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**URBAN TRANSPORTATION NETWORK DESIGN,
TRAFFIC ALLOCATION, AND AIR
QUALITY CONTROL: AN INTEGRATED
OPTIMIZATION APPROACH[†]**

ABSTRACT: Air pollution and congestion externalities due to urban transportation are accounted for in an integrated nonlinear optimization model that selects road capacity expansion projects and allocates origin-destination traffic flows on network road links while minimizing a total cost function that includes (1) travel time costs, (2) roadway capacity expansion costs, and (3) car fuel consumption costs. In addition to traditional flow conservation and capacity constraints, the model includes emissions and ambient air quality (CO - carbon monoxide) constraints. The nonlinearities of the model are related to the relationships between (1) traffic speed and traffic flow, (2) fuel use and traffic speed, and (3) car pollution emission and traffic speed. The air quality constraints are based on a pollution transfer coefficient matrix, linking all road segments to all pollution receptors, and dependent upon local meteorology. The model is applied to a hypothetical, yet realistic urban configuration made of 24 residential areas generating commuting traffic flows toward the CBD. Actual meteorological data are used to compute the pollution transfer matrix. The model is solved using the GAMS system under (1) various intra-daily O-D flow conditions (peak vs. off-peak hours), (2) alternative hypotheses of differential urban growth, (3) various ambient CO standards, and (4) different wind speed conditions.

1. INTRODUCTION

Most major cities, and particularly their Central Business District (CBD) areas, suffer from traffic congestion, which results in both higher travel times and increased air pollution emissions and concentrations. Motor vehicles are the major sources of such pollutants as carbon monoxide, CO (66%), hydrocarbons, HC (48%), nitrogen oxides, NO_x (37%), and lead (37%) (Matzoros and Vliet, 1992a), and are likely to remain major pollution contributors in the future, despite increasing enforcement of new motor vehicles emissions standards (Beiruti and Al-Omishy, 1985), primarily because of the expected increase in the number of vehicles and vehicle-miles traveled (Gordon, 1991).

Meeting the National Ambient Air Quality Standards (NAAQS) set forth in the Amendments of the Clean Air Act of 1977 requires an integrated approach to both transportation planning and air quality planning. Until quite recently, however, long range transportation planning has been undertaken in an isolated manner, to a large extent separated from environmental concerns. For example, the primary focus of traffic assignment has been on minimizing average or total travel time throughout the transportation network, sometimes in combination with capacity expansion costs. Since there is a complex interaction between network link capacity, flow, speed and pollution emission, for any given car population with given emission control devices, it is clear that an integrated approach, which accounts for these interactions and for the trade-offs between environmental goals and traditional economic efficiency goals, is necessary. The purpose of this paper is to present an optimization model that accounts for these interactions and tradeoffs, and to illustrate its usefulness through numerical applications to a hypothetical, yet realistic urban area and transportation network.

The remainder of the paper is organized as follows. Section 2 offers a succinct literature review. Section 3 describes the structure of the model, its various components, and its solution procedure. Applications of the model are analyzed in Section 4. Conclusions and areas for further research are presented in Section 5.

2. LITERATURE REVIEW

The literature relevant to the present research can be organized into three streams of studies: (1) empirical analyses of pollution emitted by motor vehicles, (2) integrated approaches to transportation and air quality planning and management, and (3) optimization approaches to transportation network design and operations.

Several studies, using pollution concentration data for specific urban areas, have shown that CO concentrations display strong diurnal variations, with the highest concentrations generally at rush hours (Ott et al., 1967, for Washington, D.C.; Johnson et al., 1973, for San Jose, California; Dabberdt et al., 1973, for St. Louis, Missouri; Singh et al., 1990, for Delhi). Other studies have emphasized the “Hot Spot” spatial pattern of concentrations, with the highest values occurring in a restricted area around a concentrated source of vehicle emissions (Schewe, 1978; Rashidi and Massoudi, 1980; Zamurs and Piracci, 1982; Sculley, 1989).

Integrated approaches to transportation air pollution control include primarily simulation models, although some simplified optimization schemes have also been proposed. Early studies include Wendell et al. (1973), who developed, for the Chicago area, a combined vehicle emissions and transportation model, that distinguishes between hot and cold vehicle operations, between trucks and autos, and among model years, and Dabberdt et al. (1973), who developed an urban diffusion model for predicting concentrations of vehicle-generated pollutants, and applied it to St. Louis, Missouri, and San Jose, California. A significant finding was that the diffusion process must be considered both at the urban mesoscale and at the street microscale, for which Dabberdt et al. introduced a street canyon effect. Horie and Fan (1973a, 1973b) considered simple systems made of either one highway link or two parallel highway links, and developed simple optimization models to determine optimal traffic control policies and network designs, accounting for both quality of service (total link performance) and air pollution concentrations, which were derived from a steady-state mass conservation equation. They showed that meteorological conditions can greatly influence both pollution level and optimal traffic assignment, and that there may exist an optimal network providing simultaneous improvement in both traffic performance and air quality. A cost-effectiveness comparison of alternative reductions in pollutant emissions through the redesign of the transportation system was conducted by Smith et al. (1975), using 1970 New York City data. They considered four alternative measures: (1) bus service improvements, (2) rapid transit system improvement, (3) increased use of the subway system, and (4) enforcement of national emission standards. Guldmann and Shefer (1980) outlined a linear program allocating traffic flows over network links and expanding link capacity while minimizing total commuting and expansion costs subject to flow conservation, capacity, land availability, and emission constraints. This model has not been implemented, and does not account for pollution diffusion and the nonlinear interactions between flows, speeds, and emissions. Kim et al. (1981), using Chicago CBD data, developed a simulation model to assess the impacts of Transportation System Management (TSM) strategies, such as traffic flow controls, parking controls, and mass transit improvements, on air quality. They

concluded that TSM strategies may result in deteriorating air quality from an area-wide viewpoint, due to an increase in vehicle-miles traveled by newly attracted vehicles and/or speed decrease in neighboring streets caused by diverted vehicles. Immers and Oosterbaan (1991) developed and tested a model that modifies route choice in urban networks to meet both pollutant emission and noise standards. In so doing, they introduced the concept of environmental capacity for a network link, which is the maximum capacity consistent with a selected environmental emission standard. Finally, Matzoros (1990) and Matzoros and Vliet (1992a, 1992b) developed a model that incorporates traffic queuing, vehicle operation modes, and an empirically modified Gaussian diffusion model.

Network flow allocation and capacity expansion methodologies have long played an important role in transportation network planning. They can be classified as user and system equilibrium models, and are based on principles of traffic assignment first presented by Wardrop (1952). In a user-equilibrium assignment, all routes actually traveled between a given set of nodes are characterized by the same average travel time/cost, which must be less than the one on any unused route. Thus, the time/cost for each individual traveler must be the same on any of these routes. A system-equilibrium assignment is characterized by the minimization of the total travel time/cost in the whole network, and thus by the equality of the marginal time/cost on all the paths/routes used between any set of nodes. The user-equilibrium problem can also be formulated as an optimization problem, wherein the objective function is the sum, over all links, of the integrals of the average time/cost functions. The constraints are similar for both types of models: allocation of given O-D flows over several paths, link flow capacity, and capacity expansion. The objective function is generally nonlinear because it accounts for link congestion effects, and may include investment costs in addition to travel time costs. Leblanc and Abdulaal (1984) have compared the computational requirements and results of the two approaches, using a 1462-link, 584-node test network. They concluded that the difference between the quality of the solutions is negligible, and that, from an algorithmic viewpoint, the system-optimum model is easier to solve. There is a considerable diversity in model formulations and algorithmic procedures in the large number of related studies reported in the literature, and it is impossible to cite them all here. For a useful sample, the reader is referred to Steenbrink (1974a, 1974b), Leblanc (1975), Leblanc et al. (1975), Chan (1976), Dantzig et al. (1979), Leblanc and Abdulaal (1979), Boyce (1980), Gartner (1980), Friesz (1985), Suwansirikul et al. (1987), Lam (1989), and Chen and Alfa (1991).

