MODELING OF AIR POLLUTION EMITTED FROM AN URBAN ROAD NETWORK

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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. 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.

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.

Typical urban transportation 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.

Formulation of the model

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
- **δ_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
- **v'_a** 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

Traffic assignment model

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.

- **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 represents the deterministic traffic demand for O-D pair w, the path flows will be:

\[
\begin{align*}
 f_{w,k} &= p_{w,k} \cdot q_w \quad (1a) \\
 \sum_{k \in K_w} f_{w,k} &= q_w \quad (1b) \\
 f_{w,k} &\geq 0 \quad (1c)
\end{align*}
\]

The link flow can then be calculated as follows:

\[
 v_a = \sum_{w_k \in K_w} f_{w,k} \cdot \delta_{w,k,a} \quad (2)
\]

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):

\[
 t_a(v_a, c_a) = t_a^0 \left( 1 + \alpha_a \left( \frac{v_a}{c_a} \right)^\beta_a \right) \quad (3)
\]

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

Equation (14) and (15) represent the emissions factors for
\[ t_{w,k} = \sum_{a \in A} \delta_{w,k,a} \cdot t_a \]  
\[ c_{w,k} = c_{w,k} \]  

- 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.

\[ f_w = g_w \cdot p_w \cdot c_w(f) \]  

where:

\[ p_{w,k} = \frac{\exp(\theta \cdot c_{w,k})}{\sum_{k \in K_w} \exp(\theta \cdot c_{w,k})} \]  

\[ f_w = \left[ f_{w,1}, \ldots, f_{w,|K_w|} \right]^T \]  

\[ f = \left[ f_1, \ldots, f_W \right]^T \]  

\[ p_w = \left[ p_{w,1}, \ldots, p_{w,|K_w|} \right]^T \]  

\[ c_w = \left[ c_{w,1}, \ldots, c_{w,|K_w|} \right]^T \]  

The superscript \( T \) denotes the transposition operator of a vector.

### 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. 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:

\[ E_a = E_{F_a} \cdot v_a \]  

where \( v_a \) is the traffic flow on link \( a \) and \( E_{F_a} \) is the emission factor of the nitrogen oxides (g/pcu/km) where pcu represents passenger car unit.

Since \( E_{F_a} \) is a function of a speed, \( l_a(t_a(v_a)) \) (km/hr), \( E_{F_a} \) can be written as:

\[ E_{F_a} = E_{F_a}(l_a(t_a(v_a))) \]  

### 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.1) is used in the experiment. Two link calibration parameters \( \alpha_a \) and \( \beta_a \) used for the BPR function shown by equation (3) are set as 0.15 and 2, respectively. 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:

\[ E_{F_a} = 10^{-5} \cdot s_a^2 - 0.0021 \cdot s_a + 0.0998 \]  

\[ E_{F_a} = 10^{-5} \cdot s_a^2 - 0.0013 \cdot s_a + 0.0625 \]  

\[ s_a = l_a(t_a(v_a)) \]  

### 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.
Table 1. Deterministic OD Demand Flow

<table>
<thead>
<tr>
<th>OD pair</th>
<th>Traffic Demand (pcu/day)</th>
<th>OD pair</th>
<th>Traffic Demand (pcu/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1,13)</td>
<td>25000</td>
<td>(4,13)</td>
<td>25000</td>
</tr>
<tr>
<td>(1,11)</td>
<td>25000</td>
<td>(4,11)</td>
<td>25000</td>
</tr>
</tbody>
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