aims to maximize the zonal car ownership conditional on both the legalized standard of air quality and the environmental efficiency. The lower level is a user equilibrium assignment model, which is used to calculate optimally assigned traffic flow over the road network, and running velocities. Car ownership and transportation environmental load are connecting variables between the two levels. In car ownership model, we calculated the modal splits between bus and car by zones, and get the car and bus trip OD for the whole city. Then traffic flows and traffic environment load on links can be calculated with output of assignment model. Since traffic environment load controls car numbers in the upper level, models in two levels depends each other.

The developed integrated model has the following features: 1) car ownership level is calculated to meet both environmental sustainability and traffic demand, where environmental efficiency is introduced as a proxy indicator to represent sustainable level; 2) spill-over effect of unsatisfied car demand is incorporated in modal split model.

To realize the feedback between the two levels and solve such special optimization models, a sensitivity analysis based optimal algorithm is adopted. Through iterated feedback between the two levels, zonal car ownership subject to environment sustainability can be obtained.
A case study in Dalian, China is carried out to confirm the effectiveness of the model. The result shows that as the increase of trip demand and car ownership, environment load from car traffic aggravates continuously. Once the interactions between upper problem and lower problem in two levels reach certain extent, sustainable car ownership is decided. Such sustainable level of car ownership could be used as a benchmark of indicating the levels of various environmental sustainable transport policies, regulations or measures to control car ownership and reduce the pollutions from road traffic from the perspective of realizing a sustainable urban development.

REFERENCES


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