3. MODEL DEVELOPMENT

3.1 Overview

Consider an urban area made of a set of R nodes (r,s) that generate and attract traffic. These nodes are characterized by exogenous O-D flows T^{rs} between any couple of nodes (r,s). The nodes are connected by a network of N links (i), all characterized by a maximum capacity, b_i^{\max} , and an existing capacity, b_i . Potential links are characterized by $b_i = 0$. The problem is to construct/expand network links and allocate the O-D flows to minimize the total cost of transportation network construction and operations while respecting several constraints. We extend here the standard system-optimal model discussed earlier by: (1) adding fuel costs to the standard travel time and capacity investment costs in the objective function, and (2) adding air pollution-related constraints to the standard flow allocation/conservation and capacity constraints.

Both link emission and ambient concentration constraints are introduced into the model. These constraints account for the nonlinear relationship between car/link emission and speed, and thus add to the nonlinearity of the standard model, primarily related to the travel time (i.e., congestion) cost function. Fuel costs are also nonlinear functions of speed, and thus of link flow and capacity expansion, and therefore further add to the nonlinearity of the objective function. In addition, the fuel consumption function takes two distinct functional forms, depending upon the speed range, requiring the introduction of 0-1 integer variables. The final form of the model is thus a mixed-integer nonlinear program, which is notoriously difficult to solve. A satisfactory approximation of the fuel cost function is proposed, that leads to a standard nonlinear program, much easier to solve. The model is designed to account for local features (i.e., meteorology and pollution diffusion), so that trade-offs between environmental goals (emission/concentration standards) and transportation economic efficiency goals can be fully investigated. In the following subsections, the major components of the model are described in detail, followed by a summary of the model and a discussion of the solution method.

3.2 Traffic Flow and Congestion

Numerous studies have shown that the relationship between travel speed and traffic volume satisfies the following conditions: (1) under free-flow (near zero traffic flow) conditions, travel time per unit distance is constant; (2) at low traffic flow, travel time increases slightly with flow; and (3) at congestion flow levels, travel time increases rapidly with flow. These conditions can be met by various functional forms (Smeed, 1968; Wardrop, 1968; U.S. Department of Transportation, 1986;

Davidson, 1966; Färe et al., 1982; Wilson, 1991). We select here the BPR (U.S. Bureau of Public Roads) curve, with:

$$T_i(x_i, z_i) = t_i \left[1 + 0.15 \left(\frac{x_i}{b_i + z_i} \right)^4 \right], \quad (1)$$

where $T_i(x_i, z_i)$ is the travel time over link i when the total flow is x_i and the capacity expansion is z_i , $b_i + z_i$ is the total capacity, and t_i is the free-flow travel time over link i . If L_i is link i length and S^{ax} the free-flow (maximum) speed for link i , then $t_i = L_i/S^{ax}$. The total travel time for all users on link i is then:

$$TT_i(x_i, z_i) = x_i T_i(x_i, z_i). \quad (2)$$

The value of in-vehicle travel time has been analyzed and estimated by Kraus et al. (1976), Keeler and Small (1977), Viton (1983), and Coulson and Engle (1987), among others. We assume an average time value of \$4.50 per vehicle-hour, based primarily on the first three studies.

3.3 Capacity Expansion

Using data in Keeler and Small (1975), Viton (1983) has estimated the cost of installing and maintaining highway capacity for limited-access freeways in the San Francisco Bay Area at \$45,934 per lane-mile (1972 dollars). Under the assumption of a real cost growth rate of 6% over 23 years, this cost is compounded to yield \$175,468 in 1995 dollars. We further assume that the construction and maintenance cost of arterial roads represents 80% of the expressway cost, i.e., \$140,374 in 1995 dollars. Expressways and arterial roads are the only links subject to capacity expansion (local roads are assumed non congested). We further assume that a capacity expansion of one lane provides for an additional flow of 1,000 veh/hr for expressways and 600 veh/hr for arterial roads. If A is the set of arterial road links, E the set of expressways links, the total cost of capacity expansion is

$$CI = \frac{1}{365.24} \left[\sum_{i \in E} \frac{175,468}{1000} L_i z_i + \sum_{i \in A} \frac{140,374}{600} L_i z_i \right], \quad (3)$$

where CI is expressed on an hourly basis, and z_i is measured in vehicles/hour.

3.4 Fuel Consumption

Evans and Herman (1978), Gartner et al. (1980), Herman and Ardekani (1985), and Fwa and Ang (1992) have shown that fuel consumption per car and unit distance, ϕ^1 , can be expressed as

$$\phi^1 = K_1 + K_2/S \quad (4)$$

for speeds not exceeding 35 mph. S is the average travel speed, K_1 a vehicle-dependent parameter (gallons/mile) associated with the fuel consumed to overcome rolling resistance and approximately proportional to the weight of the vehicle, and K_2 a vehicle-dependent parameter (gallons/hour) approximately proportional to the idle fuel flow rate. We use the estimates of K_1 and K_2 derived by Herman and Ardekani (1985) with data from Austin and Dallas, Texas, and Matamoros, Mexico, with: $K_1 = 0.0316$ and $K_2 = 0.0089$. The total fuel consumption FC_i^1 for link i of length L_i and flow x_i is then:

$$FC_i^1 = \phi^1 L_i x_i = 0.0316 L_i x_i + 0.0089 L_i x_i / S_i \quad (S_i \leq 35 \text{mph}) . \quad (5)$$

Kraus et al. (1976) have shown that fuel consumption increases with travel speed for $S > 35$ mph, more precisely that any increase of speed of 5 mph leads to a decrease in fuel economy of 0.0001 gallon/mile. The unit fuel consumption function can then be expressed as:

$$\phi^2 = K_3 + K_4 S \quad (6)$$

with $K_3 = 0.0311$ and $K_4 = 0.00002$. The total fuel consumption on link i is then:

$$FC_i^2 = \phi^2 L_i x_i = 0.0311 L_i x_i + 0.00002 L_i x_i S_i \quad (S_i > 35 \text{mph}) . \quad (7)$$

In order to integrate both functions into a unique functional form, we define, for each link i a new integer variable $y_i = (0,1)$, such that $y_i = 0$ for $S_i \leq 35$ mph and $y_i = 1$ for $S_i > 35$ mph. The final fuel consumption function is then

$$FC_i = (1 - y_i) FC_i^1 + y_i FC_i^2 . \quad (8)$$

The endogenous determination of the optimal values of the variables y_i is discussed in Section 3.7.

Note that, in the above equation, the speed variable S_i is itself a function of the primary variables x_i and z_i , with: $S_i = S_i^{\max} / [1 + 0.15 \{x_i / (b_i + z_i)\}^4]$.

3.5 Pollution Emissions

CO emissions are functions of travel speed, other driving conditions such as accelerations, decelerations, and idles, outside temperature, and, of course, the car make, age, and condition. Dabberdt et al. (1973) used historical data on average daily traffic volumes for major road segments, and derived an empirical equation of the form $E = aS^{-b}$, where E is the emission rate (g-CO/vehicle-mile), S the mean speed (miles/hour), and “a” and “b” constants that depend on the characteristics of the emission control devices installed and the mixture of old and new cars on the road: for post-1965 cars, “a” and “b” were estimated at 245 and 0.48, and, for older cars, at 1120 and 0.85. Horowitz and Pernela (1974, 1976) did expand this model to account for hot-running, cold-start, and hot-soak evaporative emissions modes, as well as for the age distribution of the automobile population. Gartner et al. (1980) estimated a relationship of the form $E = K_1 + K_2/S$ for CO, with $K_1 = 9.96$ g/mile and $K_2 = 476.1$ g/hr.

