Journal of Environmental Informatics 15(2) 87-98 (2010)

Journal of Environmental Informatics

www.iseis.org/jei

An Inexact Transportation Planning Model for Supporting Vehicle Emissions Management

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Received 12 January 2010; revised 9 May 2010; accepted 16 June 2010; published online 20 June 2010

ABSTRACT. An interval-parameter inter-community traffic planning model (ICTPM) is developed for supporting vehicle emissions management under uncertainty. With integrating interval-parameter and mixed-integer linear programming within a general optimization framework, the ICTPM can address uncertainties of traffic structure and vehicle emissions related to system costs and capacity expansion decisions. Another advantage of the proposed model is that decision variables can be obtained quickly, which make it applicable to complex traffic problems. The ICTPM is then applied to Wuhan City, China to demonstrate its applicability in the field of inter-community vehicle emissions management. In this study, one reference case and a scenario are provided for three planning periods. The results indicate that the ICTPM can provide strategies for authorities to deal with the issues of sustainable transportation system.

Keywords: inter-community, inexact planning, traffic flow, traffic system, vehicle emissions

1. Introduction

Both industrialized and developing countries suffer from severe problems caused by transportation, such as air pollution, traffic congestion and land depletion. As the natural and economic resources are limited, sustainable development of the transportation system in big cities is extremely important. Planning for sustainable transportation systems has been the subject of many debates, studies and conferences (Shiftan et al., 2003). Vehicle emissions management is a major challenge for policy makers as it involves a high level of uncertainty regarding the future effect of a given policy package on the transportation system.

Previously, a number of transportation planning models were developed for supporting traffic environment management. Although published literatures are increasing, they focus mostly on the prediction of changes in air quality caused by short-term planning (Montero et al., 2001; Samimi et al., 2009; Gamberini et al., in press), and the support tools (Bhat et al., 2009; Coelho et al., 2009). In contract, researches on controlling and reducing vehicle emissions by transportation planning are still meager. Latini et al. (2005) presented an overview on air pollution problems, and discussed current and on-going developments for reducing transport-related air pollution. The issues which were taken into account for an individual road network planning included air quality improvement, economic development and safety improvement. Then he developed an evaluation of his progresses by switching from traffic light controlled crossings to roundabouts. Coelho et al. (2005) used experimental measurements to explain the interaction between the signal control planning and vehicle emissions. The relationship between land use planning and air pollution has received additional consideration (Still et al., 1999; Waddell et al., 2007). In addition to all of the above work which dealt with transportation planning at the microscopic level, the hot issues include the community scale macroscopic transportation planning for supporting vehicle emissions management. Sim et al. (2001) provided empirical evidence of Singapore that the transportation planning of community centers could be an effective way of reducing the amount of work-travel and reliance on the car, further, alleviating traffic congestion and vehicle emissions. Zegras et al. (2004) proposed a framework for using business and organizational scenario-planning techniques for regional strategic transportation planning. It was applied to the Houston area. Though their analyses were preliminary in scope, they contributed a step forward in using scenario planning for community strategic transportation planning and traffic environment. Other achievements have been applied to various locations across the world (Garnett, 1980; Feldstein et al., 1996; Handy, 2008).

However, most of the previous studies only focused on the

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ISSN: 1726-2135 print/1684-8799 online
 doi:10.3808/jei.201000169

transportation planning in a community or a region, and rarely developed optimization models for inter-community transportation planning. The inter-community traffic optimization is as important as the inner-community one. Because the whole traffic network includes a large number of notes and paths, it is reasonable to divide a big city into several communities by different functions for feasible solutions. Only by combining the inter-community optimization and inner-community one, can we treat the transportation system as a closed-system. Besides, planning for a transportation system is a complicated task that involves a high degree of uncertainty existing in system costs, traffic factors, investigation data and even planning objectives. According to literatures, there are some achievements which address the uncertainties in the energy system management. For example, Cai et al. (2009b) proposed a fuzzy-random interval programming model which could be used for facilitating capacity expansion planning of energy production facilities within a multi-period. Further, he developed an interactive decision support system based on an inexact optimization model to aid decision makers in planning energy management systems (Cai et al., 2009a). The uncertainty method also was used in other fie- lds of environment system (Luo et al., 2004; Huang et al., 2007; Li et al., 2008). Li et al. (2008) and Tan et al. (2009) developed evacuation management models for supporting the evacuation planning under uncertainty. Through these models, complex relationships between evacuation time, environmenttal influences and economic factors could be systematically analyzed. They work focused on a specific aspect in the traffic system and provided a real-time planning method. To sum up, in the field of long-term transportation planning, the existing researches fail to address the uncertainties in the process of planning.

Therefore, in this paper, the objective is to develop an uncertainty optimization method for inter-community transportation planning and vehicle emissions management. This proposed model can be used for facilitating the generation of a range of decision alternatives, which is helpful for decision makers to formulate long-term plans under uncertainties. This study will: (a) tackle the uncertain, dynamic and complex characteristics of transportation system; (b) build inter-community optimization model under uncertainties; (c) apply the model and the related solution algorithm in a real case and generate some compromise decisions under various system conditions.

2. Interval-parameter Inter-community Transportation Planning Model (ICTPM)

Assessing in-service operations of traffic facilities is easier than predicting construction time of new facilities, because the latter involves a large number of uncertainties, for example, traffic flow, public perception, driver behavior and so on. In most transportation planning, decision makers are generally responsible for improving traffic safety and traffic flux, but they seldom consider the questions of system cost and traffic environment. Therefore, this study will figure out how to allocate funds reasonably, and realize desired environmental goals in inter-community transportation planning.

Yoram Shiftan et al. (2003) provided several primary factors related to transportation planning: traffic assignment, travel behavior and choice model, economic level, urban travel, private car and public transport, technology, and policy. On the basis of them, the following factors will be considered in the inter-community planning model: a) economic development of these communities, b) traffic structure of each of these communities, c) the geographical features, d) existing traffic control methods and schemes, e) drivers' preferences, f) traffic flow among communities, g) exhaust emission standard, and h) government policy of traffic development.

The relationships among above factors are shown in Figure 1. They together constitute a complex system within which they are interrelated. Any change in one sector may lead to a series of consequences to others. For example, with loosened local vehicle policy, the automobile ownership will increase, along with the increase in traffic jams and exhaust emissions. Moreover, it may result in shifting of the existing technologies/resources and causing additional economic cost. Transportation planning is responsible for infrastructural investments; and further, has impacts on local ecosystems. Meanwhile, some policies and strategies, especially environmental legislations, influence the increase in the automobile ownership.

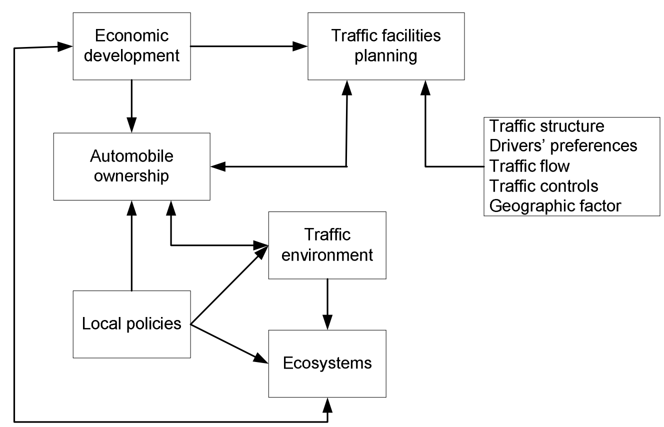

Figure 1. The relationships among factors in a community traffic system.

