Road Network Equilibrium Approaches to Environmental Sustainability

Environmental sustainability is closely related to transportation, especially the road network, because vehicle emissions and noise damage the environment and have adverse effects on human health. It is therefore important to take their effect into account when designing and managing road networks. Road network equilibrium approaches have been used to estimate this impact, and to design and manage road networks accordingly. However, no comprehensive review has summarized the applications of these approaches to the design and management of road networks that explicitly address environmental concerns. More importantly, it is necessary to identify this gap in the literature so that future research can improve existing methodologies. Hence, this paper summarizes these applications, and identifies potential future research directions in terms of theories, modeling approaches, algorithms, analyses, and applications.

Keywords: road network equilibrium; environmental sustainability; bi-level transport problems; traffic assignment; vehicle emission models; noise models

Introduction

There is no universally accepted definition of environmental sustainability (ES). Voet *et al*. (2000) stated that ES "is guaranteed when environmental interventions are kept within the limits of the environmental carrying capacity". Sutton (2004) referred to ES as the ability to maintain the qualities that are valued in the physical environment, which includes the natural and biological environments. Stead (2008) indicated that ES "means maintaining the integrity, productivity, and resilience of biological and physical systems, and preserving access to a healthy environment". Although these definitions differ from one another, they all incorporate the concept of maintaining the quality of the environment.

ES is closely related to transportation, and in particular road transportation, because motor vehicles traveling on roads emit emissions and noise, which impoverish the environment. While it is difficult to estimate the proportion of noise generated by road transport, the quantities of vehicle emissions are known to be large. For example, it was

estimated that in Hong Kong over 80% of carbon monoxide (CO), 20% of nitrogen oxide and 30% of particular matter in the atmosphere were found to emanate from road transport in 2007 (HKSAR Environmental Protection Department, 2007)

Both vehicle emissions and noise can have adverse effects on human health (Cappiello, 2002). Moreover, carbon dioxide is not only one of the major vehicle emissions, but also a greenhouse gas that contributes to global warming (Cappiello, 2002). It is therefore important to control the quantities of vehicle emissions and the level of traffic noise generated to reduce the impact of road transport activities on the environment and human health. Other than the overall emissions and noise levels, their spatial and temporal distributions need to be controlled, since these distributions are associated with an issue called environmental equity.

Road network equilibrium approaches have been used to estimate vehicle emissions and noise, and accordingly to design or plan road networks that take ES and environmental equity into account. These approaches rely on road network equilibrium models to distribute traffic onto the road network before the associated vehicle emissions and noise can be determined and environmentally sustainable road networks can be designed through the formulation of bi-level problems. In particular, equilibrium approaches rely on equilibrium travel choice principles to depict route choice of drivers and sometimes their departure time and mode choices as well. An advantage of equilibrium approaches over several other types of optimization approaches is that equilibrium approaches are capable of capturing travel choice behavior and also the response of drivers as a result of the implementation of transportation planning and traffic management policy. For example, these approaches can capture how the driver changes his/her route as a result of adding new roads to the transport network. Compared with empirical models, equilibrium approaches can also depict the vehicle emissions and noise of the system at a network level, not only at the link or route

level. However, to date no review has summarized the use of road network equilibrium approaches with regard to environmental sustainability or equity. More importantly, it is necessary to recognize this gap in the literature so that potential research directions on such approaches can be identified in order to improve the current methodologies. Therefore, the objective of this paper is to summarize the literature and to indicate these potential future research directions.

This review also deals with the estimation of vehicle emissions and noise, which are a key component in the planning of environmentally sustainable transport networks. Therefore, for the sake of completeness, we have included a review of these models with some updates. However, because these have been reviewed very recently, we only address them briefly and focus on their input requirements and their linkage with equilibrium models. We also propose a new classification for both classes of models, in which terminologies are consistent with those of traffic assignment (TA).

The remainder of this paper is organized as follows. The next section provides a brief review of road network equilibrium modeling approaches, which is followed by a review of approaches to estimate vehicle emissions and noise; the fourth section reviews traffic assignment studies that explicitly address environmental concerns; the fifth section discusses bi-level transportation problems and the literature on network designs that considered ES; and finally, the last section presents some potential future research directions.

Road network equilibrium modeling approaches

Road network equilibrium modeling approaches rely on road network equilibrium models, or TA models, to distribute traffic onto the road network and determine the flow on each link of the network. These models can generally be classified into two categories — namely, dynamic and static models. Dynamic TA (DTA) models take the departure time of

travelers and the temporal evolution of flow on the links into account, whereas static TA

(STA) models do not. However, both types of models consist of two major components —

namely, the traffic equilibrium principle and the traffic flow component.

Traffic equilibrium principles

Traffic equilibrium principles determine the traffic level on each road in a network.

They vary on the assumptions and the measures used to define equilibrium. The two classical

principles for STA are: (1) Wardrop's first principle or the user-equilibrium (UE) principle;

and (2) Wardrop's second principle or the system optimal (SO) principle (Wardrop, 1952).

These principles assume that each traveler knows the exact time he/she will spend on

traveling. Although these principles can be extended to consider generalized travel costs

rather than travel time, they may not be realistic in most situations.

To capture more realistic travel behavior, dynamic, stochastic, reliability-based and

tolerance extensions of Wardrop's principles have been proposed. The dynamic extension

(e.g., Vickrey, 1969) considers the departure time of travelers and can be used in DTA. The

stochastic extension (e.g., Daganzo and Sheffi, 1977) relaxes the Wardrop's assumption that

drivers know the travel time of each path exactly. The reliability-based extension (e.g., Hall,

1993; Chan and Lam, 2005; Lo *et al*., 2006; Szeto *et al.*, 2006, 2009a; Chen and Zhou, 2010;

Lam *et al.*, 2010; Szeto, 2011; Zhang *et al.*, 2011) provides for the fact that travel time is

uncertain and travelers can leave earlier to counter this uncertainty and avoid late arrivals.

The tolerance-based extension, such as the boundedly rational user equilibrium (BRUE) (see

Mahmassani and Chang, 1987; Szeto and Lo, 2006a for details), is based on the concept of

'bounded rationality' (Simon, 1955), which is used to describe rational choices that take into

account the limitations of the decision-maker in terms of knowledge, computational capacity

and the time needed to make decisions (Simon, 1997). This term also refers to the rational

principles that underlie the non-optimizing adaptive behaviors of real people. A recent focus of equilibrium principles has been on the reliability-based extension and its combination with the stochastic or dynamic extension (e.g., Shao *et al.*, 2006; Chen *et al.*, 2011a; Szeto *et al.*, 2011). A detailed recent review on traffic equilibrium principles can be found in Szeto and Wong (2011).

