MODELING OF AIR POLLUTION EMITTED FROM AN URBAN ROAD NETWORK

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1. INTRODUCTION

Recently, emissions from urban road networks have been a concern in transportation modeling. The idea behind this fact is that the urban life has attested an excessive use of vehicles which affect our traffic demand. This increasing use of vehicles has many effects on human health. On the other hand, road transportation systems in urban areas has a mission to provide mobility to the residents. This mission must satisfy the environmental requirements to ensure sustainable development. To facilitate decision making as well as the adoption of sustainable policies in a transportation sector, vehicle emission evaluation is essential. To that end, this study attempts to assess pollutant emissions from road network in urban area by applying a stochastic user equilibrium (SUE) traffic assignment model.

Many studies have developed air pollution models for road transportation systems. Ahn et al. (2002) proposed a method that estimates emissions from vehicles based on both instantaneous speed and acceleration levels. A similar method has been developed by Oguchi et al. (2001). They estimated vehicle emissions such as nitrogen oxides based on both the vehicle speed profile and acceleration within the study highway section.

However, in this study we will focus specifically on the average travel speed of the vehicle and the flow rate. The flow rate and the average travel speed are obtained by the SUE traffic assignment model. To estimate the emission at any traffic conditions (e.g. speeds and traffic volumes), emission factors that represent pollutant released from a passenger car during one kilometer driving are introduced. At any point of a road, emissions are given by an emission factor which depends on the local mean speed and are proportional to the local vehicle density (Salles et al. 1996). Speed plays a dominant role in transport indicators such as CO2 emissions (T. French 2005).

In this study, therefore, we develop a model which estimates the emission from a road network using the relationship between the vehicle travel speed and the emission rate. Note that the emission model of nitrogen oxides of the vehicle is addressed in this study.

This paper has six more sections. The next section explains the transportation situation in Dakar. The third section presents the modeling approach of this study. In the section four and five, the stochastic user equilibrium assignment model and the traffic emission model will be addressed respectively. Section six carries out a numerical experiment. The final section concludes the paper and discusses future research needs.

2. TYPICAL URBAN TRANSPORT IN DAKAR

Urban transport networks in many developing countries face major problems due to the growth of urban population, private vehicle ownership and congestion.

The region of Dakar is one of the major cities in west Africa. It includes a huge proportion of cars (light duty vehicles) which emit various pollutants within the city. In deed, 72.8% of vehicles in the national fleet are vehicles second hand in Dakar. The vehicles second hand are expected to emit more harmful emissions. By taking traffic condition into consideration, we can propose effective traffic management measures to reduce the emission proportion.

3. FORMULATION OF THE MODEL

(1) Notations

Notations used in this paper are shown below:

W	Set of origin-destination (O-D) pairs in the network
K_w	Set of paths serving O-D pair *w*
N	Set of nodes in the network
A	Set of links in the network
q_w	Demand flow for O-D pair *w*
v_a	Flow of link *a*
c_a	Capacity of link *a*
$t_a(v_a)$	Travel time for link *a*
$t_{w,k}$	Travel time for path *k* serving O-D pair *w*
$\delta_{w,k,a}$	Variable which equals to 1 if link *a* includes path *k*, and 0 otherwise
$p_{w,k}$	Route choice proportion of the driver choosing path *k* serving O-D pair *w*
$f_{w,k}$	Flow of path *k* serving O-D pair *w*
t_a^0	Free flow travel time in link *a*
l_a	Length of the link *a*
$c_{w,k}$	Travel cost of path *k* serving O-D pair *w*
α_a, β_a	Link-specific calibration parameters

(2) Modeling approach

Figure 1 shows the main structure of the modeling approach used in this research. Our study is structured into two main parts. First, a traffic assignment model based on stochastic user equilibrium (SUE) traffic assignment is formulated. This choice is supported by the motivation to reflect the realistic behavior of the network users. The main outputs of this traffic assignment model will be particularly the travel times and the path (or link) flows in a road. Then, the emission model will be presented.