In this study, we develop new CO emission functions, using emission factors for 1990 and at high altitudes, as available in U.S. EPA (1991a, 1991b) and presented in Table 1. For each temperature, we have estimated, through regression analysis, a log-linear function of the form $\ln E = a(T) + b(T) \ln S$ where E is measured in g/vehicle-mile. The results are presented in Table 2. The values of $a(T)$ and $b(T)$ decrease with T up to 75°F, and then increase up to 100°F. The relationship between a/b and T has been estimated through regression over the interval {0°F-75°F} and through simple interpolation over the interval {75°F-100°F}, with

$$\underline{T \leq 75^\circ\text{F}}$$

$$a(T) = 6.979 - 0.014T \quad R^2 = 0.99 \quad (9)$$

(1397.11) (-129.17)

$$b(T) = -0.869 + 0.00026T \quad R^2 = 0.99 \quad (10)$$

(-1945.67) (26.72)

$$\underline{T > 75^\circ\text{F}}$$

$$a(T) = 4.270 + 0.022T \quad (11)$$

$$b(T) = -0.804 - 0.0006T \quad (12)$$

The final non-linear emission factor models are:

$$\underline{T \leq 75^\circ\text{F}}$$

$$E(S,T) = 1074.2 e^{-0.014T} S^{-0.87+0.00026T}, \quad (13)$$

$$\underline{T > 75^\circ\text{F}}$$

$$E(S,T) = 71.53 e^{0.022T} S^{-0.804-0.0006T}. \quad (14)$$

3.6 Pollution Diffusion

Once vehicle emissions are estimated, their diffusion into the atmosphere can be analyzed with diffusion models, which provide pollution concentration estimates at various receptor points. The most common is the Gaussian line source model, which has been used by Stukel et al. (1975), Robson (1976), Chock (1978), Benson (1982), Horowitz (1982), Luhar and Patil (1989), Singh et al. (1990), and Feng (1992), among others. This model computes concentration as a function of local meteorology and traffic flows. It is adapted from the point-source Gaussian model, which assumes that the emission from a point source spreads into the atmosphere as a plume whose concentration profile is Gaussian in both the horizontal and vertical directions, and whose orientation is determined by the wind direction. Then, the concentration at a receptor point is calculated as the sum of the contributions from a series of point sources representing the road (Beiruti and Al-Omishy, 1985), under the assumption that the individual diffusion plumes are independent of each other. The validity of this additive assumption becomes questionable when the line source has an accompanying self-generated turbulence caused by traffic flows and the wind angle relative to the road is small (Chock, 1978).

Consider a ground-level point source set as the center of a three dimensional cartesian coordinate system (Ox,Oy,Oz), where the horizontal axis Ox is set in the wind direction, the horizontal axis Oy corresponds to the cross-wind direction, and Oz is the vertical axis. The concentration $C(\text{g}/\text{m}^3)$ at ground-level receptor point (x,y) is given by

$$C(x,y) = \frac{Q}{\pi u \sigma_y(x) \sigma_z(x)} \exp\left[-\frac{y^2}{2\sigma_y^2(x)}\right], \quad (15)$$

where Q is the pollution emission rate (g/sec), u the wind speed (m/sec), and σ_y and σ_z the standard

deviations of the concentration distribution in the horizontal and vertical crosswind directions at distance x (m) from the source. Diffusion in the x -axis direction, besides plume movement, is assumed negligible. The diffusion coefficients σ_y and σ_z are approximated as polynomial functions of x , of the form $ax^b + c$, where the coefficients a , b , c depend on the stability of the atmosphere. Six stability classes (A-F) are commonly considered, ranging from most unstable (A) to most stable (F). Stable conditions reduce pollution dispersion, and thus lead to higher pollution concentrations. In the following, we use Tadmor and Gur's (1969) equation for σ_y , and Martin and Tikvart's (1968) equation for σ_z .

Consider now a finite line source of length y_L , perpendicular to the x -axis, centered at O , and with an emission rate Q_L . The concentration C at a receptor at distance x downwind on the x -axis is computed as the sum of the concentration contributions from all the infinitesimally small segments that make up the line source, with:

$$C(x) = \frac{Q_L}{u\pi\sigma_y\sigma_z} \int_{-y_L/2}^{y_L/2} \exp\left(\frac{-y^2}{2\sigma_y^2}\right) dy . \quad (16)$$

Using the error function

$$\operatorname{erf}\left(\frac{y_L/2}{\sqrt{2}\sigma_y}\right) = \frac{2}{\sqrt{\pi}} \int_0^{\frac{y_L/2}{\sqrt{2}\sigma_y}} \exp(-t^2) dt , \quad (17)$$

we obtain:

$$C(x) = \frac{Q_L}{u} \sqrt{\frac{2}{\pi}} \frac{1}{\sigma_z(x)} \operatorname{erf}\left(\frac{y_L/2}{\sqrt{2}\sigma_z}\right) . \quad (18)$$

The error function $\operatorname{erf}(x)$ is virtually equal to 1 for $x \geq 2$. If $y_L \geq 5.66 \sigma_y(x)$, then

$$C(x) = \frac{Q_L}{u} \sqrt{\frac{2}{\pi}} \frac{1}{\sigma_z(x)} . \quad (19)$$

The smaller x , the smaller σ_z , and thus the more likely the above assumption is verified. In the

application of the model, we select receptors located close to the transportation links (20m). With links of length 7 miles, the assumption is always verified.

When the wind direction is not perpendicular to the line source, i.e., when it makes an angle $\theta \neq 0$ with the x-axis, we use the approximation proposed by Calder (1973) for $\theta \leq 75^\circ$:

$$C(x, \theta) = \frac{Q_L}{u} \sqrt{\frac{2}{\pi}} \frac{I}{\cos \theta \sigma_z(x / \cos \theta)} \quad (20)$$

The application of the above model is illustrated in Table 3 for various downwind distances, stability classes, and wind directions, with Q_L/u assumed equal to 1.

3.7 Model Summary

The model minimizes the sum of the travel time (TT), capacity expansion (CI), and fuel consumption (FC) costs, subject to traffic flow conservation, capacity expansion, emission standard, ambient air quality standard, and logical constraints. The decision variables included in the objective function make up the following vectors:

$\mathbf{X} = \{x_i\}$: traffic flows on links,

$\mathbf{Z} = \{z_i\}$: capacity expansions of links,

$\mathbf{Y} = \{y_i\}$: 0-1 variables characterizing speed intervals ($S_i \leq 35$ mph).

The objective function is then:

$$\text{Minimize } TC(\mathbf{X}, \mathbf{Z}, \mathbf{Y}) = \lambda_1 TT(\mathbf{X}, \mathbf{Z}) + I(\mathbf{Z}) + \lambda_2 FC(\mathbf{X}, \mathbf{Z}, \mathbf{Y}) \quad (21)$$

with

$$TT(\mathbf{X}, \mathbf{Z}) = \sum_i \frac{L_i}{S_i^{\max}} x_i \left[1 + 0.15 \left(\frac{x_i}{b_i + z_i} \right)^4 \right] \quad (22)$$

$$CI(\mathbf{Z}) = \sum_{i \in E} 0.020 L_i z_i + \sum_{i \in A} 0.027 L_i z_i, \quad (23)$$

$$FC(\mathbf{X}, \mathbf{Z}; \mathbf{Y}) = \sum_i (1-y_i) \left(0.0316L_i x_i + 0.089 \frac{L_i}{S_i^{\max}} x_i \left[1 + 0.15 \left(\frac{x_i}{b_i + z_i} \right)^4 \right] \right) \quad (24)$$

$$\sum_i y_i \left(0.0311L_i x_i + 0.00002L_i S_i^{\max} \left[1 + 0.15 \left(\frac{x_i}{b_i + z_i} \right)^4 \right]^{-1} \right)$$

$\lambda_1 = \$4.50/\text{hr}$ and $\lambda_2 = \$1.06/\text{gallon}$.