Decision makers can formulate inter-community transportation planning problem in terms of minimizing the system cost with optimized road capacity-expansion plan and reasonable traffic structure. Generally, if traffic demand is not beyond the capacity of traffic facilities, system cost will remain stable. Otherwise, capacity expansion should be considered. So, decision makers are to identify desired capacity expansion schemes with minimal system cost and maximal system reliability.

On July 1, 2007, China's State Environmental Protection Administration upgraded emission controls to National Standard III, equivalent to European III standards. The vehicles are classified into several types, and subject to a CO emission limit of 0.1 ~ 5 g/km. Then, we classify them into three types by their exhaust levels based on European III standards: high emission vehicles; middle emission vehicles; and low emission vehicles. High emission vehicles include light commercial vehicles (> 1,305 kg, gasoline); middle emission vehicles include passenger cars (gasoline), light commercial vehicles (< 1,305 kg, gasoline) and large goods vehicles; and low emission vehicles include passenger cars (diesel), light commercial vehicles (diesel) and heavy-duty diesel engine buses. Traffic information such as road length, road capacity, traffic flow, and average speed can be obtained by modern technologies. Other information such as vehicle ownership in the future can be predicted based on historical traffic records. The objective of this model is to minimize system cost, and it relates to most factors shown in Figure 1. The decision variables include two types: binary variables and continuous ones. The binary variables address road capacity-expansion options (building a new trunk road or not); the continuous ones identify flux, the number of vehicles, velocity and so on. Parameters and system objectives are described as intervals to handle with the uncertainties involved in the transportation system. The constraints are a number of inequalities to describe relationships among decision variables and system conditions. These constraints include: the number of vehicles in the system, the maximum capacity of each link, nonnegative constraints and others. A typical inter-community traffic system is shown in Figure 2 (including three communities and three thoroughfares). Three time periods are considered (each period *t* has a time interval of five years). The objective function is for- mulated as a sum of the follows:

Fuel cost: C_f

Because fuel consumption within any community is irrelevant to the inter-community planning, C_f only calculates the fuel costs of vehicles passing inter-community thoroughfares.

$$C_f = \begin{cases} \sum_{t=1}^{3}\sum_{r=1}^{rs}\sum_{vt=1}^{3} FU_t VS_{t,r,vt}(FB_{t-1,vt}RL_r + FS_{t-1,r,vt}), \text{ when building new thoroughfare} \\ \sum_{t=1}^{3}\sum_{r=1}^{rs}\sum_{vt=1}^{3} FU_t VS_{t,r,vt}(FB_{t,vt}RL_r + FS_{t,r,vt}), \text{ when keeping current facilities} \end{cases} \quad (1)$$

where *r* denotes thoroughfares; *rs* is the total number of thoroughfares between two communities (r = 1, 2, …, *rs*); *vt* represents vehicle types: high emission vehicle(vt = 1), middle emission vehicle(vt = 2) and low emission vehicle(vt = 3); FU_t is the fuel prices in period *t* ($/liter); $VS_{t,r,vt}$ is the number of vehicles which belong to type *vt* on thoroughfare *r* in period *t* (vehicles/year); RL_r is the length of thoroughfare *r*; $FB_{t,vt}$ is the average fuel consumption of vehicle type *vt* in period *t* (liter/kilometer); $FS_{t,r,vt}$ is the average fuel consumption of vehicle type *vt* under idle speed on thoroughfare *r* in period *t* (liter).

Traffic management expense: C_{tm}

As shown in Figure 3, a journey on a road can be considered as having an associated cost or price (Stopher and Meyburg, 1975). We set that the total management expence varies directly as K. When road capacity is increased, there is more road space for each vehicle, so congestion and the management costs are reduced. The function can be described as follows:

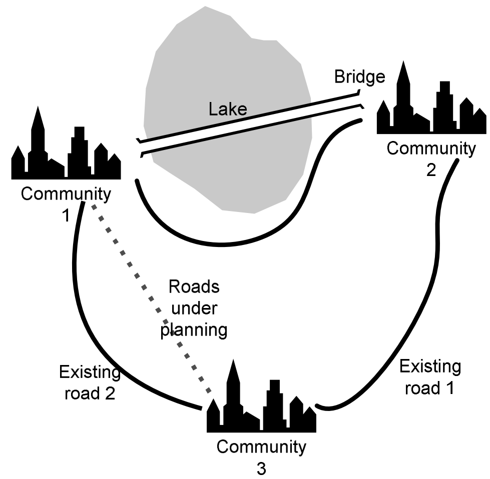

Figure 2. A demonstration of inter-community traffic system.

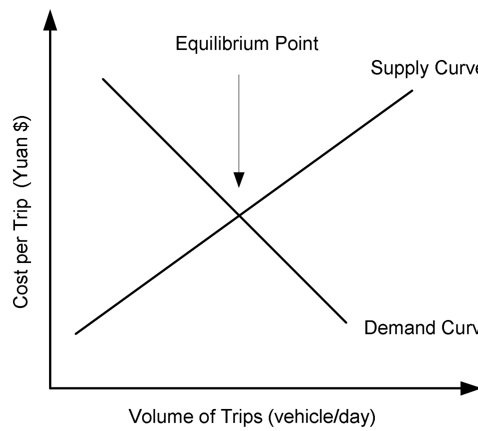

Figure 3. Equilibration of Demand and price curves.

$$C_{tm} = \sum_{t=1}^{3}\sum_{r=1}^{rs}\sum_{vt=1}^{3} kVS_{t,r,vt} \quad (2)$$

Costs for capacity expansion of traffic facilities: C_e

$$C_e = \sum_{rt=1}^{rts} NT_{r,rt}TC_{t,rt} \quad (3)$$

where *rts* is the number of types of thoroughfares between communities. If a thoroughfare is road, rt = 1; if it is a bridge, rt = 2; and when it is a tunnel, rt = 3. $NT_{r,rt}$ is a binary variable. If the new thoroughfare is type *rt*, $NT_{r,rt}$ = 1; otherwise, $NT_{r,rt}$ = 0. $TC_{t,rt}$ denotes the cost for building a new thoroughfare of type *rt* in period *t*($).

Maintenance expense: C_m

$$C_m = \sum_{t=1}^{3}\sum_{r=1}^{rs}\sum_{rt=1}^{rts} RT_{r,rt}(RX_{t,rt}RL_r + TFX_{t,r}) \quad (4)$$

where $RX_{t,rt}$ is the maintenance cost of thoroughfare type *rt* in period *t* ($/km); $RT_{r,rt}$ is a binary variable. If thoroughfare *r* belongs to type *rt*, then $RT_{r,rt} = 1$; otherwise, $RT_{r,rt} = 0$. $TFX_{t,r}$ is a random variable.