Traffic flow components

The traffic flow component depicts how traffic propagates inside a road network and, hence, governs the network performance in terms of travel time. The traffic flow component can be modeled as a unique mapping of route or path flows that yields route travel times. For DTA, the unique mapping can be achieved by using dynamic traffic flow models, which can be classified as microscopic, macroscopic, and mesoscopic (Abdulhai and Kattan, 2004). These three types of models differ in flow representation and in the level of detail of the representation of actual traffic behavior. *Microscopic models* describe vehicles individually with explicit consideration of their individual trajectories and detailed driving behavior, such as lane changing, acceleration, and overtaking. *Macroscopic models* represent traffic as fluid and mainly consider the macroscopic relationship between speed, flow and density when describing flow propagation. No trajectories are traced and no detailed driving behavior is modeled. *Mesoscopic models* group a number of vehicles with the same characteristics into a packet, and the trajectory of each packet is traced similarly to microscopic models. The macroscopic flow-density relationship is used to model flow propagation between links as in the macroscopic models.

Traffic equilibrium models

Each DTA model consists of a dynamic traffic flow component and a dynamic extension of equilibrium principle, whereas each STA model consists of a traffic flow

component and the equilibrium principle that disregards the time dimension. Both types of models can be developed by at least five approaches:

- the variational inequality problem approach (e.g., Smith, 1979),
- the non-linear complementarity problem approach (e.g., Aashtiani, 1979),
- the fixed-point problem approach (e.g., Asmuth, 1978),
- the mathematical programming approach (e.g., Beckmann *et al.*, 1956), and
- the continuum modeling problem approach (e.g., Beckmann, 1952; Jiang *et al.*, 2011).

The equivalency between the first four approaches has been discussed in Nagurney (1993).

Vehicle emissions and noise models

Emission and noise levels are closely related to traffic flow, traffic composition, travel speed, and fuel consumption, which can be estimated from TA models:

- traffic flow and composition can be obtained directly from TA models;
- average speed can be determined once the travel time and the corresponding travel distance are obtained from TA models;
- speed-time profiles can be obtained directly from some TA models (i.e., those that incorporate micro-simulation models);
- space-mean speed can be deduced from the speed-time profiles; and
- fuel consumption can be estimated with the aid of a fuel consumption model that takes information from TA models, such as travel distance and speed changes.

The above traffic flow and speed information can be used together with other inputs to estimate vehicle emissions (noise) through appropriate emission (noise) models. This section reviews existing vehicle emission and noise models, focusing on their inputs, and develops a new classification for both types of models based on whether the temporal

dimension and details of speed information are required. The main reasons for developing a new classification for both types of models are: firstly, the speed details required by these models are closely related to the TA model adopted. More accurate emission and noise modeling approaches require micro-simulation-based TA models to determine detailed speed-time profiles for input into emission and noise models. Secondly, the classifications for emission and noise models are mutually consistent with each other and are also consistent with TA terminologies, making them easier for readers to follow.

Vehicle emission estimation models

Emission models determine vehicle emissions by multiplying an emission factor by the corresponding travel activity data such as travel distance, fuel consumed etc., in which the emission factor can be calibrated using chassis (or engine) dynamometer measurements and regression analysis. Reviews on vehicle emission models have been published (e.g., Hickman *et al*., 1999; Cappiello, 2002; Boulter *et al*., 2007; Chiou and Chen, 2010; Smit *et al*., 2010; Wismans *et al.*, 2011). However, their classifications varied. Table 1 summarizes the existing emission models based on our classification — namely aggregated, static, and dynamic approaches — and these are further categorized based on the classification of Smit (2006), which is one of the most comprehensive classifications available in the literature.

Aggregated emission models

Aggregated emission models need traffic flow, traffic composition, and travel distance from any TA models or from other national annual statistical sources as inputs. The time scale considered is normally in terms of years or months. These models are mainly used for national or regional inventories, the spatial scale of which is large. These models can be further divided into area-wide (or national) emission models and fuel-based emission models. The former uses an aggregate emission factor (g/km) for the whole study area whereas the

latter uses the emission factor expressed as grams of pollutant emitted per kilogram of fuel consumed.

Static emission models

Unlike aggregated models, static emission models or simple speed-based models rely on the speed information obtained from STA models, although the more complicated DTA model can also provide this information. These simple speed-based models can determine emissions at the link level in addition to those at the network, regional or national level. However, since almost all STA models are developed mainly for transportation planning purposes rather than for environmental regulatory purposes, the average speed obtained cannot truly reflect the speed changes of vehicles but is used by average speed models for estimating overall emissions, leading to inaccurate estimates in general. The time scale is normally in terms of hours, which is smaller than that for the aggregated models, but is still longer than that for dynamic emission models (i.e., a time scale in terms of seconds). As shown in Table 1, simple speed-based emission models include average speed models, adjusted average speed models, traffic situation models, queuing emission models, and modal models. These five types of models have different input requirements, in particular those on speed information. Moreover, within the same class of models, inputs can vary from model to model. Hence, Table 1 only shows the inputs that are required by at least one model.

Average speed models are developed based on the principle that the road-type specific emission factor (g/veh/km or g/km) for a particular pollutant and a given type of vehicle varies according to the average speed during a trip (Boulter *et al.*, 2007).

Adjusted (or corrected) average speed models rely on correction factors to modify the emission factor determined from average speed.

Traffic situation models can be further classified into qualitative and quantitative

(Smit, 2006). Qualitative traffic situation models use verbal descriptions to depict traffic situations, which are inputs for the emission factor (g/km). The variables that represent traffic situations (i.e., traffic situation variables) depend on the model, but are usually related to the congestion level (e.g., free flow, stop and go), road type (e.g., arterial, motorway), speed limit (with a 120 km/h speed limit), and area type (e.g., outside or inside a built-up area). Quantitative traffic situation models use quantitative variables to describe traffic situations. In particular, the U.S. Environmental Protection Agency (US EPA) uses mean travel speed for the congestion level whereas the Netherlands Organization for Applied Scientific Research (TNO) uses space mean speed, speed limit, and traffic volume to define the congestion level. The TNO also requires the number of lanes and the length of links to define traffic situations.