We define the following path flow variable in order to formulate the flow conservation constraints: x^{rs} = traffic flow along path j between origin r and destination s . Let a_{ij} be a parameter equal to 1 if link i belongs to path (j,r,s) , and to 0 if not. We obtain

$$\sum_j x_j^{rs} = T^{rs} \quad : \quad \begin{array}{l} \text{the sum of all flows between } r \text{ and } s \text{ must} \\ \text{be equal to the exogenous O-D flow } T^{rs}, \end{array} \quad (25)$$

$$x_i = \sum_{r,s} \sum_j (a_{ij}^{rs} x_j^{rs}) \quad : \quad \begin{array}{l} \text{the flow on link } i \text{ is equal to the sum of} \\ \text{all the flows on paths using link } i. \end{array} \quad (26)$$

Capacity constraints are as follows:

$$x_i \leq 2(b_i + z_i) \quad : \quad \begin{array}{l} \text{the maximum congestion on any link is} \\ \text{set at twice its capacity,} \end{array} \quad (27)$$

$$b_i + z_i \leq b_i^{\max} \quad : \quad \begin{array}{l} \text{the expansion of link } i \text{ is limited by its} \\ \text{maximum feasible capacity } b_i^{\max}, \text{ which is} \\ \text{assumed related to physical, technical, and} \\ \text{environmental factors.} \end{array} \quad (28)$$

Emission standards may be used to limit the total pollution emission from any link, without diffusion considerations. Let E be that standard for link i . The constraint is then written as:

$$E_i(S_i, T) L_i x_i \leq E_i^*. \quad (29)$$

Refer to Eqs. (13) and (14) for the complete formulation of $E_i(S_i, T)$.

The emission rate per unit distance of link i with traffic flow x_i is given by:

$$Q_{Li} = 1.7264 \cdot 10^{-7} E_i(S_i, T) x_i. \quad (30)$$

If A_{ij} is the diffusion transfer coefficient from link i to receptor j , and C the ambient air quality standard, the resulting constraint for receptor j is:

$$\sum_i A_{ij} Q_{Li} \leq C_j^* \quad (31)$$

Finally, it is necessary to specify constraints that will force the correct determination of the 0-1 variables y_i as functions of the speed S_i . If M is set as a very large number, the following constraints are used:

$$S_i - 35 + (1 - y_i)M \geq 0 \quad (32)$$

$$35 - S_i + y_i M \geq 0. \quad (33)$$

3.8 Solution Method

The model is a mixed-integer nonlinear program (MINLP). The integer variables are related to the dichotomic nature of the fuel consumption function, and the nonlinearities characterize both the objective function (travel time and fuel consumption) and the constraints (emission and ambient standards). The procedural modeling language GAMS (General Algebraic Modeling System) is used to solve the model.

While a GAMS procedure (RMINLP) providing good approximations of the MINLP problem was available, we opted to convert the MINLP into a standard nonlinear program (NLP), with continuous variables only. To do so, we have approximated the dichotomous fuel consumption function with a continuous function of speed (S), by generating several points (FC, S) and using

regression analysis for curve fitting. We have considered polynomial functions of S and $\ln S$ up to the third degree. The estimated functions are presented in the Appendix. In order to select the final functional form, we have solved the model under each of the three approximations, as well as with RMINLP. The second-order functional approximation

$$FC = a_1 S + a_2 S^2 + b_1 \ln S + b_2 (\ln S)^2 \quad (34)$$

provides the total cost TC closest to the value generated by RMINLP, with a deviation of 0.2%. It is therefore selected. With this change, both the objective function and the constraint set are convex, and therefore a local optimum is also the global optimum. The convexity features of the objective function and constraints are discussed in detail in Kim (1995). The solution algorithm for NLP in GAMS/MINOS 5 Solver is summarized in Brooke et al. (1988, 1992).

4. MODEL APPLICATIONS

4.1 Data Input and Basic Assumptions

We consider a hypothetical network with 25 nodes and 40 links, as presented in Figure 1. Each link has a length of 7 miles. Each node is a circular residential area with a 2-mile radius, and a homogeneous density. Node 13, at the center, represents the CBD. The residential nodes can be grouped into two square-shaped rings: Ring 1, the inner ring, made of nodes 7-9, 12, 14, and 17-19, and Ring 2, the outer ring, made of nodes 1-6, 10, 11, 15, 16, and 20-25. Following Viton's (1983) model city, a set of local roads is assumed laid out radially in each residential area and is exogenous to the model. Residential areas and the CBD are connected by arterial roads and expressways that run through their centers. Two expressways are considered: (1) the East-West Expressway, composed of Links #9 through #12, and (2) the North-South Expressway, composed of Links #23, #28, #33, and #38. The other links represent arterial roads. We assume that congestion and air pollution primarily arise on arterial roads and expressways, and capacity expansion is considered only for these links.

We assume that there are 1,200 trip-makers per square-mile, and that there are 3 people in each household. Each residential area then has 15,072 trip-makers, with a total population of 45,216. The total numbers of trip-makers and residents in the city are 361,728 and 1,085,184, respectively.

We restrict the available paths between any residential node and the CBD to the shortest

paths. Because of the symmetry of the network, these paths need to be described for only a subset of nodes (1, 2, 3, 7, 8) in the North-West quadrant:

Node 1. 6 paths, of length 28 miles, with: $P_1 = (1,2,23,28)$, $P_2 = (1,22,6,28)$, $P_3 = (1,22,27,10)$, $P_4 = (21, 26,9,10)$, $P_5 = (21,5,6,28)$, $P_6 = (21,5,27,10)$.

Node 2. 3 paths, of length 21 miles, with: $P_1 = (2,23,28)$, $P_2 = (22,6,28)$, $P_3 = (22,27,10)$.

Node 3. 1 path, of length 14 miles, with: $P_1 = (23,28)$.

Node 7. 2 paths, of length 14 miles, with: $P_1 = (6,28)$, $P_2 = (27,10)$.

Node 8. 1 path, of length 7 miles, with: $P_1 = (28)$.

The links that make up the expressways have each a capacity of 4800 vehicles/hour, with a maximum speed of 55 mph, and thus a free-flow time of 0.127 hour. The links that make up the outerbelt have a capacity of 4000 veh/hr, a maximum speed of 45 mph, and a free-flow time of 0.156 hour. The links that make up the inner ring (i.e., 6, 7, 29, 34, 15, 14, 32, 27) have a capacity of 3500 veh/hr, a maximum speed of 40 mph, and a free flow time of 0.175 hour. Finally, the links connecting the two belts (i.e., 5, 22, 8, 24, 16, 39, 14, 37) have a capacity of 3000 veh/hr, a maximum speed of 34 mph, and a free-flow time of 0.200 hour. We assume that the maximal link capacity is equal to twice the existing capacity (e.g., for expressways, $2 \times 4800 = 9600$ veh/hr).

We assume that, on a typical day, traffic from the residential areas to the CBD (and vice versa) includes: (1) a morning peak flow (8:00-9:00 a.m.) and an afternoon peak flow (5:00-6:00 p.m.), (2) a morning near-peak flow (7:00-8:00 and 9:00-10:00 a.m.) and an afternoon near-peak flow (4:00-5:00 and 6:00-7:00 P.M.), and (3) the off-peak flows. Table 4 presents the assumed distribution of traffic flows over a 24-hour period.