The constraints are listed as follows:

$$\sum_{vt=1}^{3} VS_{t,r,vt} \le VT_{t,r}\ ,\ \forall\ t, r \quad (5)$$

$$\sum_{r=1}^{rs} VS_{t,r,i} \le \sum_{r=1}^{rs}\sum_{vt=1}^{3} VS_{t,r,vt}a_i\ ,\ \forall\ t, i = 1, 2, 3 \quad (6)$$

$$VS_{t,r,i} \le \sum_{vt=1}^{3} VS_{t,r,vt}b_i\ ,\ \forall\ t, r, i = 1, 2, 3 \quad (7)$$

$$\sum_{r=1}^{rs}\sum_{vt=1}^{3} f(v_{t,r}, VS_{t,r,vt}) \le UPE_t\ ,\ \forall\ t \quad (8)$$

$$\sum_{vt=1}^{3} f(v_{t,r}, VS_{t,r,vt}) \le UPER_{t,r}\ ,\ \forall\ t, r \quad (9)$$

$$VS_{t,r,vt} \ge 0\ ,\ \forall\ t, r, vt \quad (10)$$

where, $VT_{t,r}$ denotes the capacity limits of thoroughfare *r* in period *t*; a_i and b_i are expressed as percentages. Therefore, (6) can ensure all kinds of vehicle in a reasonable ratio in the whole transportation system, and (7) can ensure all kinds of vehicle in a reasonable ratio on every thoroughfare. UPE_t is the limitations of emissions of the whole system; $UPER_{t,r}$ is the limitations of vehicle emissions of thoroughfare *r*; $f(v_{t,r}, VS_{t,r,vt})$ is used to calculate vehicle emissions.

However, this model cannot handle with the uncertainties in the traffic system. For example, the number of each kind of vehicles cannot be known exactly. With dynamic traffic features, the flux of each thoroughfare is also uncertain. To deal with uncertainties, many methods were developed, which were related to fuzzy mathematical programming (Chanas and Zielinski, 2000), stochastic programming (Henn and Ottomanelli, 2006), and interval programming (Sae-lim, 1999). In the probabilistic approach, probability distributions are used to describe random variability. However, probability distributions and membership functions are difficult to establish. Interval linear programming (ILP) is an alternative for handling with uncertainties. ILP does not require distribution information for its parameters since interval numbers are acceptable for the uncertain inputs (Huang, 1998). In traffic planning, data can hardly be obtained exactly, but they can be expressed as interval value.

Interval linear programming allows interval information to be directly communicated into the optimization process. The ILP model can be expressed as follows (Huang et al., 1993):

$$\text{Min} \quad f^{\pm} = C^{\pm}X^{\pm} \quad (11)$$

Subject to:

$$A^{\pm}X^{\pm} \le B^{\pm} \quad (12)$$

$$X^{\pm} \ge 0 \quad (13)$$

where $A^{\pm} \in \{R^{\pm}\}^{m\times n}$, $B^{\pm} \in \{R^{\pm}\}^{m\times 1}$, $C^{\pm} \in \{R^{\pm}\}^{1\times n}$, $X^{\pm} \in \{R^{\pm}\}^{n\times 1}$, and $R^{\pm}$ denotes a set of interval variables. The basic definitions related to interval parameters and their operations were listed in some work (Huang et al., 1993; Huang et al., 1994; Huang, 1998; Huang et al., 2001).

Based on this methodology, the planning problem can be expressed as an interval-parameter model as follows:

$$Min\ f^{\pm} = \sum_{t=1}^{3}\sum_{r=1}^{rs}\sum_{vt=1}^{3} FU_t^{\pm}VS_{t,r,vt}^{\pm}(FB_{t-1,vt}^{\pm}RL_r + FS_{t-1,r,vt}^{\pm}) + \sum_{t=1}^{3}\sum_{r=1}^{rs}\sum_{vt=1}^{3} k\, VS_{t,r,vt}^{\pm} + \sum_{rt=1}^{rts} NT_{r,rt}TC_{t,rt}^{\pm} + \sum_{t=1}^{3}\sum_{r}^{rs}\sum_{rt}^{rts} RT_{r,rt}(RX_{t,rt}^{\pm}RL_r + TFX_{t,r}^{\pm}),\ \text{when building new thoroughfare} \quad (14)$$

$$Min\ f^{\pm} = \sum_{t=1}^{3}\sum_{r=1}^{rs}\sum_{vt=1}^{3} FU_t^{\pm}VS_{t,r,vt}^{\pm}(FB_{t,vt}^{\pm}RL_r + FS_{t,r,vt}^{\pm}) + \sum_{t=1}^{3}\sum_{r=1}^{rs}\sum_{vt=1}^{3} k\, VS_{t,r,vt}^{\pm} + \sum_{t=1}^{3}\sum_{r=1}^{rs}\sum_{rt=1}^{rts} RT_{r,rt}(RX_{t,rt}^{\pm}RL_r + TFX_{t,r}^{\pm}),$$
$$\text{when keeping the existing facilities} \quad (15)$$

Subject to:

$$\sum_{vt=1}^{3} VS_{t,r,vt}^{\pm} \le VT_{t,r}\ ,\ \forall\ t, r \quad (16)$$

$$\sum_{r=1}^{rs} VS_{t,r,i}^{\pm} \le \sum_{r=1}^{rs}\sum_{vt=1}^{3} VS_{t,r,vt}^{\pm}a_i\ ,\ \forall\ t, i = 1, 2, 3 \quad (17)$$

$$VS_{t,r,i}^{\pm} \le \sum_{vt=1}^{3} VS_{t,r,vt}^{\pm}b_i\ ,\ \forall\ t, r, i = 1, 2, 3 \quad (18)$$

$$\sum_{r=1}^{rs}\sum_{vt=1}^{3} f(v_{t,r}, VS_{t,r,vt})^{\pm} \le UPE_t\ ,\ \forall\ t \quad (19)$$

$$\sum_{vt=1}^{3} f(v_{t,r}, VS_{t,r,vt})^{\pm} \le UPER_{t,r}\ ,\ \forall\ t, r \quad (20)$$

$$VS_{t,r,vt}^{\pm} \ge 0\ ,\ \forall\ t, r, vt \quad (21)$$

where the '-' and '+' superscripts represent lower and upper bound, respectively. For example, $FU_t^{\pm}$ is the interval parameter of FU_t, i.e. the lower and upper bound of the fuel price in period *t*.