Queuing emission models require information on signal settings, free flow speed and the type of intersection to determine the change in queue length over time, which is used to predict the time spent for each of the four fundamental driving modes — namely idling, acceleration, deceleration, and cruising. One emission factor (g/s) is associated with each mode.

Modal emission models (or fundamental driving mode models) assign an emission factor (g/s or g/km) for each driving mode but the inputs for each mode (i.e., modal variables), such as the numbers of major stops and queue move-up, delays, and distribution of mode, can be obtained from the field or the STA models with detailed predictions of queues and delays.

Dynamic emission models

Dynamic emission models require the speed-time profiles or instantaneous driving pattern data from DTA models. They can be used for detailed temporal and spatial analyses of emissions, and can be classified into speed and speed fluctuation emission models and

instantaneous models.

Speed and speed fluctuation models incorporate variables that reflect average speed and average speed fluctuation (e.g., acceleration or deceleration) over time, which can only be deduced from the speed-time profiles obtained from DTA models.

Instantaneous emission models also require speed-time profiles and vehicle-specific parameters as inputs. These models can be further classified into four types:

- *instantaneous acceleration-speed matrix models* (e.g., DRIVE-MODEM (Joumard *et al.*, 1995)), in which the instantaneous emission factors are defined by both instantaneous speed and acceleration that are presented in matrix/table form and deduced from the speed-time profiles;

- *instantaneous speed/load matrix models* (e.g., PHEM (Zalinger *et al.*, 2005)), in which the emission factors are defined by both engine speed and load that are presented in matrix form, and are in turn functions of road gradient, gear shift, gear ratio, and speed-time profiles;

- *instantaneous analytical speed-acceleration function models* (e.g., Modal Analysis Model (Kunselman *et al.*, 1974)), in which emission factors are functions of speed and acceleration; and

- *instantaneous power-based models* (e.g., the Comprehensive Modal Emissions Model (Scora and Barth, 2006)), in which variables related to engine power, such as engine capacity, power generation efficiency, vehicle mass, and vehicle frontal area, are used as additional inputs in comparison with instantaneous analytical speed-acceleration function models.

The accuracy of estimates obtained from dynamic emission models depends on the accuracy of the time-speed profiles obtained from DTA models. However, the DTA models always require a lot of data for calibration and validation, and some of them such as vehicle

type and age for each origin-destination pair can be difficult and very expensive to obtain precisely. Hence, dynamic emission models may not be able to give accurate emissions estimates.

Noise prediction models

Some principal factors that are normally taken into account when developing noise prediction models are traffic flow, traffic composition, average speed, measure distance, and the characteristics of the road, such as the gradient and type of the road surface. Steele (2001) provided a critical review of some commonly applied traffic noise prediction models. Quartieri *et al.* (2009) presented a quantitative review of those most commonly used in Europe and exploited their main features and peculiarities. This section summarizes the three main categories of noise prediction models — namely, aggregated, static, and dynamic noise prediction models.

Aggregated noise prediction models

Aggregated noise prediction models mainly rely on regression analysis of noise data to develop statistical noise prediction models. One of the oldest models was reported in the Handbook of Acoustic Noise Control (Anon., 1952), and determined L_{50}, where L_m is the noise level exceeded for m% of the measurement duration. This sound level is modeled as a log function of *traffic volume* and the *distance* from the observation point to the centre of the traffic lane, and vehicle and road types are not specified. Nickson (1965) and Lamure (1965) improved the original model using a parameter that linked the model with experimental data.

Josse (1972) proposed a model to determine the equivalent noise level or average noise level, L_{eq}, which is the level of a hypothetical time-invariant noise that would produce the same noise energy as the measured time-varying noise during the same period. Other model inputs are *traffic volume* and *distance*. The French Centre Scientifique et Technique du

Batiment (1991) developed a model to estimate the equivalent sound level, L_{eq}, based on L_{50}, in which L_{50} is calculated by considering only equivalent vehicle flows, which are also log functions of traffic volume and distance.

Burgess (1977) proposed two models based on L_{10} and L_{eq} as two sound level descriptors. The two models consider not only *traffic volume* and *distance* from the traffic but also the *percentage of heavy vehicles* as inputs.

Quartieri *et al.* (2009) proposed a general expression of the equivalent sound level that can deduce all the previously mentioned noise prediction models as special cases. This model considers *traffic volume*, *distance*, the *percentage of heavy vehicles* and the *acoustic equivalent of heavy vehicles on the link* (i.e., the number of light vehicles that produces the same acoustic noise as a heavy vehicle on that link). This number can be estimated by both the regression method and single vehicle emission measurements.

Some models have been proposed to consider the effect of *composition of traffic* on the noise level, not just the percentage of heavy vehicles, traffic volume and distance. For example, Cvetković *et al.* (1997) developed a model to determine L_{eq} as a function of the numbers of light vehicles, heavy vehicles and buses. Fagotti and Poggi (1995) further incorporated the number of motorcycles to determine L_{eq}.

Static noise prediction models

The earliest static (or average speed-based) noise prediction models were also developed based on regression analysis but they considered the *average speed of vehicles* as an additional factor. For example, Johnson and Saunders (1968) presented a model to take into account the mean speed of vehicles in addition to distance and traffic flow, assuming that the percentage of heavy vehicles is 20%. Later, Galloway *et al.* (1969) improved this by incorporating the *percentage of heavy vehicles* into the resultant model as an additional

independent variable.

Subsequent average-speed models focused on the inclusion of additional factors that affect noise prediction. Table 2 compares the inputs required and factors considered by recent models. All of these models not only consider the effects of speed and distance, the flow mix, the gradient of the road, the type of road surface, the nature of the ground surface between the edge of the carriageway and the measurement location, and the presence of buildings, walls and barriers, but also include other considerations. For example, RLS considers car parks, the time-of-day effect and the speed limit.

It should be noted that not all of these models were developed purely on the basis of a statistical approach. Some models, such as MITHRA, have adopted the theory of physics (e.g., ray tracing or beam tracking) in predicting noise propagation to improve the accuracy of predictions.

