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An integrated model system and policy evaluation tool for maximizing mobility under environmental capacity constraints: A case study in Dalian City, China

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ABSTRACT

This paper presents an integrated model system for mobility maximization based on a quantified specification of environmental capacity, and evaluates policy interaction and effectiveness by simulating a number of policy scenarios. The system is designed to specify the maximum level of car ownership and number of trips by private and public modes subject to an environmental capacity constraint defined as the frontier emission under maximum system efficiency. Four types of hypothetical policies (population change, urban sprawl, land-use pattern and network improvement) are designed and the effects of 13 policy scenarios are simulated using data of Dalian City, China. Results reveal that the integrated model system reacts sensitively to policy interventions. The urban sprawl reflected in a changing residential distribution from central to suburban areas is most instrumental from the perspective of pollution alleviation. If the goal is to simultaneously reduce emissions while accommodating mobility, two combinational policy scenarios outperform all others.

1. Introduction

In most Chinese cities, vehicles have become the major source of greenhouse gas (GHG) emissions (Cai and Xie, 2007) due to rapidly increasing car ownership. The standard limit for pollution concentration is, however, often the same for all areas in a city regardless of any spatial differences in travel behavior. Given potential local geographical variations in pollution there may be a justification for a more dynamic scheme with flexible thresholds.[1]

On the basis that it is important to simultaneously consider traffic pollution control and mobility management (MM), we develop an integrated model system that specifically addresses the interaction between mobility levels, defined by car ownership and car use, and traffic-induced pollution based on transport equilibrium theory and using the concept of environmental capacity (EC). Taking EC as a constraint, the objective of the system is to find the maximum car ownership and number of trips possible. Compared to the earlier model in Yang et al. (2005) and Feng et al. (2007) several changes are made.

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[1] Prior studies of traffic-related pollution have mainly looked at emission prediction, the simulation of diffusion (Dirks et al., 2003; Feng et al., 2006), and the assessment of exposure (Torres, 2008). Few have involved the specification of pollution limits. Equally, In the past, several integrated urban models and decision support tools have been developed, vary from those analyzing interactions between land use and transportation based on the concept of an equilibrium (Waddell, 2002), to more integrated frameworks incorporating urban dynamics and/or environmental performance indicators using activity-based models (Hatzopoulou et al., 2007; Beckx et al., 2009) but none consider environmental capacity as a constraint.

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The paper examines the improved integrated model system, and its policy effectiveness, in a case study of policy scenarios using data from Dalian City, China.

2. The integrated model system

The modeled system involves an equilibrium with trip distribution and mode choice treated at the aggregate level. The system consists of multiple interactive sub-models that focused on a single objective: maximizing car ownership and the number of trips, with the objective of meeting an increasing demand for private cars, while simultaneously controlling their use by balancing the number of trips between private and public transport modes. The model involves constraining the traffic-related environmental load so that is does not exceed a frontier standard of air quality. The environmental load is estimated on the results of traffic assignments, while environmental capacity is specified in terms of car ownership and road network density. When the maximum car ownership is estimated, an update of origin–destination (OD) trip matrix for private and public modes is activated through the mode choice module. The new O–D trip matrix is assigned to the road network and used to predict the emission levels on links. This process is iterated until the estimation error falls below some convergence criterion (Fig. 1).

A bi-level (BL) programming approach representing the interaction between decision makers at the upper level and followers in the lower adopted. This allows for the simultaneous consideration of both bottom-up and top-down policy decision-making that may in political terms be effective in achieving a smooth consensus building among different stakeholders.

Two levels of problems, the upper level (ULP) and lower (LLP) are identified. The former entails maximizing the sum of zonal car ownership and the number of trips by car and public modes, while the LLP is a combined trip distribution and assignment model that explicitly incorporates route choice behavior mechanisms. A logit-type aggregate modal split model is used to connect the levels as follows:

- *Upper level problem*

$$\text{Maximize } \lambda_u \sum_{i \in I} u_i + \lambda_v \sum_i \sum_j (\varphi_{ij}^c \cdot q_{ij}^c + \bar{\varphi}_{ij}^c \cdot \bar{q}_{ij}^c) \tag{1}$$

$$\text{Subject to } E_i(u_i) \leqslant E_{0i}, \quad i \in I \tag{2}$$

$$E_i(u_i) = \sum_{a \in A_i} e_a, \quad A_i \in A \tag{3}$$

$$e_a = \gamma_{ak} \times v_a \times l_a, \quad a \in A, \; k \in K \tag{4}$$

$$q_{ij}^c(u_i) = Q_{ij} \cdot P_{ij}^c(u_i) \tag{5}$$

$$\bar{q}_{ij}^c(u_i) = Q_{ij} \cdot (1 - P_{ij}^c(u_i)) \tag{6}$$

$$0 \leqslant u_i \leqslant u_{0i}, \quad i \in I \tag{7}$$

where u_i represents car ownership in zone i, and u_{0i} is the maximum car ownership in zone i; q_{ij}^c and $\bar{q}_{ij}^c$ are trip demand between O–D pair (i, j) by car and public mode; E_i is the emissions in zone i and E_{0i} is the emissions capacity in zone i; e_a represents the emission on link a; γ_{ak} is the emission factor of category k on link a and k indicates travel speed category; v_a represents the link volume; l_a represents the length of link a; Q_{ij} is the trips between O–D pair (i, j); P_{ij}^c is the probability of choosing car mode from zone i to zone j; I, A, and K are the set of zones, links and travel speed and; $\lambda_u, \lambda_v, \varphi_{ij}^c$ and $\bar{\varphi}_{ij}^c$ are the pre-defined parameters relating to u_i and q_{ij}.

The upper level problem is a standard optimization problem where the objective function is the weighted sum of car ownership and the number of trips, as shown in Eq. (1). The inequality constraint condition is the emission in each zone i ($E_i(u_i)$) which is the function of zonal car ownership (u_i) which is less than the related EC (E_{0i}). The number of trips is calculated from the travel demand between O–D pairs (Q_{ij}) and mode choice probability (P_{ij}^c), where the latter is also a function of zonal car ownership.

This objective function allows the simultaneous representation of two or more policy goals. The parameters λ_u, λ_v, ϕ_{ij}^c, and $\bar{\phi}_{ij}^c$ reflect different weights for these goals. Larger values of $\bar{\phi}_{ij}^c$ may result in more trips by public mode and less by car while ensuring that the aggregate number of trips maximized. Parameters such as λ_u and λ_v can also be used to reflect different emphasis between car ownership and trips.

The emissions associated with each link are calculated as the product of link length, traffic volume and emission factors, which depend on the average driving speed on each link. Traffic volume (v_a) and average travel speed come from the traffic assignment. The emission factors are based on previous third-part studies. The emissions E_i from zone i equal the sum of emissions from links (e_a) associated with zone i. Thus, the area and spatial location of each zone affects the emission and concentration levels. For instance, zones within the central business district (CBD) generally have a dense road networks with heavy traffic flows, and therefore high emission/pollution concentrations, although small in area. In contrast, suburban zones are usually larger, but because of thinner road network densities, suffer less pollution than CBD zones.

The car ownership in each zone is restricted within the range $[0, u_0]$. Theoretically, this limit could be equal to or greater than the maximal ownership derived from the BL programming approach.