According to Huang et al. (1993, 1994), the problem can be solved by decomposing the model into two parts. The lower bound of the objective function is solved first:

$$Min\ f^- = \sum_{t=1}^{3}\sum_{r=1}^{rs}\sum_{vt=1}^{3} FU_t^- VS_{t,r,vt}^- (FB_{t-1,vt}^- RL_r + FS_{t-1,r,vt}^-) + \sum_{t=1}^{3}\sum_{r=1}^{rs}\sum_{vt=1}^{3} k\, VS_{t,r,vt}^- + \sum_{rt=1}^{rts} NT_{r,rt} TC_{t,rt}^- + \sum_{t=1}^{3}\sum_{r}^{rs}\sum_{rt}^{rts} RT_{r,rt}(RX_{t,rt}^- RL_r + TFX_{t,r}^-), \text{ when building new thoroughfare} \quad (22)$$

$$Min\ f^- = \sum_{t=1}^{3}\sum_{r=1}^{rs}\sum_{vt=1}^{3} FU_t^- VS_{t,r,vt}^- (FB_{t,vt}^- RL_r + FS_{t,r,vt}^-) + \sum_{t=1}^{3}\sum_{r=1}^{rs}\sum_{vt=1}^{3} k\, VS_{t,r,vt}^- + \sum_{t=1}^{3}\sum_{r=1}^{rs}\sum_{rt=1}^{rts} RT_{r,rt}(RX_{t,rt}^- RL_r + TFX_{t,r}^-), \text{ when keeping the existing facilities} \quad (23)$$

Subject to:

$$\sum_{vt=1}^{3} VS_{t,r,vt}^- \le VT_{t,r}\ ,\ \forall\, t, r \quad (24)$$

$$\sum_{r=1}^{rs} VS_{t,r,i}^- \le \sum_{r=1}^{rs}\sum_{vt=1}^{3} VS_{t,r,vt}^- a_i\ ,\ \forall\, t, i = 1, 2, 3 \quad (25)$$

$$VS_{t,r,i}^- \le \sum_{vt=1}^{3} VS_{t,r,vt}^- b_i\ ,\ \forall\, t, r, i = 1, 2, 3 \quad (26)$$

$$\sum_{r=1}^{rs}\sum_{vt=1}^{3} f(v_{t,r}, VS_{t,r,vt})^- \le UPE_t\ ,\ \forall\, t \quad (27)$$

$$\sum_{vt=1}^{3} f(v_{t,r}, VS_{t,r,vt})^- \le UPER_{t,r}\ ,\ \forall\, t, r \quad (28)$$

$$VS_{t,r,vt}^- \ge 0\ ,\ \forall\, t, r, vt \quad (29)$$

And then, the upper bound is solved:

$$Min\ f^+ = \sum_{t=1}^{3}\sum_{r=1}^{rs}\sum_{vt=1}^{3} FU_t^+ VS_{t,r,vt}^+ (FB_{t-1,vt}^+ RL_r + FS_{t-1,r,vt}^+) + \sum_{t=1}^{3}\sum_{r=1}^{rs}\sum_{vt=1}^{3} k\, VS_{t,r,vt}^+ + \sum_{rt=1}^{rts} NT_{r,rt} TC_{t,rt}^+ + \sum_{t=1}^{3}\sum_{r}^{rs}\sum_{rt}^{rts} RT_{r,rt}(RX_{t,rt}^+ RL_r + TFX_{t,r}^+), \text{ when building new thoroughfare} \quad (30)$$

$$Min\ f^+ = \sum_{t=1}^{3}\sum_{r=1}^{rs}\sum_{vt=1}^{3} FU_t^+ VS_{t,r,vt}^+ (FB_{t,vt}^+ RL_r + FS_{t,r,vt}^+) + \sum_{t=1}^{3}\sum_{r=1}^{rs}\sum_{vt=1}^{3} k\, VS_{t,r,vt}^+ + \sum_{t=1}^{3}\sum_{r=1}^{rs}\sum_{rt=1}^{rts} RT_{r,rt}(RX_{t,rt}^+ RL_r + TFX_{t,r}^+), \text{ when keeping the existing facilities} \quad (31)$$

Subject to:

$$\sum_{vt=1}^{3} VS_{t,r,vt}^+ \le VT_{t,r}\ ,\ \forall\, t, r \quad (32)$$

$$\sum_{r=1}^{rs} VS_{t,r,i}^+ \le \sum_{r=1}^{rs}\sum_{vt=1}^{3} VS_{t,r,vt}^+ a_i\ ,\ \forall\, t, i = 1, 2, 3 \quad (33)$$

$$VS_{t,r,i}^+ \le \sum_{vt=1}^{3} VS_{t,r,vt}^+ b_i\ ,\ \forall\, t, r, i = 1, 2, 3 \quad (34)$$

$$\sum_{r=1}^{rs}\sum_{vt=1}^{3} f(v_{t,r}, VS_{t,r,vt})^+ \le UPE_t\ ,\ \forall\, t \quad (35)$$

$$\sum_{vt=1}^{3} f(v_{t,r}, VS_{t,r,vt})^+ \le UPER_{t,r}\ ,\ \forall\, t, r \quad (36)$$

$$VS_{t,r,vt}^+ \ge VS_{t,r,vt}^-\ ,\ \forall\, t, r, vt \quad (37)$$

where $VS_{t,r,vt}^-$ is the lower bound which has been solved first. So, the interval values of the objective function can be obtained: $f^{\pm} = [\, f^-, f^+]$.

3. Case Study

Generally, a community is a geographically localized area, often within a large city or suburb. In a community, the traffic structure and land-use are similar, no matter what size the area is. In this paper, we take Wuhan City as our study object. It lies at the east of Jianghan Plain, and the intersection of the middle reaches of the Yangtze and Han River in China. Wuhan is a major transportation hub, with dozens of railways, roads and expressways passing through the city. The city of Wuhan, is recognized as transportation center of central China. To Wuhan inter-community transportation planning (from 2005 to 2019, each period is five years) and vehicle emissions reduction, one reference case (business-as-usual, BAU) and a scenario (scenario A) are developed in the following parts based on above model. In the BAU case, the planning model is simulated without any regulatory barriers (for example, no punishment for driving a gas-guzzler, no trunk road expansion); all parameters and decision variables represent the existing and predicted technological and environmental conditions. In the simulation of the reference case, the scheme with the lowest cost will be chosen. The scenario A is designed to identify pollution mitigation strategies. In the scenario, vehicle emissions are assumed to be stabilized at the 2005 level during three planning periods, even though the automobile ownership increases. By the planning model, a prioritization scheme will be proposed to meet the environment standards.

3.1. Data Collection

In main urban zone of Wuhan, there are three thoroughfares (the Tunnel of Wuhan, the First Yangtze River Bridge of Wuhan and the second Yangtze River Bridge of Wuhan) connecting two communities: Wuchang and Hankou. The traffic network is shown in Figure 4. The lines denote main roads.

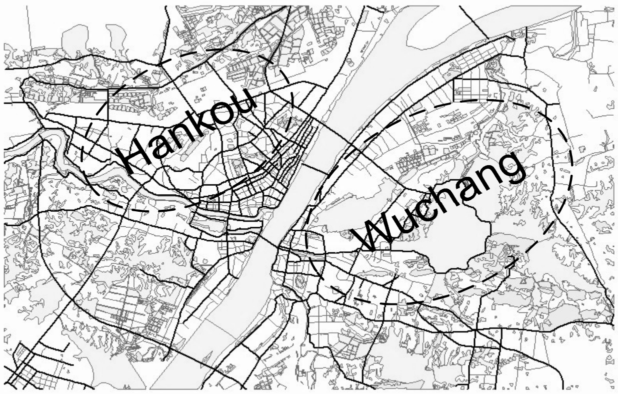

Figure 4. A part of traffic network in Wuhan City.

There is no scheduled rail service between Wuchang and Hankou. The traffic demands are satisfied by community road-net and several inter-community thoroughfares. Although the public transportation network covers all communities, the residential and commercial activities necessitate a large number of cars. It has been estimated that about 0.8 million cars take passengers to their workplaces every day. In 2008, the average trip times of the residents was 2.41, compared with 1.98 in 1998. Increasing trip time results in the raising of flux between Hankou and Wuchang. Through investigations and questionnaires, the data of Wuhan transportation system were collected: fuel prices, traffic demand, the existing road capacities and so on. The inputs are expressed as interval values and indicated in Tables 1 to 3.