Dynamic noise prediction models

Unlike the previous two approaches, these models take into account dynamic traffic flow characteristics, such as variations in speed and flow over time. This approach requires dynamic traffic flow models together with advanced speed-based noise prediction models, such as ASJ, for the estimation of traffic noise at every time step (usually 1 s). The dynamic traffic flow models used are either macroscopic (e.g., Leclercq and Lelong, 2001; Lelong and Leclercq, 2003) or microscopic (e.g., De Coensel, 2005; Bhaskar *et al*., 2007; Chevallier *et al*., 2009; Can *et al*., 2010; Tsukui *et al*., 2010). The former (latter) is normally used to predict noise from roads without traffic signals (signalized intersections or roundabouts). Mesoscopic models have not been used for noise prediction to the best of our knowledge.

Traffic assignment with environmental considerations

TA models with environmental considerations can be broadly classified into three categories, namely models with environmental objectives, models with environmental constraints, and models for environmental impact assessment (EIA).

Models with environmental objectives

Environmental objectives have been captured in TA models through using emission-based assignment principles. They can be considered as extensions from UE and SO principles. One line of research purely considered *emissions* as the only objective. For example, Rilett and Benedek (1994) proposed two concepts, the first of which can be considered as an extension to SO, which is referred to as emission optimum (EO). Travelers select routes to ensure that the total environmental impact (noise or emissions) rather than total travel time is minimized. The second concept was based on an extension of UE. Travelers select routes based on travel costs, which include the toll charges that represent the impact on the environment. The first concept was based on the need of the system as a whole, whereas the second concept was based on the need of individual drivers. Benedek and Rilett (1998) found that the EO assignment under congested conditions can result in about 7% CO reduction compared to the UE and SO assignments. Sugawara and Niemeier (2002) further found that the reduction depends on the level of congestion. When the network is uncongested, the reduction can be more than 20%. Using microsimulation for finding speed profiles, Ahn and Rakha (2008) found that the EO assignment can reduce CO emissions up to 92% of CO emissions over the UE and SO assignments.

Another line of research was Rilett and Benedek (1994) which focused on *environmental equity*. It can be considered as an extension of UE, in which vehicles are routed in such a way that the amount of emissions or noise released on all streets (or a subset

of streets) is the same. Under this TA, no group of residents near the traffic network is affected more than any other group.

Multiple objectives including environmental objectives have been studied in the SO framework. Tzeng and Chen (1993) proposed a multi-criteria SO TA model with an explicit pollution minimization criterion. The SO objective that affects decision-making is the sum of total travel time for road users, air pollution for non-users, and travel distance. The assumptions in this model are the same as those of the SO assignment in which a central controller can control and route traffic in such a way that the resultant traffic pattern is optimal from a system (or societal) perspective. Similarly, Nasiri *et al*. (2009) proposed an optimality assessment framework to assist freight transportation planning with environmental considerations, in which a multiple-objective optimization model with cost and environmental objectives is constructed. Zhang *et al.* (2010) proposed a cell-based assignment model to minimize the weighted sum of travel time and emissions.

Multiple objectives including environmental objectives have also been studied in the UE framework. Nagurney *et al*. (2002) considered multiple classes of travelers and each class is assumed to select route with the least weighted sum of travel time, travel cost, and emissions. The weights are not only class-dependent but also link-dependent. Jaber and O'Mahony (2009) further extended this model to include the value of time and travelers equipped with route guidance services.

Capturing environmental objectives in TA generally lead to non-convex objective functions in mathematical programming formulations, or non-monotone mappings in variational inequality formulations. Hence, using the classical algorithms such as the Frank-Wolfe algorithm (e.g., Tzeng and Chen, 1993; Rilett and Benedek, 1994; Benedek and Rilett, 1998), the method of successive averages (e.g., Rilett and Benedek, 1994; Benedek and Rilett, 1998), projection method (e.g., Nagurney *et al*., 2002) and the generalized reduced

gradient algorithm (e.g., Jaber and O'Mahony, 2009) to solve the TA models cannot guarantee that the solution obtained is globally optimal. To address this issue, Sugawara and Niemeier (2002) modified the Frank-Wolfe algorithm by introducing Simulated Annealing for finding the step size. Zhang *et al.* (2010) further adopted genetic algorithm (GA) to solve for solutions. Still, very few solution methods were particularly developed for these models and tested for large-network applications.

Models with environmental constraints

Environmental constraints have been considered in three forms: Environmental capacity constraints, equity constraints, and marketable pollution permits.

Environmental capacity has been proposed by Buchanan (1963), and represents the maximum acceptable pollutant or noise level imposed by planners. To portray this concept in TA, an environmental capacity constraint is included in the formulation (e.g., Yang *et al.*, 2005, 2010; Zhao and Gao, 2006; Feng *et al.*, 2010; Chen *et al.*, 2011b; Li *et al.*, 2012; Zhong *et al.*, 2011), which requires that total emissions or the noise from a link cannot exceed the corresponding environmental capacity.

Environmental equity proposed by Rilett and Benedek (1994) can also be captured in constraints. This concept is that traffic is routed through a given network by the system operators in such a way that vehicle emissions or noise levels on the adjacent streets do not exceed some maximum safety standard, for example for health reasons. This can be viewed as an extension of a capacitated UE assignment.

Marketable pollution permits have been examined in the framework of congested TA (Nagurney *et al.*, 1998) in which a fixed number of permits of each link is issued by the government to allow drivers to buy the permits for emitting pollutants on that link at certain rate and the permit holders can sell their permits to others. This idea has been extended to

consider path-based and OD-based permits (e.g., Nagurney, 2000a) and dynamic networks (e.g., Nagurney and Zhang, 2001).

The above environmental constraints are always nonlinear, leading to a non-convex solution set in general. Hence, solving TA models with environmental constraints is more difficult than those without. Heuristic methods (e.g., Ferrari, 1995) have been developed for these models formulated as constrained optimization models. Classical methods such as the inner penalty technique (e.g., Yang and Bell, 1997) and augmented Lagrangian multiplier technique (e.g., Yang *et al*., 2010) have also been used to solve these models. Recently, Chen *et al*. (2011b) developed a predictor-corrector decomposition algorithm to solve the variational inequality model. Xu *et al*. (2012) reformulated the constrained model as an unconstrained optimization model through a gap function and solved the resultant model based on a gradient-based solution algorithm with a self-regulated averaging stepsize scheme. However, all these approaches have not been tested for large-scale networks.