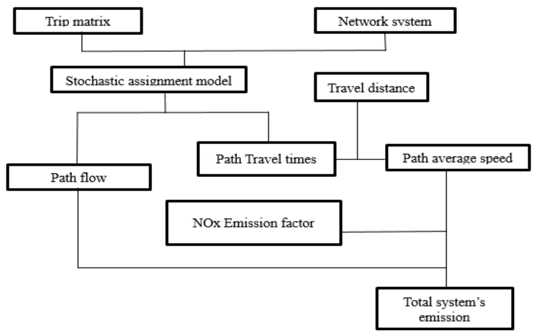

Fig.1 Modeling approach

4. TRAFFIC ASSIGNMENT MODEL

In general, an assignment model is used to allocate the content of trip matrix to a road network. To analyze the route choice in the network, the stochastic user equilibrium (SUE) assignment model can be adopted. Sheffi (1986) has formulated a general problem for stochastic user equilibrium assignment model, based on the concept of utility maximization. Consequently, the utility itself is modeled as random, meaning that the route choice is given as a probability distribution. The perceived travel time can then be looked upon as a random variable distributed across the population of drivers.

(1) Flows and Travel times in the network

Since the perceived travel time of each path is a random variable, it is associated with some probability density function. Once the distribution is specified, the choice probability of each alternative route can be calculated and the flow is assigned to the route accordingly. Assuming that q_w represents the deterministic traffic demand for O-D pair *w*, the path flows will be:

$$f_{w,k} = p_{w,k} \cdot q_w \tag{1a}$$

$$\sum_{k \in K_w} f_{w,k} = q_w \tag{1b}$$

$$f_{w,k} \geq 0 \tag{1c}$$

The link flow can then be calculated as follows:

$$v_a = \sum_{w \in W} \sum_{k \in K_w} f_{w,k} \cdot \delta_{w,k,a} \tag{2}$$

where $\delta_{w,k,a}$ represents a variable that equals to 1 if link *a* is part of path *k*, and equals 0 otherwise.

In this study, the link travel time is represented by the following BPR function (Bureau of Public Roads, 1964):

$$t_a(v_a, c_a) = t_a^0 \cdot \left(1 + \alpha_a \cdot \left(\frac{v_a}{c_a}\right)^{\beta_a}\right) \tag{3}$$

The travel time on a particular path is the sum of the travel time of the links that comprises the path (Sheffi 1986). This relationship can be expressed mathematically as:

$$t_{w,k} = \sum_{a \in A} \delta_{w,k,a} \cdot t_a \tag{4}$$

$$c_{w,k} = -t_{w,k} \tag{5}$$

(2) Driver's path choice behavior

In this study, a logit-based SUE traffic assignment model is assumed. The path choice probabilities can be formulated as the following fixed-point problem.

$$\mathbf{f}_w = q_w \cdot \mathbf{p}_w(\mathbf{c}_w(\mathbf{f})) \tag{6}$$

where:

$$p_{w,k} = \frac{\exp(\theta \cdot c_{w,k})}{\sum_{k \in K_w} \exp(\theta \cdot c_{w,k})} \tag{7}$$

$$\mathbf{f}_w = \left(f_{w,1}, \ldots, f_{w,|K_w|}\right)^T \tag{8}$$

$$\mathbf{f} = \left(\mathbf{f}_1, \ldots, \mathbf{f}_{|W|}\right)^T \tag{9}$$

$$\mathbf{p}_w = \left(p_{w,1}, \ldots, p_{w,|K_w|}\right)^T \tag{10}$$

$$\mathbf{c}_w = \left(c_{w,1}, \ldots, c_{w,|K_w|}\right)^T \tag{11}$$

The superscript *T* denotes the transposition operator of a vector.