Vehicle types and traffic flow features influence vehicle emissions. Li (2001) proposed a model to calculate CO emissions of vehicles in Chinese cities. The formula was as follows:

$$Eco_i = \alpha_i + \beta_i v + \gamma_i v^2 \tag{38}$$

where Eco_i is CO emissions of a vehicle whose type is i (g/km); v is the average velocity of the vehicle (km/h); α_i, β_i and γ_i are coefficients shown in Table 4 (Wu et al., 2010).

3.2. Result Analyses

3.2.1. Transportation Planning under BAU Conditions

Figure 5 shows the lower bounds and the upper bounds solutions of decision variable $VS_{t,r,vt}$ in BAU conditions. The lower bounds of the total costs (e.g. 994.4222 million Yuan/year) can be obtained when decision variable $VS_{t,r,vt}$ (t = 1, 2, 3; r = 1, 2, 3; vt = 1, 2, 3) are at their lower bounds levels, and the upper bounds of the total costs (e.g. 1,419.165 million Yuan/year) can be obtained when $VS_{t,r,vt}$ (t = 1, 2, 3; r = 1, 2, 3; vt = 1, 2, 3) reach their upper bounds levels. Therefore, the system costs vary within [994.4222, 1,419.165] (million Yuan/year).

Table 1. The Parameters of Three Thoroughfares

r	t	RL_r (km)	Average vehicle speed (km/h)	$RX_{t,rt}$ (million \$/km)	Maximum traffic flow allowed (vehicle/day)
1	1	1.6704	[24.5-26.3]	[4.0-4.6]	100000
	2		[23.5-24.5]	[4.5-5.2]	
	3		[22.6-23.3]	[5.5-5.8]	
2	1	3.2274	[24.2-25.3]	[4.2-4.8]	150000
	2		[23.1-23.9]	[4.8-5.7]	
	3		[22.1-22.8]	[6.0-6.3]	
3	1	3.63	[38.2-40.5]	[20.0-22.0]	75000
	2		[36.4-38.1]	[23.0-24.5]	
	3		[34.8-37.2]	[27.0-28.0]	

Table 2. Oil Price, Traffic Flow and Expansion Cost in Each Period

t	FU_t (\$/liter)	C_e (billion per bridge)	C_e (billion per tunnel)	Daily flow (10^4 vehicle/d)
1	[6.1-6.9]	[2.0-2.5]	[2.0-2.2]	[23.2-25]
2	[7.0-8.1]	[2.5-3.0]	[2.5-2.7]	[25-27]
3	[8.2-8.9]	[3.0-3.5]	[3.0-3.2]	[27-30]

Figure 5(a) shows the lower bounds of the decision variables during three periods. In period 1, the flux of each thoroughfare does not reach maximum transmission capability, so drivers can tolerate occasional traffic congestion on every thoroughfare. There are no high emission vehicles on thoroughfare 1 (the first Yangtze River Bridge of Wuhan) during three periods because the government made a policy to protect the bridge. High emission vehicles must be assigned to other thoroughfares. The number of high emission vehicles on thoroughfare 3 is greater than that on thoroughfare 2. High emission vehicles generally consume more fuel during normal engine operation and idle operation and bring negative effects on air quality. For thoroughfare 3, it is a tunnel which can provide higher average speed and less idle time. If type 1 vehicles pass through thoroughfare 3, they consume less fuel. Thoroughfare 3 is also the first choice of type 2 vehicles, but some of them must choose other thoroughfares because of the restriction of road capacity. According to the results, half of them should choose thoroughfare 2, and only about 10% of them are assigned to thoroughfare 1. Low emission vehicles, as the main part of Wuhan vehicles, take up a considerable amount capacity of every road (more than 50%). In period 2 (from 2010 to 2014), thoroughfare 3 will be saturated. There are little changes in the flux of thoroughfare 2 during period 1 and period 2. However, the flux of thoroughfare 1 will increase. In period 3 (from 2015 to 2019), thoroughfare 1 and thoroughfare 3 will be saturated, so it is a sticky task for authorities to assign extra vehicles. Type 1 vehicles will continuously increase on thoroughfare 3; however, their number has

Table 3. Fuel Consumption of Each Type of Vehicle under Idle Situation and Normal Situation

vt	*Under idle situation (10^{-3}liter per thoroughfare)*						*Under normal situation (liter/km)*		
	Period 1		Period 2		Period 3		Period 1	Period 2	Period 3
	Bridge	Tunnel	Bridge	Tunnel	Bridge	Tunnel			
1	[5.7-6.2]	[2.8-3.3]	[8.5-9.3]	[5.6-6.2]	[11.3-12.0]	[8.0-8.77]	[0.17-0.19]	[0.20-0.22]	[0.22-0.25]
2	[4.0-4.8]	[2.0-2.5]	[6.0-6.7]	[3.5-4.0]	[8.0-8.7]	[5.0-5.8]	[0.12-0.15]	[0.13-0.17]	[0.15-0.19]
3	[2.7-3.2]	[1.1-1.7]	[3.2-3.8]	[3.0-3.5]	[4.3-5.0]	[3.2-4.0]	[0.065-0.09]	[0.08-0.12]	[0.09-0.13]

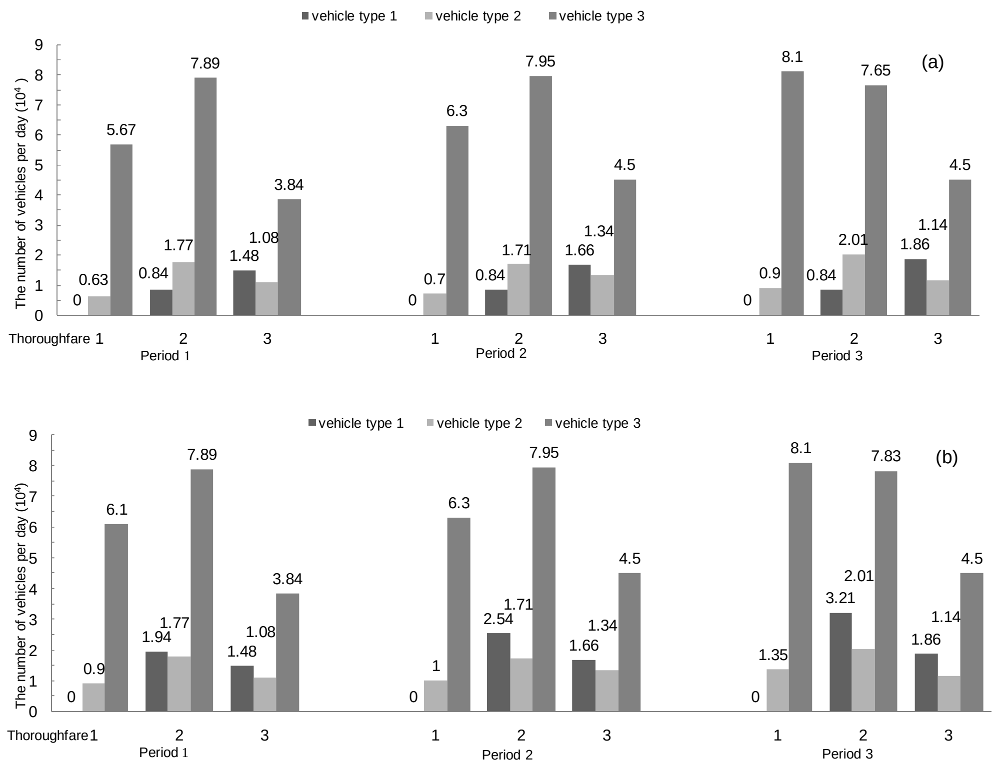

Figure 5. The lower bounds (a) and upper bounds (b) of the number of each type vehicles in every period.

stabilized on thoroughfare 2 from period 1 to period 3. In period 3, about 50% of middle emission vehicles should pass thoroughfare 2, but its number will decrease on thoroughfare 3 because of the capacity limit of road and the increase of type 1 vehicles.