Models for EIA

Environmental impacts have been evaluated by TA models. For example, Nagurney (2000b) demonstrated the existence of emissions paradox using the classical TA framework. That is, the total emissions increase after adding the new link to the network. Nagurney and Dong (2001) further considered emissions paradox in a combined transportation and telecommunication networks. Szeto *et al*. (2008a) analyzed the conditions of the simultaneous occurrence of Braess' and emission paradoxes for Braess' network. In addition, Szeto *et al*. (2008b) also discovered that providing better traffic information to travelers can result in higher overall emissions. Nagurney *et al*. (2010) proposed EIA indices to evaluate the environmental effects of link capacity degradation in transportation networks.

Bi-level transportation problems with environmental considerations

The bi-level transportation problem with environmental considerations (BTPE) can be formulated as:

$$\min_{\mathbf{x}} f(\mathbf{x}, \mathbf{y}) \qquad\qquad (1)$$

subject to

$$
\begin{aligned}
&\mathbf{x} \in \boldsymbol{\omega}, \\
&\min_{\mathbf{y}} \ F(\mathbf{x}, \mathbf{y}) \qquad\qquad (2)\\
&\mathbf{y} \in \mathbf{S}(\mathbf{x}),
\end{aligned}
$$

where $\mathbf{x} \in R^n$ and $\mathbf{y} \in R^m$ are the decision variables of the upper- and lower-level problems respectively; $f\left[R^n \times R^m \to R\right]$ and $F\left[R^n \times R^m \to R\right]$ are the objective functions of the upper- and lower-level problems respectively; and $\boldsymbol{\omega} \subset R^n$ and $\mathbf{S}\left[R^n \Rightarrow R^m\right]$ are the solution sets of the upper- and lower-level problems respectively. Depending on the context, the upper-level problem often includes *environmental impact measures* such as fuel consumption or emissions in either the *objective function* or *environmental constraints* as indicated in Table 3. In some problems, the impact on the environment is portrayed by a toll charge. Moreover, the lower-level problem is a TA problem or its generalization. This implies that BTPE is a special type of general bi-level problems.

Similar to typical bi-level problems, BTPE can be viewed as a two-stage optimization problem or a leader-follower problem, in which the upper level is the leader's problem and the lower level is the follower's problem. The leader makes a decision taking the reaction of the follower into consideration, and the follower only makes his/her decision after the leader has made his/hers.

BTPE can also be reformulated as a mathematical program with equilibrium

constraints (MPEC) by replacing the lower-level problem with its first-order optimality conditions and assuming that certain conditions of regularity hold. Mathematically, the MPEC can be formulated as:

$$\underset{\mathbf{x},\mathbf{y}}{\text{Min}} \; f(\mathbf{x},\mathbf{y}) \qquad (3)$$

subject to

$$\mathbf{x} \in \omega,$$
$$\left(\mathbf{y}\text{-}\mathbf{y}^*\right)^{\mathrm{T}} \mathbf{H}\left(\mathbf{y}^*\right) \geq 0, \forall \mathbf{y} \in \mathbf{S}(\mathbf{x}), \qquad (4)$$

where $\mathbf{y}^* \in R^m$ is an optimal solution of the equilibrium problem in the form of a variational inequality given $\mathbf{x}$; and $\mathbf{H}(.) \in R^m$ is the vector function of $\mathbf{y}$ in the variational inequality.

Table 3 also presents different applications of BTPE, including the road network expansion problem (RNEP), the toll design problem (TDP), the combined signal control and assignment problem (CSCAP), the ramp metering problem (RMP), the car ownership control problem (COCP) and combinations thereof. RNEP is concerned with the addition of new highways to the existing highway system or widening existing highways taking into account traveler behavior. TDP is to determine the optimal toll level on each link of the road network if the link is allowed to charge a toll. CSCAP is to determine the optimal traffic signal timing in a road network while considering the route choice behavior of travelers. RMP is to determine traffic signal timing to control the number of vehicles entering freeways in order to improve their performance. In some cases, the performance of the surface streets is also taken into account. COCP is to determine an optimal car ownership in each zone of the study. Currently, CP mainly focuses on either the combined signal control and road network expansion problem, (e.g., Cantarella and Vitetta, 2006; Zhang *et al*., 2006; Zhao and Gao, 2006; Huang *et al*., 2010) or the combined network expansion and tolling problem (e.g.,

Dimitriou *et al*., 2009).

According to Table 3, to date, only a few studies are related to BTPE especially CSCAP, COCP, and RMP with ES consideration. Moreover, these studies mainly focus on emissions and very few focuses on other dimensions of ES such as noise, environmental justice, and environmental pollution, where environmental justice can be considered as an extension of equity with a focus on minority and low income population but it includes social and economic effects in addition to environmental effects. When ES is captured in the objective function, it is always considered in form of either total network emissions or emission costs. The environmental objective is often combined with other objectives using the weighted sum approach, but it is sometimes treated as the only objective in the model or one of the objectives in the multi-criteria optimization model to find the Pareto front. When ES is captured in the constraint, it is always in form of environmental capacity constraint (to restrict link flow not to be greater than environmental capacity), link emission constraint (to restrict link emissions not to exceed the acceptable value), and equilibrium constraints with the emission tolls involved. The latter is derived from problems with the total network emission constraint (to restrict the total emissions in the network).

The solution methods mainly relied on heuristics such as sensitivity analysis-based heuristics or meta-heuristics such as GA or Particle Swarm Optimization (PSO) without considering the mathematical properties of their problem. Furthermore, only Zhao and Gao (2006) has attempted to develop exact global optimization methods to solve the combined signal control and road network expansion problem.

Future research directions

The following research directions are proposed and can generally be classified into theories, modeling approaches, algorithms, analyses, and applications.

Theories

Extensions of the BRUE to consider travel time reliability

BRUE can be extended to include reliability in terms of travel time, which can be used to consider the trade-off between travel time and the penalty for being late due to unpredictability. Boundedly rational reliability-based UE can be defined using the concept of a travel time budget or mean excess travel time. This new concept, which fills a gap in the literature, can be applied to the evaluation of ES and transport network design.

Extensions of environmental equities to consider its dimensionally distributive effects

Environmental equity can be extended to consider its horizontal and vertical dimensions which are analogous in their definitions to those of horizontal and vertical equities that are applied in transportation (e.g., Litman, 2002). Horizontal environmental equity is concerned with the equal distribution of negative environmental impact *within the same group* or class of people who have the same abilities and needs, such as social class, value of time or income. The environmental equity proposed in Rilett and Benedek (1994) is indeed an example of this, which considered equity in terms of emissions during the same period. However, it can also include the impact of noise, and take into consideration the distributional effects across different periods similar to the equity in Szeto and Lo (2006b). This horizontal environmental equity across different periods is said to be achieved if the differences in total environmental impact measures (such as emission or noise levels) between two consecutive periods are acceptable.