In order to deal with hourly CO emissions and concentrations, hourly values for wind speed and direction, atmospheric stability, and ambient temperature must be used. We draw on the meteorological data for Urbana-Champaign, Illinois, during the periods of August 1-2 and October 3-4, 1973, as presented in Stukel et al. (1975), to generate typical summer meteorological conditions data, as presented in Table 5.

Sixteen receptors (R1-R16) are considered, as shown in Figure 1. Each receptor is located close to an intersection, at 20 meters from each line source. The transfer coefficients computation under an infinite line source assumption has been discussed in Section 3.6. As the time frame of the model is the hour, we use the U.S. one-hour average ambient concentration standard for CO: 40 mg/m^3 . In all the following applications, we discard the emission standard constraints (Eq. 29).

4.2 Benchmark Analysis: Impact of Hourly Variations in Traffic Demand and Meteorological Conditions on a Typical Summer Day

The model has been solved separately for each hourly condition of the typical summer day. As expected, the total cost (TC), travel time (TT), capacity investment (CI), and fuel consumption (FC) costs are highest at the peak-hour. Overall, the various costs display substantial variations, closely related to the magnitude of the O-D demands, as illustrated in Figure 2. Consider the following three travel patterns: morning peak (8:00-9:00 a.m.), afternoon peak (5:00-6:00 p.m.), and off-peak (3:00-4:00 a.m.). The two peak-hour costs are \$187,620 and \$198,100, respectively, while the off-peak hour cost is only \$779. As shown in Figure 2, link capacity expansions are necessary only accommodate the peak-hour traffic flows (i.e., 7:00-10:00 a.m. and 4:00-7:00 p.m.). There are 8 links selected for expansion, with a maximum expansion required at each of the two peak hours, as shown in Table 6. These links make up the North-South and East-West Expressways.

The optimal hourly link flows are presented in Figure 3. The largest flows take place at the peak hours and over the links selected for expansion. As a result, the heaviest CO concentrations occur at these hours around the CBD, in particular at receptors 7, 6 and 11, as illustrated in Figure 4. The highest CO concentration--11.5 mg/m³--is reached at receptor 7 in the afternoon peak hour (5:00-6:00 p.m.). Note, however, that this concentration is well below the standard (40 mg/m³). Thus, the air quality standard constraint of the model is never binding in this application.

4.3 Impact of Spatially-Differentiated Population Growth

In order to analyze the impacts of major changes in O-D traffic demands, we consider the following population growth situations:

Hypothesis 1: The population of Ring 2 increases by 10% (Scenario 1), 20% (Scenario 2), and 30% (Scenario 3), while the population of Ring 1 remains the same.

Hypothesis 2: The population of Ring 1 increases by 20% (Scenario 1), 40% (Scenario 2) and 60% (Scenario 3), while the population of Ring 2 remains the same.

For each scenario, the total population and number of trips are the same under both hypotheses. The O-D traffic demands under each case are presented in Table 7.

The model has been solved for each hypothesis/scenario combination under the 8:00-9:00 a.m. peak-hour conditions of the typical summer day. The resulting costs and pollution concentrations are presented in Table 8. Travel time and fuel consumption costs are clearly lower under Hypothesis 2 (population growth concentrated around the CBD). The capacities of all the

Expressway links are expanded to their maximum in all cases. However, additional links are expanded under Scenario 3 of Hypothesis 1 to accommodate the increased traffic from the outer ring. While the resulting CO concentrations are still well below the standard (40 mg/m^3) in all cases, they are slightly higher overall under Hypothesis 1 (suburban population growth), simply because of larger link emissions due to longer travel distances.

4.4 Impact of Changes in the CO Concentration Standard

In the benchmark analysis, the highest CO concentration takes place at receptor 7 at 5:00-6:00 p.m., and is below 12 mg/m^3 , with a standard of 40 mg/m^3 . In order to assess the effects of changes in the standard, we consider the following scenarios: (1) standard = 10 mg/m^3 , (2) standard = 9 mg/m^3 , and (3) standard = 8.5 mg/m^3 . The model is applied under the afternoon peak-hour conditions, with benchmark O-D traffic demands. The results are presented in Table 9 and are discussed below.

The total cost slightly increases from \$198,100 to \$199,420 (0.7%) for Scenario 1, to \$202,110 (2.0%) for Scenario 2, and to \$204,227 (3.1%) for Scenario 3. In the case of Scenario 1, the incremental shift of the total cost is due to changes in total travel time and fuel consumption. However, in the case of Scenarios 2 and 3, the change in total cost is also affected by capacity expansion. The tightening of the air quality constraint leads to increases in travel time and fuel consumption due to other route choices, as well as to additional capacity expansion (links 15, 19, 26, and 27, in addition to the links making up the Expressways, which are maximally expanded in all cases) in order to reduce congestion. In order to allocate excessive CO concentrations elsewhere (e.g., from receptor 7 to receptors 6 and 11), traffic flows along links 11, 12, 23, and 28 do decrease, and flows along links 9, 10, 33, and 38 do increase. The CO standard at receptor 7 around the CBD is binding under Scenarios 1 through 3. CO concentrations at receptors 6 and 11 increase from 6.3 mg/m^3 to 7.3 mg/m^3 (Scenario 1), 8.2 mg/m^3 (Scenario 2), and 8.5 mg/m^3 (Scenario 3). If the CO standard is reduced below 8.0 mg/m^3 while keeping all the other constraints unchanged, there is no feasible solution.

4.5 Impacts of Changes in Wind Speed

In order to assess the sensitivity of the model output to changes in wind speed, we modify the benchmark wind speeds of the morning and afternoon peak hours (8:00-9:00 a.m. and 5:00-6:00 p.m.). Four speed scenarios are considered (9, 7, 5, 3 m/sec). The model has no solution with

speeds of 1 m/sec (anytime) and 3 m/sec (afternoon only), i.e., the CO standard of 40 mg/m³ cannot be achieved under such wind conditions. The concentrations at all the receptors in all the other cases are presented in Table 10. Concentrations increase more strongly with decreasing speed in the afternoon because of the stable atmospheric conditions (stability class D), whereas the unstable conditions in the morning (stability class C) mitigate the effects of the decreasing speed. Clearly, these results underscore the sensitivity of the optimal transportation system to meteorological conditions.

5. CONCLUSIONS

We have presented an optimization model dealing with transportation network design, traffic assignment, and pollution emissions, diffusion, and concentrations. The model is a nonlinear program that minimizes the sum of travel time, capacity investment, and fuel consumption costs, while accounting for origin-destination traffic flow, capacity, emission, and concentration constraints, and the complex interactions between traffic flows, capacity of links, travel speeds, and pollution emissions. The model has been applied to a hypothetical, yet realistic urban transportation system, and the results of these applications underscore the importance of the intra-daily variations in traffic demand and meteorological conditions, of the impact of various urban growth strategies, and of the sensitivity of the optimal network to environmental constraints (e.g., ambient air quality standards) and meteorological variables (e.g., wind speed). The model thus demonstrates the importance of air quality considerations in designing and managing an urban transportation system. It could be extended to account for (1) modal split and the impact of improved transit systems, (2) the impact of land use changes on traffic generation/attraction, and possibly the optimal allocation of new activities in urban areas, and (3) other ambient air quality standards (e.g., 8-hour average CO concentrations). Research is underway in these areas and will be reported in the near future.