In terms of traffic structure, it will be stable on thoroughfare 1 and thoroughfare 2 during three periods. In period 3, for thoroughfare 3, the proportion of middle emission vehicles will decrease, but the proportion of high emission vehicles will increase. During three periods, the average proportion of daily traffic flow to road maximum capacity is 79.58%. In period 2, thoroughfare 1 and thoroughfare 2 can allow extra vehicles to go through; however in period 3, only thoroughfare 2 is not saturated. From a global perspective, the proportion of high emission vehicles to whole vehicles is 10%, the proportion of middle emission vehicles is 15%, and the low emission vehicle's proportion is 75%.

As shown in Figure 5(b), during three periods, the traffic structure on thoroughfare 1 is stabilized. For traffic structure

Table 4. The Coefficients of Emission Factors

Coeff.	Value	Coeff.	Value	Coeff.	Value
α_1	454.813	α_2	138.905	α_3	81.8760
β_1	-11.811	β_2	-3.1472	β_3	-1.8551
γ_1	0.0878	γ_2	0.0209	γ_3	0.0123

of thoroughfare 2, there are no substantial variations from period 1 to period 2, and the same situations happen to thoroughfare 3. In period 3, the proportion of middle emission vehicles will decrease on thoroughfare 2, but high emission vehicles will increase sharply. The opposite situations happen to thoroughfare 3.

From period 1 to period 3, thoroughfare 3 keep saturated status. The flux of thoroughfare 2 and thoroughfare 3 will close their respective capacity ceiling, and in period 3, thoroughfare 2 will be saturated too. The proportion of daily traffic flow to road maximum capacity is 86.77%, which is far beyond the tolerance range. From a global perspective, the proportion of

Table 5. The CO Emissions in the Three Periods under BAU

t	r	CO of every type vehicle (kg/km•day) type 1	type 2	type 3	CO in every period (kg/day)
1	1	[0,0]	[468.4, 635.3]	[2484.0, 2537.3]	[37755.1, 47677.7]
	2	[1782.4, 4275.9]	[1286.1, 1327.2]	[3378.1, 3486.3]	
	3	[1783.1, 1950.0]	[493.8, 531.1]	[1033.7, 1112.1]	
2	1	[0,0]	[535.4, 743.4]	[2760.0, 2840.0]	[42431.7, 56252.9]
	2	[1922.1, 5656.1]	[1293.2, 1322.8]	[3542.9, 3624.1]	
	3	[2195.6, 2344.3]	[661.1, 697.3]	[1307.3, 1379.1]	
3	1	[0,0]	[706.1, 1038.4]	[3671.7, 3744.9]	[46594.1, 66378.8]
	2	[1988.0, 7420.4]	[1568.1, 1599.1]	[3586.8, 3600.0]	
	3	[2547.2, 2792.2]	[578.6, 623.5]	[1344.9, 1449.6]	

high emission vehicles to whole vehicles is 19.961%, the proportion of middle emission vehicles is 15%, and the low emission vehicle's proportion is 65.039%.

In period 1, three thoroughfares have enough room for vehicles, so the authority will reap benefits in terms of the flexibilities in managing thoroughfares flux and traffic structure. In period 2 and period 3, for thoroughfare 3, daily traffic flux will reach its highest point with increased automobile ownership in Wuhan. As the optimization results shown, the value of each decision variable referring to thoroughfare 3 is definite, so there is no room left for the authority. A heavily congested or poorly connected traffic system restricts economic and social development, so for period 2 and 3, it will be necessary to build new thoroughfares between two communities.

According to above data and formulas, the amount of CO emissions of every thoroughfare during three periods is shown in Table 5. For thoroughfare 1, the average growth rate of CO emissions is 12.279% in period 2, and 33.181% in period 3. As far as thoroughfare 2 is considered, the average growth rate of CO emissions is 10.744% in period 2, and 12.353% in period 3. For thoroughfare 3, an average growth rate of 24.404% is for period 2; however, in period 3, the increments speed of CO emissions is 8.711%. The growth trends are shown in Figure 6. From period 1 to period 3, as the increase in automobile ownership, the flux increases on every thoroughfare, so do CO emissions. On thoroughfare 1, the CO emissions will increase sharply, and, especially in period 3, its growth rate is twice as high as that in period 2. The change tendency of thoroughfare 3 is distinct, because its flux has been saturated from period 2 to period 3. If its traffic structure does not change, the amount of emissions will be similar during both periods. Base on the optimization data, the number of high emission vehicles will decrease in period 3, and the number of middle emission vehicles will increase. So CO emissions will increase slightly. To sum up,

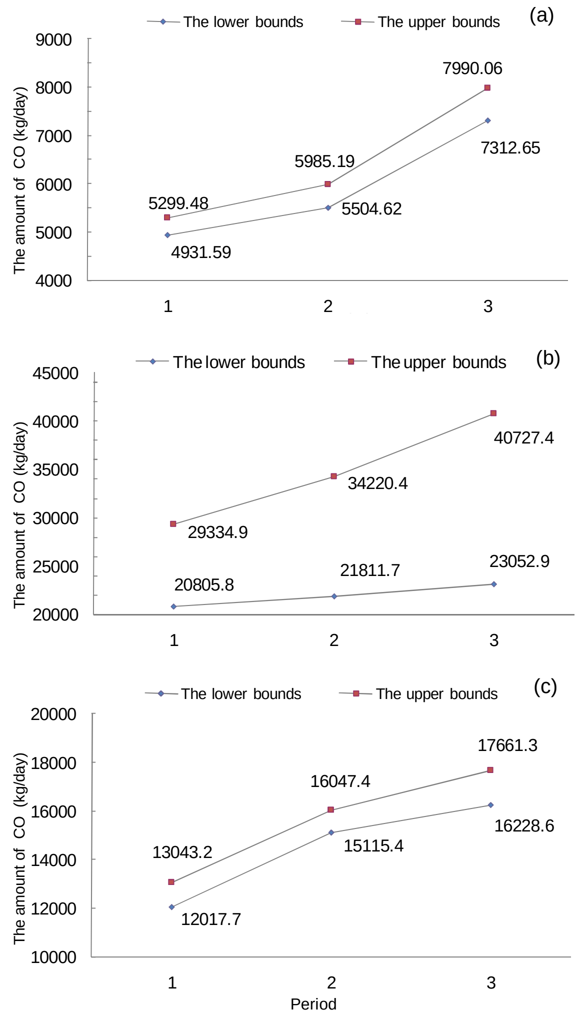

Figure 6. The amounts of CO emissions on thoroughfare 1(a), 2(b) and 3(c) during the three periods.

for all thoroughfares, vehicle emissions will rise, especially in period 3.

