Modeling Time-dependent Tolls under Transport, Land Use, and Environment Considerations

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Abstract

Recently, there has been resurgence of interest in road pricing (Lo and Szeto, 2005). Along with the popularity of the concept of sustainability, transport planners no longer ignore the environmental considerations when analyzing and designing a transportation system for pricing. This paper develops an analytical model to determine the optimal tolls over time to control the traffic emissions while capturing the land use-transport interaction. To illustrate the effect of tolls on the transportation system with land use and environmental considerations, a numerical study is performed. The results show that the implementation of tolls can reduce the overall traffic emissions, generate more transit revenue and alter the travelers' choices of modes, routes, living and working locations.

Introduction

Environmental pollution due to traffic is one of the most critical problems confronted by policy makers as well as the public. Transport planners no longer ignore the environment when designing and evaluating a sustainable transport system, and they do not ignore the dynamic relationships between land use, transport, and environment. One popular method adopted by transport planners to manage the transport system is by charging tolls on roads. In the past, much research has been carried out to address some practical perspectives when designing an optimal road pricing scheme (e.g. Mun et al., 2001; Hyman and Mayhew, 2002; Zhang and Yang, 2004). In particular, Sumalee (2005) proposed an optimization algorithm considering a time factor to design an optimal implementation path for a charging cordon scheme. Nonetheless, he did not address the relationships between land use, transport and environment. To address this, we develop an analytical model to determine the time varying optimal tolls to control the traffic emissions while capturing the land use-transport interaction. This model is new in the sense that there was no analytical model to determine time-varying tolls capturing the land use-transport-environment interaction. We study the effect of tolls on environment, the land use-transport interaction as well as the public transit system. In the following, the second section

depicts the proposed model and its structure. The third section is the numerical study. Finally, the last section gives concluding remarks.

Model and its structure

An analytical model is developed to determine the tolls over time while capturing land use and environmental considerations. The way in which land use interacts with transport and environment over time is outlined in figures 1 and 2 below.

Figure 1. Dynamic relations in the land use and transport systems with environmental consideration.

Figure 2. General structure of an integrated land use-transport model with environmental consideration.

To simplify the analysis, the following assumptions are made in this paper. 1. Basic employment, basic employment growth rate over time, and the zonal attractiveness are known; 2. Each zone has only one characteristic, and the residential zone and the

employment zone are not mixed; 3. Traffic assignment follows the user-equilibrium principle; 4. The link cost and travel demand functions are separable; 5. The interest and inflation rates are constant over time for the sake of simplicity. These assumptions are not restrictive from a modelling perspective; most of these assumptions can be relaxed in further studies.

In this paper, the air pollution caused by traffic can be measured by vehicular emissions. The proposed model can be stated as:

$$\mathbf{M1} \quad \min_{E,R,f,\rho} Q = \sum_{\tau} \sum_a Q_{a,\tau} = \sum_{\tau} \sum_a h_{a,\tau}^e f_{a,\tau}, \quad (1)$$

subject to Lowry-based land use model constraints, and the annual-based traffic assignment constraints which are referred to by Lo and Szeto (2006). In this model, E, R, f, ρ represent, respectively, the vectors of service employment trips, residential trips, path flows, and tolls. Q is the overall vehicular emissions; $Q_{a,\tau}$ is the vehicular emissions due to traffic on link a in year τ ; $h_{a,\tau}^e$ is the emission factor on link a in year τ , which is assumed to be given for all links. The variables affecting the value of $h_{a,\tau}^e$ are discussed in Nagurney (2000); $f_{a,\tau}$ represents the hourly traffic flow on link a in year τ . According to (1), the vehicular emissions on a particular link is the product of the link flow and the corresponding emission factor, and the overall vehicular emissions are obtained by summing all the vehicular emissions of each link over time.

Numerical studies

To illustrate the effect of tolls on the vehicular emissions and dynamic relationships between land use and transport systems, a simple scenario is set up. The scenario network is shown in figure 3 with five nodes, six links and six origin-destination (OD) pairs as well as the public transit system operated between each OD pair. The six OD pairs are E1-R3, E1-R4, E1-R5, E2-R3, E2-R4, and E2-R5 respectively. E1 and E2 represent employment zones 1 and 2 respectively. R3, R4, and R5 correspondingly represent residential zones 3, 4, and 5. The parameters adopted in this scenario are shown in table 1 below.

Figure 3. Illustration of the transport network.

Table 1. Model parameters.

Planning horizon: 3 years.
Transport model parameters: The interest rate=0.03; the inflation rate=0.01; Value of time=€10/hour; The road network: Free flow travel times (mins): $T_{13}=T_{24}=20$, $T_{15}=T_{25}=T_{53}=T_{54}=15$; Car-specific constant=0.8; The public transit system: Travel times (mins): $T_{13}=T_{24}=12$, $T_{14}=T_{23}=20$, $T_{15}=T_{25}=10$; Transit fares (euros/person): $f_{13}=f_{24}=2$, $f_{14}=f_{23}=2$, $f_{15}=f_{25}=1$; Transit-specific constants: $p_{13}=p_{24}=1.8$, $p_{14}=p_{23}=p_{15}=p_{25}=1$.

