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Notes and comments

Traffic assignment considering air quality

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ABSTRACT

This paper presents a methodology of assigning traffic in a network with the consideration of air quality. Traffic assignment is formulated as an optimization problem considering travel cost and on-road emissions. It introduces a cell-based approach to model emission concentrations so that either the average or maximum emissions in a network can be considered in the optimization process. The emissions in a cell are modeled taking into consideration the influence of the emission sources from all cells in the network. A case study demonstrates that minimizing travel cost and reducing air pollutants may not be always achieved simultaneously. The traffic assignment procedure can effectively reduce emission concentrations at those locations with the worst air quality conditions, with only a marginal increase in travel time and average emission concentration in the network.

1. Introduction

The US Environmental Protection Agency (EPA) (2009) identified many metropolitan nonattainment areas where the monitored pollutant concentrations exceeded the limits of the National Ambient Air Quality Standards (NAAQS). In these metropolitan areas, many vulnerable objects, such as schools and hospitals, have been subject to high emission levels generated by vehicle traffic for years and it is typically infeasible to improve the air quality by relocating these vulnerable objects or the roadways. Some recent studies have proposed to reduce emissions by regulating traffic (e.g., Nagurney, 2000; Yin and Lawphongpanich, 2006; Ahn and Rakha, 2008). These air quality based studies on traffic re-assignment only took into account emissions produced on a link by the traffic on the same link, but failed to consider link geometries, the superposition of emissions from multiple links, and emission concentrations in the locations that are some distances away from the roads. In reality, many vulnerable objects are not located on a roadway but often near an intersection, and they are under the combined influence of emissions from more than one roadway. By taking into account this combined influence of emissions, we model the emission concentration for any location in the study area. Traffic assignment considering air quality is then formulated as an optimization problem.

2. Model formulation

This paper proposes the concept of optimizing network traffic assignment by minimizing the combined cost of travel and emissions in the network. In order to consider both the travel cost and on-road emissions, the methodology proposed in this paper employs an additive objective function, as shown in the following equation:

$$\text{Min } \beta_1 * f(X) + \beta_2 * g(X) \tag{1}$$

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where $f(X)$ is the function of travel cost; $g(X)$ is the function of on-road emissions; and β_1, β_2 are weights for the travel cost and on-road emissions.

In Eq. (1), X is the path flow matrix in the network from a traffic assignment solution for a given O–D matrix. β_1 and β_2 put relative emphasis on the travel cost and on-road emissions. On-road emissions $g(X)$. can be either the maximum emissions in the network or the average emissions for the study area.

There are many different ways to estimate the travel cost when assigning traffic in a network. In this study, the travel time is used to evaluate the total travel cost $f(X)$. On each link, we can calculate the average travel time from dividing the link length by the average speed. Therefore,

$$f(X) = \sum_i TC_i = \sum_i \left[\frac{L_i}{ls_i(X)} * lv_i(X)\right] \tag{2}$$

where TC_i is the travel cost on the ith link; L_i is the length of the ith link; $lv_i(X)$ is the volume on the ith link; and $ls_i(X)$ is the speed on the ith link.

The on-road emissions in this study are calculated for the entire area, which is made of many equally-sized cells. Traffic density and speed on any link are considered to have an air quality impact on the entire study area, not only just on that link itself. In order to evaluate on-road emissions $g(X)$, the study area is divided into $I * J$ cells with a side length of d_C for each cell. Two performance indicators (PIs) representing the air quality of the network, the maximum emissions among all cells $g_1(X)$ and the average emissions among all cells $g_2(X)$, are developed as:

$$g_1(X) = \max_{i \in \{1,2,\ldots,I\}, j \in \{1,2,\ldots,J\}} Cell(i,j) \tag{3}$$

or

$$g_2(X) = \operatorname*{average}_{i \in \{1,2,\ldots,I\}, j \in \{1,2,\ldots,J\}} Cell(i,j) \tag{4}$$

where $Cell(i, j)$ is the emission concentration in cell (i, j), which is the sum of emission impacts from all the cells in the study area, calculated using:

$$Cell(i,j) = \sum_{m \in \{1,2,\ldots,I\}, n \in \{1,2,\ldots,J\}} E(i,j,m,n) \tag{5}$$

where $E(i, j, m, n)$ is the emission impact of the (source) cells (m, n) on the (target) cell (i, j).

The commonly used method to estimate this cell based emission impact is the Gaussian model (Lin and Ge, 2006). The original form of the Gaussian model is

$$E(x,y,z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right)\left(\exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right)\right) \tag{6}$$

where $E(x, y, z)$ is emission concentration at some point with the coordinate (x, y, z); Q is emission rate of the pollution source; u is average wind speed; σ_y is standard deviation in the y direction; σ_z is standard deviation in the z direction; and H is height of the emission source.

The heights of both the emission source and the location are assumed to be zero, i.e., $z = 0$, $H = 0$. σ_y and σ_z are calculated according to the atmospheric stability at class C, based on the wind speed (Ott, 1995; Weiner and Matthews, 2002). Only when the source cell (m, n) is in the upstream of target cell (i, j) along the direction of wind, can the emissions be transferred from cell (m, n) to cell (i, j); otherwise, there is no emission impact from cell (m, n) on cell (i, j). The ground level coordinates are derived from the locations of both the emission source cell (m, n) and target cell (i, j), e.g., $x = (m - i) * d_C$, $y = (n - j) * d_C$. The emission rate in the emission source cell (m, n) in terms of gram per second (g/s) is a function of the traffic condition, which can be derived from the link volume and speed, i.e., $Q = q(lv_i(X), ls_i(X))$.

Table 1
Relationship between speed and emission rate.

Speed (mph)	Emission rate produced by Mobile 6.2		Prediction	
	(g/veh/mile)	(g/veh/s)	(g/veh/s)	Relative difference
35	14.30	0.139028	0.139047	−0.00014
40	14.77	0.164111	0.164082	0.00018
45	15.23	0.190375	0.190401	−0.00014
50	15.70	0.218056	0.218005	0.00023
55	16.16	0.246889	0.246895	−0.00002
60	16.62	0.277000	0.277069	−0.00025
65	17.09	0.308569	0.308529	0.00013

Note: $\frac{\text{Relative difference} = \text{Prediction} - \text{Produced Value}}{\text{Produced Value}}$.