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APPENDIX

Estimations of the Fuel Consumption Function

Model	FC Function	[R ²]	GAMS SOLVER
MINLP	FC = (1-Y)FC1 + YFC2		MINOS 5 (RMINLPP)
NLP 1	$FC = aS + b\ln S$ $= -0.000614S + 0.015803\ln S$ <p style="text-align: center;">(-5.12)¹ (12.18)</p>	[0.965]	MINOS 5 (NLP)
NLP 2	$FC = a_1S + a_2S^2 + b_1\ln S + b_2(\ln S)^2$ $= 0.004367S + 0.038021\ln S$ <p style="text-align: center;">(7.95) (28.54)</p> $- 0.000024S^2 - 0.017919(\ln S)^2$ <p style="text-align: center;">(-5.99) (-12.83)</p>	[0.997]	MINOS 5 (NLP)
NLP 3	$FC = a_1S + a_2S^2 + a_3S^3$ $+ b_1\ln S + b_2(\ln S)^2 + b_3(\ln S)^3$ $= -0.038567S + 0.197850\ln S$ <p style="text-align: center;">(-2.67) (4.02)</p> $+ 0.000223S^2 - 0.096227(\ln S)^2$ <p style="text-align: center;">(2.16) (-4.50)</p> $- 0.000000861S^3 + 0.036904(\ln S)^3$ <p style="text-align: center;">(-1.78) (3.35)</p>	[0.999]	MINOS 5 (NLP)

¹t-values are given in brackets below each estimated parameter.

Table 1. U.S. EPA Emission Factor (g/vehicle-mile)

Speed (mph)	Temperature				
	0°F	25°F	50°F	75°F	100°F
2.5	496.87	349.88	250.67	179.81	310.38
5.0	266.09	188.21	135.53	97.84	167.41
10.0	141.49	100.52	72.58	52.42	88.43
19.6	81.76	58.24	42.07	30.28	50.38
35.0	47.86	34.18	24.81	18.01	29.81
55.0	34.31	24.63	18.06	13.36	22.09

Source: U.S. EPA (1991a, 1991b).

Table 2. Vehicle Emission - Speed Model

Temperature	Model	R ²
0°F	lnE = 6.984 - 0.869lnS (232) ¹ (-80)	0.99
25°F	lnE = 6.628 - 0.863lnS (217) (-78)	0.99
50°F	lnE = 6.288 - 0.857lnS (191) (-72)	0.99
75°F	lnE = 5.947 - 0.850lnS (153) (-61)	0.99
100°F	lnE = 6.507 - 0.865lnS (156) (-57)	0.99

¹ t-values are given in brackets below each parameter.

Table 3. Transfer Coefficients for Various Wind Directions, Stability Classes,
and Downwind Distances

Downwind Distance x(m)	Stability Class	0°	30°	45°	60°	70°	75°
5	C	1.596	1.629	1.661	1.717	1.780	1.827
	D	2.418	2.495	2.371	2.664	2.787	2.881
	E	3.069	3.184	2.845	3.418	3.590	3.721
10	C	0.858	0.870	0.887	0.917	0.950	0.976
	D	1.330	1.355	1.388	1.446	1.513	1.564
	E	1.698	1.741	1.787	1.869	1.963	2.034
20	C	0.456	0.465	0.474	0.490	0.508	0.521
	D	0.719	0.736	0.754	0.785	0.822	0.849
	E	0.928	0.952	0.977	1.022	1.073	1.112
50	C	0.199	0.203	0.207	0.214	0.221	0.226
	D	0.322	0.328	0.336	0.350	0.358	0.369
	E	0.420	0.429	0.440	0.460	0.478	0.500
100	C	0.106	0.108	0.110	0.113	0.117	0.120
	D	0.175	0.176	0.178	0.185	0.196	0.206
	E	0.229	0.232	0.238	0.251	0.272	0.290
150	C	0.073	0.075	0.076	0.078	0.081	0.083
	D	0.119	0.121	0.124	0.131	0.141	0.150
	E	0.159	0.163	0.170	0.182	0.199	0.214
200	C	0.056	0.057	0.059	0.060	0.062	0.064
	D	0.092	0.094	0.098	0.104	0.112	0.120
	E	0.125	0.129	0.135	0.146	0.161	0.173
500	C	0.025	0.025	0.025	0.026	0.027	0.028
	D	0.043	0.045	0.047	0.051	0.057	0.062
	E	0.061	0.064	0.068	0.074	0.083	0.092
1000	C	0.013	0.013	0.014	0.014	0.014	0.015
	D	0.025	0.026	0.028	0.032	0.036	0.040
	E	0.037	0.039	0.041	0.047	0.055	0.062
2000	C	0.007	0.007	0.007	0.007	0.008	0.008
	D	0.016	0.017	0.018	0.021	0.024	0.027
	E	0.023	0.025	0.027	0.032	0.038	0.045

Table 4. Hourly Weighting Factors for Traffic Flows on a Typical Day

Time Period	Weighting Factor (%)	Time Period	Weighting Factor (%)
12:00 a.m. - 1:00 a.m.	1.5	12:00 p.m. - 1:00 p.m.	2.2
1:00 a.m. - 2:00 a.m.	0.5	1:00 p.m. - 2:00 p.m.	2.5
2:00 a.m. - 3:00 a.m.	0.2	2:00 p.m. - 3:00 p.m.	3.0
3:00 a.m. - 4:00 a.m.	0.1	3:00 p.m. - 4:00 p.m.	3.5
4:00 a.m. - 5:00 a.m.	0.2	4:00 p.m. - 5:00 p.m.	9.0
5:00 a.m. - 6:00 a.m.	0.6	5:00 p.m. - 6:00 p.m.	18.0
6:00 a.m. - 7:00 a.m.	2.0	6:00 p.m. - 7:00 p.m.	10.0
7:00 a.m. - 8:00 a.m.	7.5	7:00 p.m. - 8:00 p.m.	3.0
8:00 a.m. - 9:00 a.m.	17.5	8:00 p.m. - 9:00 p.m.	2.2
9:00 a.m. - 10:00 a.m.	5.0	9:00 p.m. - 10:00 p.m.	1.8
10:00 a.m. - 11:00 a.m.	3.0	10:00 p.m. - 11:00 p.m.	2.2
11:00 a.m. - 12:00 p.m.	2.5	11:00 p.m. - 12:00 a.m.	2.0

Table 5. Typical Summer Hourly Meteorological Data

Hour	Time Period	Wind Speed (m/sec)	Wind Direction ¹	Stability Class	Ambient Temperature (F)
1	12:00 a.m. - 1:00 a.m.	5	0	E	65
2	1:00 a.m. - 2:00 a.m.	5	0	E	65
3	2:00 a.m. - 3:00 a.m.	5	0	E	70
4	3:00 a.m. - 4:00 a.m.	5	0	E	70
5	4:00 a.m. - 5:00 a.m.	5	30	E	75
6	5:00 a.m. - 6:00 a.m.	5	30	E	75
7	6:00 a.m. - 7:00 a.m.	5	30	E	80
8	7:00 a.m. - 8:00 a.m.	5	30	C	80
9	8:00 a.m. - 9:00 a.m.	9	30	C	80
10	9:00 a.m. - 10:00 a.m.	9	30	C	85
11	10:00 a.m. - 11:00 a.m.	9	30	D	85
12	11:00 a.m. - 12:00 a.m.	10	30	D	85
13	12:00 p.m. - 1:00 p.m.	10	45	D	90
14	1:00 p.m. - 2:00 p.m.	12	45	D	90
15	2:00 p.m. - 3:00 p.m.	12	45	D	90
16	3:00 p.m. - 4:00 p.m.	14	45	D	85
17	4:00 p.m. - 5:00 p.m.	12	45	D	85
18	5:00 p.m. - 6:00 p.m.	10	45	D	80
19	6:00 p.m. - 7:00 p.m.	12	45	D	80
20	7:00 p.m. - 8:00 p.m.	8	60	D	75
21	8:00 p.m. - 9:00 p.m.	8	60	D	75
22	9:00 p.m. - 10:00 p.m.	6	60	E	70
23	10:00 p.m. - 11:00 p.m.	5	60	E	70
24	11:00 p.m. - 12:00 a.m.	5	60	E	65

¹ Measured by the angle with the x-axis in the (x, v) coordinate system.