5. TRAFFIC EMISSION MODEL

The approach is based on both the average speed obtained from the SUE traffic assignment model and NOx emissions factors equations. The NOx emissions factor depends basically on the vehicle speed. Vehicle speed, which is introduced into the calculation, has a major influence on the emissions of the vehicles (Hickman et al. 1999). At this point we need to set the emission factor which quantifies the amount of pollutant emitted. In general, the emission intensity is the average emission rate of a given pollutant from a given source relative to the intensity of a specific activity. It can be calculated by applying the method proposed in Xia and Shao (2005). The nitrogen oxides emission from link *a* on road is given by:

$$E_a = EF_a \cdot v_a \cdot l_a \tag{12}$$

where v_a is the traffic flow on link *a* and EF_a is the emission factor of the nitrogen oxides (g/pcu/km) where pcu represents passenger car unit.

Since EF_a is a function of a speed, $l_a/t_a(v_a)$ (km/hr), EF_a can be written as:

$$EF_a = EF_a\left(l_a / t_a\left(v_a\right)\right) \qquad (13)$$

6. SIMULATION RESULTS / ANALYSIS

In this section, numerical experiment is carried out to demonstrate the model proposed in this study. A road network in Dakar (Senegal) with 4 O-D pairs (Fig.2) is used in the experiment. Two link calibration parameters α_a and β_a ,used for the BPR function shown by equation (3) are set as 0.15 and 2, respectively. The method of successive average (MSA) is used as a calculation algorithm. In this experiment, we adopt a dispersion parameter $\theta = 1$. Each traffic demand was set as 25000 pcu/day. All vehicles are assumed as passenger cars. In this case, the following two equations will be used:

$$EF_a = 10^{-5} \cdot s_a^2 - 0.0021 \cdot s_a + 0.0998 \qquad (14)$$

$$EF_a = 10^{-5} \cdot s_a^2 - 0.0013 \cdot s_a + 0.0625 \qquad (15)$$

$$s_a = l_a / t_a\left(v_a\right) \qquad (16)$$

Equation (14) and (15) represent the emissions factors for gasoline vehicle and diesel vehicle respectively (Dohi and Sone, 2012).

Table 1 shows the set of paths, which are represented by the sequence of links for the network shown in Fig.3. Table 2 shows the results of the total NOx emissions for each link calculated by assuming 40% of the total vehicles are equipped with gasoline engines and 60% are equipped with diesel engines. The considered network has generated a total amount of 82.6 kilograms of NOx.

Fig.2 Global view of the considered network (Dakar)

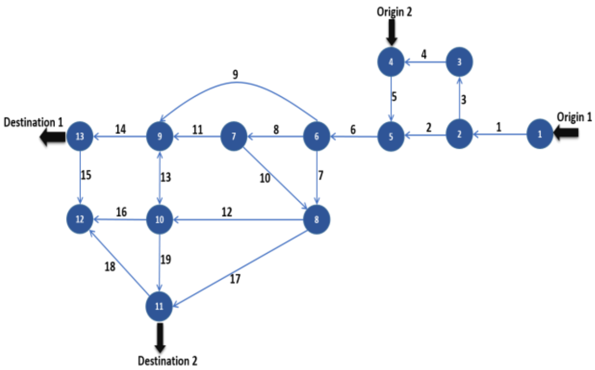

Fig.3 Test Network Topology

Table 1: Combination of paths and links.

O-D pair	Path number	Link sequence	O-D pair	Path number	Link sequence	O-D pair	Path number	Link sequence
(1,13)	1	1-3-4-5-6-9-14		16	1-2-6-7-12-16-15		31	5-6-7-12-13-14
	2	1-3-4-5-6-8-11-14		17	1-2-6-7-17-19-13-14		32	5-6-7-12-16-15
	3	1-3-4-5-6-7-12-13-14		18	1-2-6-7-17-19-16-15		33	5-6-7-17-19-13-14
	4	1-3-4-5-6-7-12-16-15		19	1-2-6-7-17-18-15		34	5-6-7-17-19-16-15
	5	1-3-4-5-6-17-19-13-14		20	1-2-6-8-10-12-13-14		35	5-6-7-17-18-15
	6	1-3-4-5-6-7-17-19-16-15		21	1-2-6-8-10-12-16-15		36	5-6-8-10-12-13-14
	7	1-3-4-5-6-7-17-18-15		22	1-2-6-8-10-17-19-13-14		37	5-6-8-10-12-16-15
	8	1-3-4-5-6-8-10-12-13-14		23	1-2-6-8-10-17-19-16-15		38	5-6-8-10-17-19-13-14
	9	1-3-4-5-6-8-10-12-16-15		24	1-2-6-8-10-17-18-15		39	5-6-8-10-17-19-16-15
	10	1-3-4-5-6-8-10-17-19-16-15	**(1,11)**	25	1-3-4-5-6-7-17		40	5-6-8-10-17-18-15
	11	1-3-4-5-6-8-10-17-19-16-15		26	1-3-4-5-6-8-10-17	**(4,11)**	41	5-6-7-17
	12	1-3-4-5-6-8-10-17-18-15		27	1-2-6-7-17		42	5-6-8-10-17
	13	1-2-6-9-14		28	1-2-6-8-10-17		43	5-6-8-11-13-19
	14	1-2-6-8-11-14	**(4,13)**	29	5-6-9-14		44	5-6-7-12-19
	15	1-2-6-7-12-13-14		30	5-6-8-11-14		45	5-6-8-10-12-19
							46	5-6-9-13-19