The approximate growth rate of CO emissions is 15.187 percent in period 2, compared to 13.905 percent in period 3. Rapid increment of CO emissions puts great pressure on traffic environment. These results are based on the optimization results which have already optimized the traffic structure on each thoroughfare. So, these data are a conservative estimate of CO emissions during three periods. Without management and optimization, traffic environment will deteriorate after about two decades. In period 2 and period 3, building new thoroughfares (bridges or tunnels) should be considered.

3.2.2. Transportation Planning in Scenario A

In this scenario, vehicle emissions of period 2 and 3 are assumed to be stabilized at the 2005 level. According to above results and analyses, without building new thoroughfares, CO emissions will increase sharply in the future. To meet this goal,

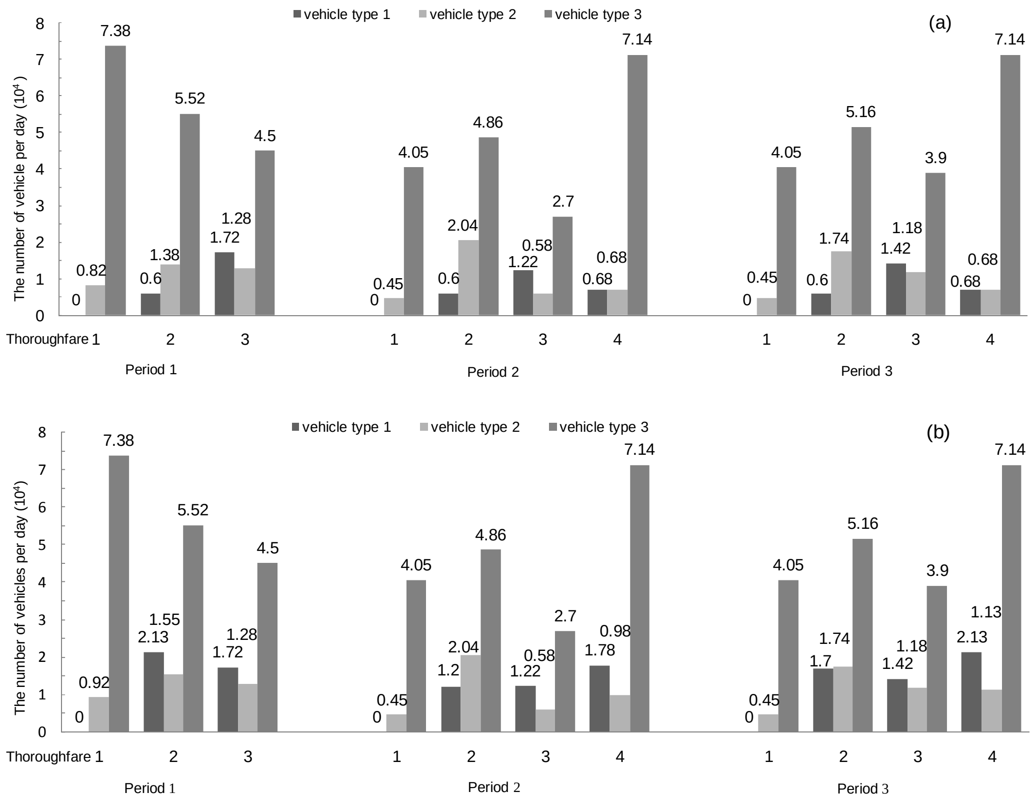

Figure 7. The lower bounds (a) and upper bounds (b) of the number of each type of vehicle (with a new bridge).

the authority can take the following measures: firstly, building a new thoroughfare to siphon off some vehicles from current thoroughfares; secondly, adopting some policies to control the increment speed of automobile ownership in Wuhan; thirdly, encouraging residents to buy new types of vehicle using clean energy. In this paper, we focus on when to build a new thoroughfare.

There are two options to Wuhan to expand road capacities: building a tunnel and building a bridge. In general, bridges with low construction costs are more competitive than tunnels. Besides, the maintenance cost per kilometer of a tunnel is about 20 times more than that of a bridge. So, building a bridge is a reasonable choice. Based on the geographic information of the Yangtze River, the new bridge's length will be about 3 kilometers, and it is normally to have six lanes or more. The cost will be about 1.35 to 1.55 billion Yuan.

When a new bridge is built in period 2, traffic congestion will be relieved in periods 2 and 3 (in Figure 7). For the lower bounds, in period 1, the flux on thoroughfare 1 approaches its peak. But in period 2 and period 3, its flux will drop by almost half. So, the new bridge will particularly benefit thoroughfare 1, and the results cater to the government policy for protecting thoroughfare 1 (it is a bridge with a long history). For thoroughfare 3, its flux will decrease in period 2; however, as the automobile ownership increases in the city, the flux on thoroughfare

Table 6. The CO Emissions in the Three Periods under Scenario A

t	r	CO of every type vehicle (kg/km•day)			CO in every period (kg/day)
		type 1	type 2	type 3	
1	1	[0,0]	[609.6, 649.4]	[3069.7, 3233.1]	[35162.9, 48501.6]
	2	[1273.2, 4694.6]	[1002.7, 1162.2]	[2363.4, 2439.1]	
	3	[2072.3, 2266.2]	[585.3, 630.0]	[1211.4, 1303.2]	
2	1	[0,0]	[273.9, 289.1]	[1452.4, 1533.1]	[33788.4, 44881.1]
	2	[1065.2, 2217.5]	[1279.8, 1322.5]	[1796.2, 1856.3]	
	3	[1210.0, 1322.9]	[226.1, 243.3]	[619.2, 666.6]	
	4	[1207.3, 3289.3]	[426.6, 635.3]	[2638.9, 2727.1]	
3	1	[0,0]	[282.3, 297.8]	[1496.8, 1579.3]	[34111.0, 53456.4]
	2	[1104.8, 3256.6]	[1124.6, 1161.9]	[1965.0, 2030.1]	
	3	[1463.9, 2350.6]	[474.9, 699.0]	[923.6, 1360.9]	
	4	[1252.1, 4080.3]	[440.0, 754.6]	[2719.0, 2809.1]	

3 will increase again in period 3. With the highest average velocity in all of thoroughfares, thoroughfare 3 will still be the first choice of high emission vehicles. During three periods, the average proportion of daily flow to road maximum capacities is 60.29%. The proportion of high emission vehicles to whole vehicles is 10%, the proportion of middle emission vehicles is 15%, and the low emission vehicle's proportion is 75%. The minimum cost is 1,361.4172 million Yuan.

Compared with the lower bounds results, traffic structure has not changed much in Figure 7(b) (the upper bounds results). The proportion of high emission vehicles to whole vehicles is 16.22%, the proportion of middle emission vehicles is 15%, and the low emission vehicle's proportion is 68.78%. The minimum cost is 1,833.469 million Yuan/year. The variations of CO emissions of four thoroughfares are shown in Table 6.