Land use model parameters:

Basic employment: $E1=1000$ jobs, $E2=800$ jobs; Population to employment ratio=5; Service employment to population ratio=0.1; Parameter for accessibility to the residential zone=0.8; Parameter for accessibility to the employment zone=0.6; parameter for the composite cost=1; Attractiveness: $E1=E2=1000$ jobs; $R3=R4=R5=1000$ houses; population and employment growth rates=0.04.

Environment parameters:

Emission factors (liter/veh): $e_{13}=0.7$, $e_{24}=0.6$, $e_{53}=0.4$, $e_{54}=0.3$, $e_{15}=e_{25}=0.5$; maximum allowable vehicular emissions (liters/hour/link): $S_{13}=S_{24}=1000$, $S_{53}=S_{54}=S_{15}=S_{25}=900$.

Figure 4. The overall vehicular emissions and the maximum allowable vehicular emissions over the entire planning horizon on the whole network.

control the traffic emissions. However, the toll operator has to select the toll level carefully, because not any toll value can be set to achieve the overall vehicular emissions under the maximum allowable vehicular emissions. For example, in the scenario studied, when the toll is greater than €2.4, the overall vehicular emissions is under the maximum allowable vehicular emissions of 1.68E3 liters/hour. In particular, when the toll is greater than €3, the overall vehicular emissions remain at the same level. Thus, this problem raises an issue for the government of how the optimal toll can be chosen when implementing tolls on the transport network. The proposed model can be used for this purpose.

The implementation of tolls on links not only lowers the traffic emissions but also has a significant impact on the public transit system and the land use pattern. Figure

Figure 5. Number of passengers on OD pair 1-3 on the public transit system and the total transit revenue over the entire planning horizon.

In this scenario, we vary the toll level on link 1 from €0 to €5. The overall vehicular emissions on the entire network are plotted in figure 4. From this figure, we can observe that the tolls can be implemented to

5 depicts the number of passengers on OD pair E1-R3 on the public transit system and the total transit revenue over the entire planning horizon. It is demonstrated from this figure that the toll implementation on link 1 causes travelers between OD

pair E1-R3 to change their mode choice and take public transit instead of private cars. When the toll level rises, more passengers are attracted to the public transit system in order to decrease their travel costs. Beyond the toll level of €3, the number of passengers on transit between OD E1-R3 goes stable. Figure 5 also reveals the implementation of tolls can generate more transit revenue. When there is no toll on the transport network, the total transit revenue is only €1.35E7. However, after charging a toll of €3 on link 1, a 21.5% increase up to €1.65E7 on the revenue is obtained.

Figure 6. Total number of residents in zones 3, 4 and 5 over the entire planning horizon.

Figure 7. Total employment in zones 1 and 2 over time.

Figure 8. Number of residents in zones 3, 4 and 5 over time.

Figures 6, 7 and 8 illustrate that the implementation of tolls has an impact on the land use pattern. Figure 6 reveals the change of the total number of residents in zones 3, 4 and 5 due to the implementation of tolls over the entire planning horizon. Figure 7 shows the rearrangement of employment due to the change of tolls on the network. Figure 8 indicates the change of the number of residents in residential zones 3, 4 and 5 over time. From figure 8, it is revealed that there are dramatic changes in the numbers of residents in zones 3 and 5 over three years when tolls are ranged from €0-€3. These results demonstrate tolls can alter traveler's choice to choose their working and living locations, which has a strong implication on land owners' profits as the profits depend on the population and the size of the population-serving sector on their land.

Concluding remarks

In this paper, we propose an analytical model to determine the optimal tolls over time to control traffic emissions while capturing the land use-transport interaction. The model is a single level minimization program in which the objective function is to minimize the overall vehicular emissions over the entire modeling horizon. This paper also studies the impacts of the toll implementation on the environment in terms of vehicular emissions, the total transit revenue and the change of the number of residents and employment locations in a simple example. The results demonstrate that: (i) regarding to road pricing policy effectiveness, road pricing is a tool to mitigate the traffic emissions by diverting some travelers to take public transit. However, we need to set an optimal toll; (ii) road pricing contributes to generate more transit revenue; (iii) pricing has a great impact on the distribution of residents and employees in the land use system, which has an implication on land owners' profits. In this case, tolls must be carefully selected, and; (iv) not all toll values can affect the land use pattern and traffic pattern (not shown here due to space limitation). In the future, we can extend this study to consider the impact of road pricing on society such as social welfare and the land use owner's profits. It would also be interesting to model the transport network under the stochastic user equilibrium assumption in order to study the performance of the transport system effectively, as the model with the deterministic user equilibrium assumption does not represent the real world scenario.

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