Table 6. Optimal Link Capacity Expansions - Benchmark Analysis (veh/hr)

Link	7:00-8:00 a.m.	8:00-9:00 a.m.	9:00-10:00 a.m.	4:00-5:00 p.m.	5:00-6:00 p.m.	6:00-7:00 p.m.
9	680	4800		1776	4800	2504
10	3415	4800	1136	4800	4800	4800
11	3403	4800	442	4800	4800	4800
12	680	4800		1776	4800	2504
23	679	4800		1776	4800	2506
28	3431	4800	1139	4800	4800	4800
33	3430	4800		4800	4800	4800
38	679	4800		1775	4800	2508

Table 7. Changes in O-D Demands in Ring 1 and Ring 2

		Number of Nodes	Basic O-D Demands of Each Residential Area	Scenario 1	Scenario 2	Scenario 3
Hypo. 1	Ring 1	8	15.072	15.072	15.072	15.072
	Ring 2	16	15.072	16.579	18.086	19.594
Hypo. 2	Ring 1	8	15.072	18.086	21.100	24.116
	Ring 2	16	15.072	15.072	15.072	15.072
Total Trips			361,728	385,840	409,952	434,080
Total Population			1,085,184	1,157,520	1,229,856	1,302,240

Table 8. Impacts of Increased O-D Demands on Cost (\$/hr) and CO Pollution (mg/m3)

	Benchmark *	Hypothesis 2			Hypothesis 1		
		Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
TT (\$/hr)	144590	164140	188110	217380	169710	199540	234670
FC (\$/hr)	37659	39038	40558	42249	40568	43611	46817
CI (\$/hr)	5376	5376	5376	5376	5376	5376	5721
TC (\$/hr)	187620	208560	234050	265010	215660	248530	287200
Receptor1	0.3	0.3	0.3	0.3	0.4	0.5	0.6
Receptor2	0.5	0.5	0.6	0.6	0.6	0.7	0.8
Receptor3	1.5	1.6	1.7	1.7	1.7	1.8	2.0
Receptor4	0.3	0.3	0.3	0.2	0.4	0.5	0.7
Receptor5	1.6	1.7	1.7	1.8	1.7	1.8	1.9
Receptor6	4.0	4.8	5.7	6.9	4.8	5.8	7.0
Receptor7	7.3	8.8	10.6	12.8	8.8	10.5	12.8
Receptor8	1.5	1.6	1.7	1.7	1.7	1.8	1.9
Receptor9	0.6	0.6	0.6	0.6	0.7	0.8	0.8
Receptor10	0.7	0.8	0.9	0.9	0.8	0.9	1.1
Receptor11	4.0	4.8	5.7	6.9	4.8	5.8	6.9
Receptor12	0.5	0.5	0.6	0.6	0.6	0.7	0.9
Receptor13	0.4	0.4	0.4	0.4	0.4	0.5	0.5
Receptor14	0.6	0.6	0.6	0.6	0.7	0.8	0.8
Receptor15	1.6	1.7	1.7	1.8	1.7	1.8	1.9
Receptor16	0.3	0.3	0.3	0.3	0.4	0.5	0.6

* 8:00 - 9:00 a.m.: Typical summer day

Table 9. Effects of Changes in CO Ambient Standard on Costs, Link Flows, and CO Concentrations

	Benchmark 40 mg/m ³	Scenario 1 10 mg/m ³		Benchmark 40 mg/m ³	Scenario 1 10 mg/m ³		Benchmark 40 mg/m ³	Scenario 1 10 mg/m ³
X1	1356.4	1213.9	Z1	0	0	R1	0.5	0.5
X2	3114.0	2891.7	Z2	0	0	R2	0.8	0.7
X3	3114.1	3166.2	Z3	0	0	R3	2.3	2.2
X4	1356.7	1355.3	Z4	0	0	R4	0.5	0.5
X5	955.6	785.6	Z5	0	0	R5	2.4	2.6
X6	2311.6	1730.9	Z6	0	0	R6	6.3	7.3
X7	2312.1	2259.8	Z7	0	0	R7	11.5	10.0
X8	955.4	904.9	Z8	0	0	R8	2.3	2.2
X9	8941.2	9177.9	Z9	4800	4800	R9	0.9	0.9
X10	16277.8	17081.0	Z10	4800	4800	R10	1.1	1.1
X11	16277.7	15474.5	Z11	4800	4800	R11	6.3	7.3
X12	8941.0	8770.2	Z12	4800	4800	R12	0.8	0.7
X13	955.4	1030.5	Z13	0	0	R13	0.6	0.6
X14	2312.2	2387.8	Z14	0	0	R14	0.9	0.9
X15	2311.7	2802.3	Z15	0	0	R15	2.4	2.6
X16	955.7	1033.2	Z16	0	0	R16	0.5	0.5
X17	1356.2	1356.8	Z17	0	0			
X18	3113.9	3038.2	Z18	0	0			
X19	3114.0	3426.8	Z19	0	0			
X20	1356.0	1501.2	Z20	0	0			
X21	1356.6	1499.0	Z21	0	0			
X22	955.3	1035.2	Z22	0	0			
X23	8941.1	8770.9	Z23	4800	4800			
X24	955.6	902.0	Z24	0	0			
X25	1356.3	1357.6	Z25	0	0			
X26	3113.9	3426.4	Z26	0	0			
X27	2312.3	2802.9	Z27	0	0			
X28	16277.7	15474.5	Z28	4800	4800			
X29	1311.8	2260.0	Z29	0	0			
X30	3113.9	3165.7	Z30	0	0			
X31	3114.4	3038.6	Z31	0	0			
X32	2311.3	2387.3	Z32	0	0			
X33	16277.7	17080.9	Z33	4800	4800			
X34	2311.9	1731.3	Z34	0	0			
X35	3114.2	2891.5	Z35	0	0			
X36	1356.8	1356.2	Z36	0	0			
X37	955.2	1031.6	Z37	0	0	TT (\$/hr)	154050	155340
X38	8940.9	9177.9	Z38	4800	4800	CI (\$/hr)	5376	5376
X39	954.9	787.4	Z39	0	0	FC (\$/hr)	38673	38703
X40	1357.0	1211.7	Z40	0	0	TC (\$/hr)	198100	199420

X_i = flow on link i (veh/hr)

Z_i = capacity expansion on link i (veh/hr)

R_i = concentration at receptor i (mg/m³)

Table 9. Effects of Changes in CO Ambient Standard on Costs, Link Flows, and CO Concentrations (continued)