Vertical environmental equity is concerned with the equal distribution of negative environmental impact between various groups or classes of people. This equity is said to be achieved if the absolute difference in the environmental impact measure between each class

is acceptable and no social or income class experiences a considerably larger environmental impact.

Modeling approaches

Modeling pollutant concentrations due to vehicle emissions

Much research was focused on the estimation of vehicle emissions but very few (e.g., Wang *et al*., 2009) has attempted to go further to estimate the changes in pollutant concentration levels due to traffic emissions. However, a complete EIA should comprise estimating emissions and ambient pollutant concentration. It is therefore important to pay more attention to developing methodologies to estimate the concentration. One future direction can be extending the model of Wang *et al*. (2009) to consider the speed profiles in the concentration estimation.

Developing noise prediction models based on mesoscopic traffic model outputs

Existing dynamic noise prediction models mainly rely on the traffic flow output from either macroscopic or microscopic traffic flow models. Microscopic traffic flow models can include detailed vehicle dynamics, such as the acceleration and deceleration of vehicles, which are suitable for some traffic noise prediction applications, including noise from signalized intersections and roundabouts. However, these models are the most computationally demanding and require a large amount of data for calibration and validation. Thus, they are normally used for small- to medium-scale study areas. Macroscopic models are the most computationally efficient and can produce good results (Can *et al*., 2008) in some situations, but they may not be accurate for detailed noise modeling at signalized intersections or roundabouts. Mesoscopic modeling seems to strike a balance between including a sufficient level of detailed vehicle dynamics and meeting the computational

requirements for large-scale study applications, and can be extended for dynamic traffic noise prediction. Further work is needed on developing noise prediction models based on mesoscopic traffic model outputs.

Developing a multi-objective optimization framework with emissions and noise considerations

Previous studies of BTPE mainly focused on the aspect of either emissions or noise. However, bi-level models with a single objective could generate designs which may mitigate congestion problems but exacerbate environmental problems, for example, through increased vehicle emissions and noise. Such designs can cause paradoxical situations (e.g., Szeto *et al.*, 2008). A compromised design using a multi-objective optimization framework is needed to cope with congestion and environment problems simultaneously. Szeto *et al.* (2009b) proposed such a framework through the hybrid approach in which the multiple objectives did not focus on ES, more specifically both vehicle emissions and noise. One potential research direction would be to extend this framework to incorporate both aspects.

A stochastic or reliability approach to incorporating environmental concerns into bi-level models

Most of the bi-level models that involve environmental considerations, as depicted in the fifth section, are deterministic models in which there are no uncertainties of model inputs and the input values are fixed and known. However, the inputs can be the output of other models that may be inaccurate. For example, the forecast of demand in 10 years' time may not be very accurate but for transport network improvement planning, it normally takes such long-term considerations into account. Therefore, it is necessary to extend these bi-level models to consider uncertainties. Incorporating recent stochastic modeling approaches (see Chen *et al.*, 2011c) into these models is definitely one possible research direction. Moreover,

one can define and incorporate reliability measures to evaluate environmental impacts in the upper-level objective functions or constraints, and adopt the reliability-based extension of Wardrop's principles in the lower-level problem, so that a new and more realistic reliability-based framework for ES can be developed.

A multi-dimensional, multi-criteria approach to incorporating economic, social, and environmental concerns into transport network modeling

Transportation networks are large-scale in nature and transportation is always associated with economic, social, and environmental issues that are faced by public and local authorities simultaneously. Therefore, it is important to develop appropriate transport network models to address these issues. For this purpose, one direction is to extend the model of Szeto *et al*. (2009b) to include indicators of the three dimensions of sustainability. In addition, the multiple-criteria model proposed by Jaber and O'Mahony (2009) can be used in the lower-level of the extended model.

Algorithms

Developing efficient, convergent, and robust algorithms for TA with environmental considerations for large-scale network applications

The environmental considerations result in nonlinear and non-convex constraint sets, non-convex objective functions in mathematical programming formulations, or non-monotone mappings in variational inequality formulations, leading to the resultant models more difficult to solve for global optimality than classical TA models. Moreover, existing solution algorithms for TA with environmental considerations have only been applied to small and medium-sized networks. The robustness of the algorithms has also not been tested. As such, developing efficient, convergent and robust algorithms for solving the TA models with environmental considerations for large-scale network applications may consider as an

important and challenging future research direction.

Development of tailored meta-heuristics to solve proposed or existing non-linear, non-convex bi-level transport problems

The proposed and existing models for BTPE with ES are non-convex and non-linear due to equilibrium constraints. In addition, when integer decision variables are involved, the resultant problems are non-deterministic polynomial-time-hard. It is therefore difficult to find a solution for exact global optima for realistic applications purely using exact methods, such as the branch-and-bound method. The development of meta-heuristics that consider the special structures of the models may be another potential future research direction. For example, repairing procedures can be developed to handle environmental equity constraints and ensure solution feasibility.

Improvement of the speed and quality of solution of meta-heuristics by incorporating sensitivity analysis-based heuristics or mathematical programming techniques

To reduce computation time, sensitivity analysis-based heuristics for handling equilibrium constraints can be developed and incorporated into meta-heuristics. The meta-heuristics can also be combined with mathematical programming techniques, such as the successive quadratic programming method, to reduce computation time further. To improve the quality of the solution, the α branch-and-bound technique can be employed where the upper bound is obtained by the proposed meta-heuristics. For this purpose, the work conducted in Lo and Szeto (2002a,b), Szeto *et al*. (2006), Szeto and Wu (2011), and Miandoabchi *et al*. (2011) can be used as a starting point.