In Figure 8, CO emissions are taken into account. In Euro III, the emission standards improve about 5% per year, so we made CO emissions decrease extra 5% per year to cater to the abatement technologies in the final results. For thoroughfare 1, total emissions of CO will decline 56.642% in period 2. The upper-bounds and the lower-bounds results have the similar variation tendency. However, in period 3, CO emissions will be stable, and even be reduced 0.532% responding to the new emission abatement technologies and the change of vehicle energy. For thoroughfare 2, the upper bounds will reduce sharply in period 2 compared with period 1, and CO emissions will decrease from 26,774.3 to 16,110.0 kg; however, in period 3, CO emissions will increase 9.812%. As far as the lower-bounds results are concerned, the decline tendency is gentle during three periods. For thoroughfare 3, the change trends of lower bounds and upper bounds are similar: in period 2, the lower bound and upper bound will decline 50.862 percent and 50.811 percent respectively; in period 3, the lower bound and upper bound will increase due to the saturation of thoroughfare 3 in this period. For thoroughfare 4, its CO emissions variation tendency is different from other thoroughfares'. As shown in Figure 8(d), the lower bound will decrease by 5.15% while its upper bound will increase by 5.60% in period 3.

The total CO emissions would be [35,162.9, 48,501.6] kg in period 1. In period 2, both lower bound and upper bound are less than those in period 1. The main reason is that the average velocity increases and clean energy vehicles are popularized. Compared with CO emissions of period 2, the emissions increase 10.03% in period 3. According to the demand of scenario A, the emissions in periods 2 and 3 should be stable at the level of period 1. Based on the optimization results, the lower bound is less than that of period 1, but the upper bound will increase by 10.22% compared to the upper bound of period 1.

3.3. Discussion

The results of ICTPM for Wuhan city were presented from Figure 5 to 8 and Table 5 to 6. The BAU was for reference. Its results reflected the growth of CO emissions without any traffic facilities investments and vehicle emissions controls. This study found that CO emissions would increase from [37,755.1, 47,677.6] (in period 1) to [46,594.1, 66,378.8] g (in period 3). While these thoroughfares can still satisfy residents' demands, the negative impacts of exhausts will intensify in the next 20 years. Measures will have to be made to accelerate the elimination of aging automobiles to guarantee reduction of total vehicle emissions while the vehicle fleet keeps growing. Besides, clean energy vehicles should be popularized. Considering the increase of automobile ownership, the authority

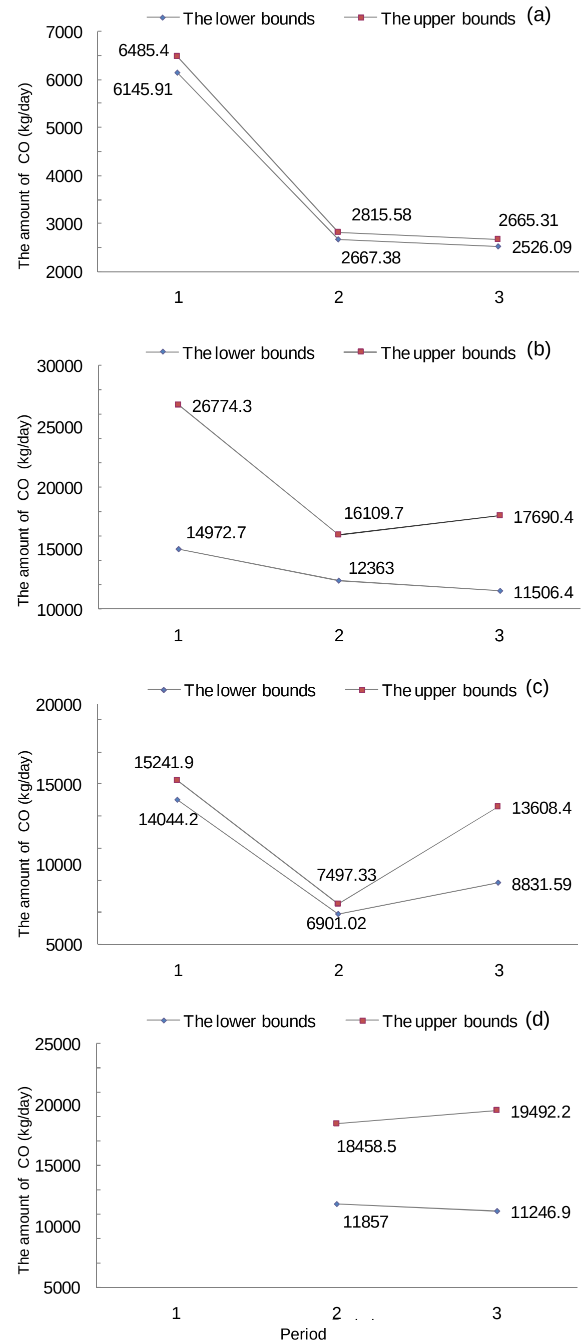

Figure 8. The amounts of CO emissions on thoroughfare 1(a), 2(b), 3(c) and 4(d) during the three periods.

will need to make decisions when to build new roads to relieve traffic congestion. If the emissions can be stable during three periods just as Scenario A, it is a good thing for emission control and the residents' health. Scenario A provided guidelines for the planning and managing of Wuhan's transporttation system in future. The time of building a new road and the traffic structure of each thoroughfare were given by the optimization results. CO emissions will decrease from [35,162.9, 48,501.6] to [34,111.0, 53,456.4] g. The lower bounds of three periods are stable, while the upper bound of the period 3 is larger than that of the period 1. So, with some probability, the CO emissions in period 3 would be higher than that in period 1.

To sum up, if a new thoroughfare is built in period 2, the demand for emission control can be totally satisfied in the next ten years. It is also indicated that reducing CO emissions has a price. Obviously, there are tradeoffs between environmental and economic goals. The tradeoff can be effectively analyzed through the developed ICTPM: in the BAU conditions, corresponding to the lowest costs, CO emissions will be at the highest level; in scenario A, a higher system costs is associated with lower CO emissions.

4. Conclusions

On one hand, it is necessary for traffic system to ensure economic development; on the other hand, it is important for the whole society to control vehicle emissions. Therefore, intercommunity transportation planning becomes very significant. For this purpose, the ICTPM is proposed to assess the minimum of system costs and the best time to build a new road between communities. Through integrating mixed-integer and interval-parameter linear programming methods within a general optimization framework, the ICTPM can tackle uncertainties expressed as interval value and dynamics of capacity-expansion issues. The ICTPM was then applied to the City of Wuhan, China. One BAU and one emission reduction scenario were carried out. Based on the ICTPM, the authority could figure out easily when new roads should be built in the conditions of current road network and traffic environment.

Previous achievements focused on large-scale planning, for example, city transportation planning and even regional planning (including several cities) which were based on the traffic network and had extremely high requirements to the optimization model. However, with the community-scale planning, a complex transportation planning problem can be decomposed into several small problems, and then be solved easily.

In most cities of developing countries, public transport provides a cheap way to get around in communities and cities. For the proposed model, it might be better to further incurporate travelers' preferences to various travel modes and emission fees in environmental constraints. In future work, more accurate methods should be used to estimate the traffic demand between communities and the influence of emission reduction techniques. Though these will involve more comprehensive consideration on modeling, the results could be more precise.

Acknowledgments. This work was supported by National Basic Research Program of China (2005CB724205).

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