Table 2: Nitrogen Oxides Total Emissions

link number	tt (hr)	speed (km/h)	EF(g/km)-d	EF(g/km)-g	flow pcu/day	gasoline veh.(40%)	diesel veh. (60%)	emission (diesel)	emission (gasoline)	total emisionns (g)
1	0.20	81.01	0.02	0.00	50000.0	20000.0	30000.0	0.0	0.0	0.0
2	0.11	34.76	0.03	0.04	25639.6	10255.8	15383.7	1736.3	1460.3	3196.6
3	0.02	81.80	0.02	0.00	24360.4	9744.2	14616.3	556.4	0.0	556.4
4	0.02	71.65	0.02	0.00	24360.4	9744.2	14616.3	456.7	0.0	456.7
5	0.12	21.34	0.04	0.06	74360.4	29744.2	44616.3	4525.3	4431.1	8956.4
6	0.18	8.88	0.05	0.08	100000.0	40000.0	60000.0	4843.1	5000.6	9843.7
7	0.12	39.29	0.03	0.03	40433.8	16173.5	24260.3	2997.3	2300.7	5298.0
8	0.09	17.83	0.04	0.06	48564.5	19425.8	29138.7	2080.7	2080.3	4161.0
9	0.08	95.21	0.03	0.00	11001.7	4400.7	6601.0	1450.5	0.0	1450.5
10	0.08	23.53	0.04	0.05	38337.5	15335.0	23002.5	1550.4	1493.9	3044.4
11	0.06	46.29	0.02	0.02	10227.1	4090.8	6136.2	389.1	242.6	631.7
12	0.06	66.34	0.02	0.00	31268.5	12507.4	18761.1	1521.0	135.0	1656.0
13	0.09	46.84	0.02	0.02	23454.3	9381.7	14072.6	1391.7	850.0	2241.6
14	0.24	30.47	0.03	0.04	26871.0	10748.4	16122.6	3750.2	3364.5	7114.7
15	0.07	39.13	0.03	0.03	23129.0	9251.6	13877.4	1009.4	777.7	1787.1
16	0.10	38.43	0.03	0.03	16999.5	6799.8	10199.7	1086.3	850.3	1936.6
17	0.61	11.40	0.05	0.08	47502.8	19001.1	28501.7	9771.3	10022.6	19794.0
18	0.22	47.77	0.02	0.02	6129.4	2451.8	3677.7	913.6	537.7	1451.3
19	0.34	21.27	0.04	0.06	27011.8	10804.7	16207.1	4575.8	4482.7	9058.5
										82635.4

7. CONCLUSION AND FUTURE TASKS

In this study, we have proposed an air pollution model which estimates the nitrogen oxide emissions from a road network. The SUE traffic assignment model is used to estimate both the speed of vehicles and traffic flows. The emissions are then calculated by using these two variables.

The results obtained in this study are only for nitrogen oxides from a diesel and gasoline vehicles. Thus, this model should be formulated and calibrated for the other pollutants which contribute to the atmospheric pollution.

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