Analyses

The impact of various route choice behaviors on vehicle emissions and noise under different

transportation and financing strategies

As shown in the fifth section, most of previous studies have focused on the impact of transportation strategies on vehicle emissions only. The impact on vehicle noise is seldom mentioned. In addition, traditional equilibrium principles such as Wardrop's are used to describe the route choice behavior of travelers in these evaluations. More realistic route choice behavior principles, such as the reliability-based, boundedly rational, and robust principles, have not been applied to the evaluation of the effectiveness of transportation strategies on emission and noise reduction. It would be interesting and meaningful to analyze and compare the impact of various route choice behaviors on vehicle emissions and noise under different transportation management strategies such as road pricing and route guidance. It will also be essential to evaluate the impact of proposed extensions of the BRUE route choice behavior on vehicle emissions and noise under different transportation infrastructure financing schemes such as build-operate-transfer and cost recovery schemes. All of the results based on more realistic route choice behavior principles can be compared with those based on traditional Wardrop's principles, which will provide useful insights for transportation network planners and policy makers, for example, in terms of the importance of including the risk-aversive behavior of drivers into the analysis. All of these analyses are worthy of consideration in the future.

Deriving and analyzing speed-dependent second best tolls with simultaneous consideration of costs of emission and noise

Deriving speed-dependent marginal tolls with the consideration of the cost implication of emissions and noises to drivers in transportation networks is not novel (Guo and Hsu, 2010). However, these tolls are first-best and may not be practical because not all roads can be tolled in reality. Hence, it is important to derive second-best tolls for practical reasons. In addition, using the analytical, speed-dependent, best-second toll relationship, it

will then be possible to analyze the effect of speed on the second-best tolling strategies, and compare this with the corresponding first-best toll and marginal congestion cost tolling in terms of charging locations and magnitude. New insights are expected from this analysis.

Horizontal and vertical environmental equities under different transportation strategies

Under different transportation strategies, one or more environmental inequities are possible. It is therefore important to analyze the environmental impact of the implementation of transportation strategies on people over time, space and social classes. The multi-objective model proposed in Szeto *et al*. (2009b) can be used for this purpose. This model can be combined with that in Szeto and Lo (2006b) to help determine the most equitable strategy. Definitely, other frameworks can be derived for this analysis in the future.

Applications

Traveler information provision

The bi-level programming approach has been applied to the analyses of traveler information provision (e.g. Szeto, 2007). In these analyses, travelers who use information provision services or who are equipped with route guidance services are usually assumed to possess better traffic information than unequipped travelers. The lower-level problem is normally formulated as a multi-class TA problem. Nevertheless, these analyses do not take into account the impact of traveler information provision on ES. Providing too much traffic information may result in more overall emissions and noise or a more uneven distribution of the environmental impact. Therefore, ES could be incorporated into these analyses in future research.

On-ramp metering

According to Table 3, only one study related to ramp metering considered emissions. This problem is based on the static approach and the UE principle is adopted to depict the lower-level problem. Recent developments on dynamic ramp metering (e.g., Zhang *et al*., 2001; Meng and Khoo, 2010) can be used to determine more realistic time-varying metering rates and include the effect of emissions and noise in the model.

Car ownership control

To date, two studies have used this application to consider emissions (Table 3). Further work is needed on this application with regard to the consideration of noise. Moreover, other advanced route choice models depicted in the second section can be used to replace the UE model and new solution methods based on meta-heuristics can be used together with sensitivity analysis-based heuristics to improve the quality of the solution.

Combined signal control and assignment problem and its extension

Currently, only one study has been carried out on the combined signal control and assignment problem with the consideration of emissions, and four studies have dealt with combined signal control and network design problems (see Table 3). Further studies could extend the existing frameworks, which rely on a link performance function that cannot taken into account the stochastic nature of driver behavior, day-to-day variability in traffic demand, or traffic dynamics such as queue spillback, which greatly affect the spatial dispersion of emissions. These frameworks can be improved by using microscopic traffic simulation models. For example, Park *et al*. (2009) presented a sustainable traffic signal control and speed management framework which includes a microscopic traffic simulation model, a microscopic fuel consumption and emission model, and a GA-based optimizer. The

framework was formulated into a stochastic optimization problem in which total emissions can be used as an objective function. The advantage of encapsulating the microscopic traffic simulation model and the microscopic fuel consumption and emission model is that the emission estimation is more accurate. However, traveler's route choice behavior is not taken into account. Another future research direction could be to incorporate the UE problem into the framework, and a further research direction could be to incorporate noise consideration. A third direction would be to incorporate the variance estimation technique discussed in Park *et al*. (2007) to estimate the variability of emissions and noise.

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Table 1. A comparison of existing emission models

Categories	Aggregated		Static					Dynamic	
Types	Fuel based emission	Area wide	Average speed	Adjusted average speed	Traffic situation	Queuing emission	Modal	Speed and speed-fluctuation Emission	Instantaneous
Examples	The IPCC method for national greenhouse gas inventories (IPCC, 1996)	The Energy Workbook for Transport (AGO, 2003)	MOBILE (NRC, 2000)	TEE (EC, 1995)	US EPA (1997); TNO (2001)	The Matzoros emission model (Matzoros, 1990)	CALINE4 (Benson, 1989); COPERT 4 (EEA, 2012); EMFAC2007 (CARB, 2010); IVE (2008); MOVES (US EPA, 2010)	MEASURE (Fomunung et al., 1999)	MAM (Kunselman et al.,1974); DRIVE-MODEM (Joumard et al., 1995); PHEM (Zalinger et al., 2005); CMEM (Scora and Barth, 2006)
Emission factor unit	g/kg fuel burned	g/km	g/mile	g/km	g/km, g/mile	g/s	g/s, g/mile, g/km, g/veh (MOVES)	g/km, g/s	g/s
Input:									
The speed-time profiles								√	√
Modal variables							√		
Intersection type				√		√			
Signal settings				√		√			
Cruise Speed						√	√		
Traffic situation variable					√				
Road type			√		√		√		
Link flow				√	√	√			
Number of lanes				√	√	√			
Link length				√	√	√			
Average speed			√	√	√				
Climatic conditions							√		
Inspection and maintenance							√		
Detailed traffic composition			√	√	√	√	√	√	√
Link VKT/VMT			√	√	√	√	√	√	√
Network VKT/VMT		√							
Basic traffic composition					√				
Network-wide fleet composition	√	√			√				
Fuel sales	√								
Road grade							√		

Acronyms used: CALINE4, CAlifornia LINE Source Dispersion Model version 4; CMEM, Comprehensive Modal Emissions Model; COPERT 4, Computer Programme to calculate Emissions from Road Transport version 4; DRIVE-MODEM, MODelling of EMissions and fuel consumption in urban areas, derived from the DRIVE research program; EEA, European Environment Agency; EMFAC2007, the EMission FACtors model 2007; IPCC, the Intergovernmental Panel on Climate Change; IVE, International Vehicle Emissions; MAM, Modal Analysis Model; MEASURE, the Mobile Emissions Assessment System for Urban and Regional Evaluation model; MOVES, MOtor Vehicle Emission Simulator; PHEM, the Passenger car and Heavy-duty vehicle Emission Model; TEE, Traffic Energy and Emissions model; TNO, Netherlands Organization for Applied Scientific Research; US EPA, the United States Environmental Protection Agency.

Table 2. A comparison of various speed-based noise models

Models	CoRTN	StL	RLS	CNR	ASJ	MITHRA	NMPB-Routes	FHWA TNM
References	DOT (1988)	EMPA (1987)	RLS 1990	Cocchi *et al.* (1991)	Yamamoto (2010)	MITHRA (2011)	Dutilleux *et al.* (2008)	FHWA (2011)
Country of origin	UK	Switzerland	Germany	Italy	Japan	France	France	USA
Output	L_{10}	L_{eq}	L_{eq}	L_{eq}	L_{eq} , L_{50}	L_{eq}	L_{eq}	L_{eq}
Inputs:								
Speed	√	√	√	√	√	√	√	√
Distance	√	√	√	√	√	√	√	√
Gradient	√	√	√	√	√	√	√	√
Heavy vehicle & automobile	√	√	√	√	√	√	√	√
Medium vehicle					√			√
Bus and motorcycle								√
Tram/light rail		√						
Railways		√				√		
Unknown traffic flow		√	√			√		
Vehicle % mix	√		√	√	√	√	√	√
Speed limit			√					
Uphill and hill flow		√						
Traffic interruption		√	√	√	√	√		√
Road surface type	√	√	√	√	√	√	√	√
Ground surface nature	√	√	√	√	√	√	√	√
Presence of obstacles	√	√	√	√	√	√	√	√
Car parks			√					
Meteorological conditions			√		√	√	√	√
Traffic flow type			√		√	√		√
Time-of-day			√					

Acronyms used: ASJ, Acoustical Society of Japan; CNR, Consiglio Nazionale delle Ricerche; CoRtn, Calculation of Road Traffic Noise; FHWA, Federal Highway Administration; NMPB-Routes, Nouvelle Méthode de Prevision du Bruit des Routes; RLS, Richtlinien für den Lärmschutz an Strassen; StL, French Calculation of Road Traffic Noise Model for Computers; TNM, Traffic Noise Model.

Table 3. Summary of BTPE

References	Problem	Focus of ES	Objective function	Constraint	Objective function(s) or type of environmental constraints used	Solution method
Kim and Kim (2006)	RNEP	E	√		Sum of highway maintenance, emission, accident, vehicle operation, and network travel time costs	GA and bit comparison algorithm
Mathew and Sharma (2006)		E		√	User equilibrium constraint with the sum of travel time costs and emission toll charges	GA
Qiu and Chen (2007)		EP	√		Sum of network travel time, investments, environmental pollution, land use, and energy consumption costs	An algorithm based on extremal optimization
Duthie and Waller (2008)		EJ	√		Four travel time related functions to measure equity	Selectorecombinative GA
Huang et al. (2009)		N		√	Constraint of traffic noise pollution	PSO
Jaber (2009)		E		√	Link emission constraint	GRG
Jia et al. (2009)		E	√		Cumulative costs including emission cost over the modeling horizon	GA, SA and ABC
Ferguson et al. (2010)		E	√		Total network emissions	GA
Chen and ~~Zhou~~ Xu (2012)		E	√		Total carbon monoxide (CO) emissions; total travel time; maximum ratio of origin-destination travel times after and before capacity enhancement	Simulation-based GA
Yin and Lu (1999)	TDP	E	√		Total CO emissions	GA
Nagurney (2000c)		E		√	User equilibrium constraint with congestion and emission costs	Modified projection method
Hizir (2006)		E	√		Sum of all pollutants in the network	The GAMS/NLPEC solver
Yin and Lawphongpanich (2006)		E	√		Total travel time and total traffic emissions	GA
Li et al. (2007)		E		√	Link emission constraint	GRG
Jaber and O'Mahony (2009)		E		√	Multiclass stochastic equilibrium constraint with congestion and emission costs	GRG
Jakkula and Asakura (2009)		E		√	Environmental capacity constraint	Augmented Lagrangian dual algorithm
Guo and Huang (2010)		E & N		√	User equilibrium constraint with congestion and emission costs	Newton-Raphson's method
Yang et al. (2010)		E		√	Environmental capacity constraint	Iterative two-stage adjustment algorithm
Sharma and Mishra (2011)		E	√	√	Total network emissions; weighted sum of network emissions and travel time; total network emission constraint; link emission constraint	GA
Zhong et al. (2011)		E		√	Access constraint (dynamic environmental capacity constraint)	Euler scheme, SQP & Padé approximant
Li et al. (2012)		E		√	Environmental capacity constraint	Sample average approximation & sensitivity analysis-based methods
Zhou et al. (2008)	CSCAP	E	√		Total vehicle emissions at intersections	GA
Lv et al. (2006)	RMP	E	√		Weighted sum of network emissions and network travel cost	GA
Yang et al. (2005)	COCP	E		√	Environmental capacity constraint	Sensitivity analysis-based heuristic
Feng et al. (2010)		E		√	Environmental capacity constraint	GA
Cantarella and Vitetta (2006)	CP	E	√		Total travel time; total walking time; total CO emissions; number of vehicles that park outside the desired destination; number of users that change their mode from car to bus	GA
Zhang et al. (2006)		E	√		Weighted sum of total travel cost and total emissions in the network	PSO
Zhao and Gao (2006)		E		√	Signalized, environmental capacity constraint	The branch-and-bound method
Dimitriou et al. (2009)		E	√		Total travel cost; construction cost minus toll revenue; network CO_2 emissions	GA
Huang et al. (2010)		E	√		Total network emissions from junctions and road sections	PSO

Acronyms used: ABC: artificial bee colony algorithm; COCP: the car ownership control problem; CP; the combined problem; CSCAP; the combined signal control and assignment problem; E: emissions; EJ: environmental justice; EP: environmental pollution; GA: genetic algorithm; GRG: the generalized reduced gradient algorithm; N: Noise; PSO: particle swarm optimization algorithm; RMP: the ramp metering problem; RNEP: the road network expansion problem; SA: simulated annealing; SQP; Sequential quadratic programming technique; TDP: the toll design problem.