	Scenario 2 9.0 mg/m ³	Scenario 3 8.5 mg/m ³		Scenario 2 9.0 mg/m ³	Scenario 3 8.5 mg/m ³		Scenario 2 9.0 mg/m ³	Scenario 3 8.5 mg/m ³
X1	1136.5	908.7	Z1	0	0	R1	0.5	0.4
X2	2803.0	2763.7	Z2	0	0	R2	0.6	0.4
X3	3186.3	3195.3	Z3	0	0	R3	2.2	2.2
X4	1356.5	1356.5	Z4	0	0	R4	0.5	0.5
X5	483.0	10.0	Z5	0	0	R5	2.7	3.1
X6	1215.8	924.4	Z6	0	0	R6	8.2	8.5
X7	2239.6	2230.7	Z7	0	0	R7	9.0	8.5
X8	883.1	874.1	Z8	0	0	R8	2.2	2.2
X9	9462.3	9980.0	Z9	4800	4800	R9	0.9	0.9
X10	17684.8	18015.6	Z10	4800	4800	R10	1.2	1.3
X11	14870.7	14539.9	Z11	4800	4800	R11	8.2	8.5
X12	8702.3	8671.9	Z12	4800	4800	R12	0.6	0.4
X13	1126.5	1309.7	Z13	0	0	R13	0.6	0.6
X14	2483.0	2666.1	Z14	0	0	R14	0.9	0.9
X15	3026.6	2656.5	Z15	107	0	R15	2.7	3.1
X16	1046.4	858.0	Z16	0	0	R16	0.5	0.4
X17	1356.5	1356.5	Z17	0	0			
X18	2942.9	2759.8	Z18	0	0			
X19	3806.4	4507.2	Z19	442	1259			
X20	1576.5	1804.2	Z20	0	0			
X21	1576.5	1804.3	Z21	0	0			
X22	1046.4	858.0	Z22	0	0			
X23	8702.3	8671.9	Z23	4800	4800			
X24	883.1	874.2	Z24	0	0			
X25	1356.5	1356.4	Z25	0	0			
X26	3806.4	4507.2	Z26	442	1259			
X27	3026.6	2656.5	Z27	107	0			
X28	14870.7	14539.9	Z28	4800	4800			
X29	2239.6	2230.7	Z29	0	0			
X30	3186.3	3195.2	Z30	0	0			
X31	2942.9	2759.8	Z31	0	0			
X32	2483.0	2666.1	Z32	0	0			
X33	17684.8	18015.6	Z33	4800	4800			
X34	1215.8	924.4	Z34	0	0			
X35	2803.0	2763.7	Z35	0	0			
X36	1356.5	1356.5	Z36	0	0			
X37	1126.5	1309.6	Z37	0	0	TT (\$/hr)	157760	159580
X38	9462.3	9980.0	Z38	4800	4800	CI (\$/hr)	5583	5852
X39	483.0	10.0	Z39	0	0	FC (\$/hr)	38772	38837
X40	1136.5	908.7	Z40	0	0	TC (\$/hr)	202110	204227

Table 10. Impact of Wind Speed Changes on CO Pollution Concentrations (mg/n

	8:00 - 9:00 a.m.				5:00 - 6:00 p.m.		
	3 m/sec	5 m/sec	7 m/sec	9 m/sec	5 m/sec	7 m/sec	10 m/sec
Receptor	1.0	0.6	0.4	0.3	1.1	0.8	0.5
Receptor	1.5	0.9	0.7	0.5	1.6	1.1	0.8
Receptor	4.6	2.8	2.0	1.5	4.6	3.3	2.3
Receptor	0.9	0.6	0.4	0.3	1.0	0.7	0.5
Receptor	4.9	3.0	2.1	1.6	4.9	3.5	2.4
Receptor	12.0	7.2	5.1	4.0	12.6	9.0	6.3
Receptor	21.9	13.1	9.4	7.3	23.0	16.5	11.5
Receptor	4.6	2.8	2.0	1.5	4.6	3.3	2.3
Receptor	1.9	1.1	0.8	0.6	1.9	1.3	0.9
Receptor	2.1	1.3	0.9	0.7	2.2	1.6	1.1
Receptor	12.0	7.2	5.1	4.0	12.6	9.0	6.3
Receptor	1.5	0.9	0.7	0.5	1.6	1.1	0.8
Receptor	1.1	0.7	0.5	0.4	1.1	0.8	0.6
Receptor	1.9	1.1	0.8	0.6	1.9	1.3	0.9
Receptor	4.9	3.0	2.1	1.6	4.9	3.5	2.4
Receptor	1.0	0.6	0.4	0.3	1.1	0.8	0.5

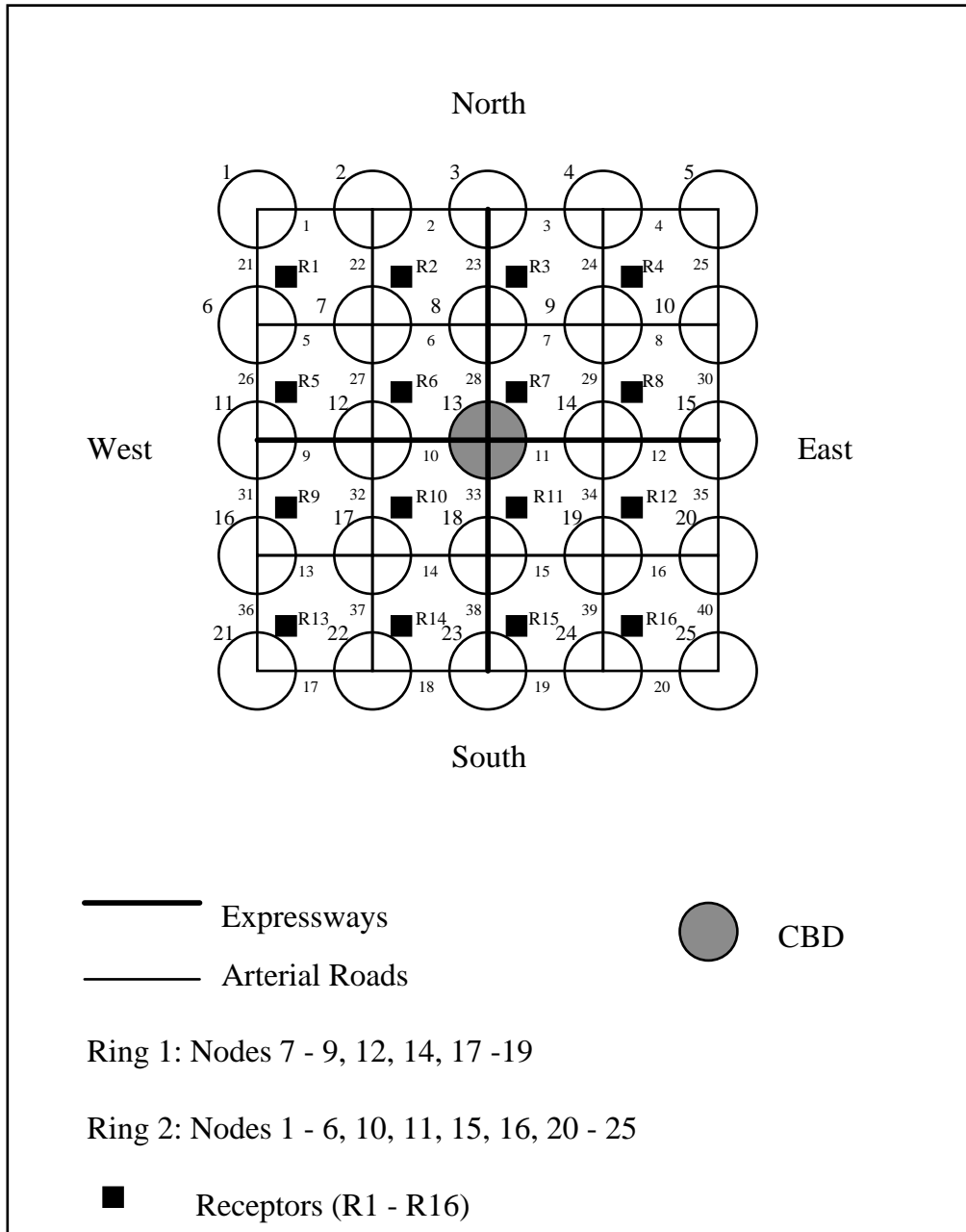


Figure 1. Hypothetical Transportation Network

\$/hour

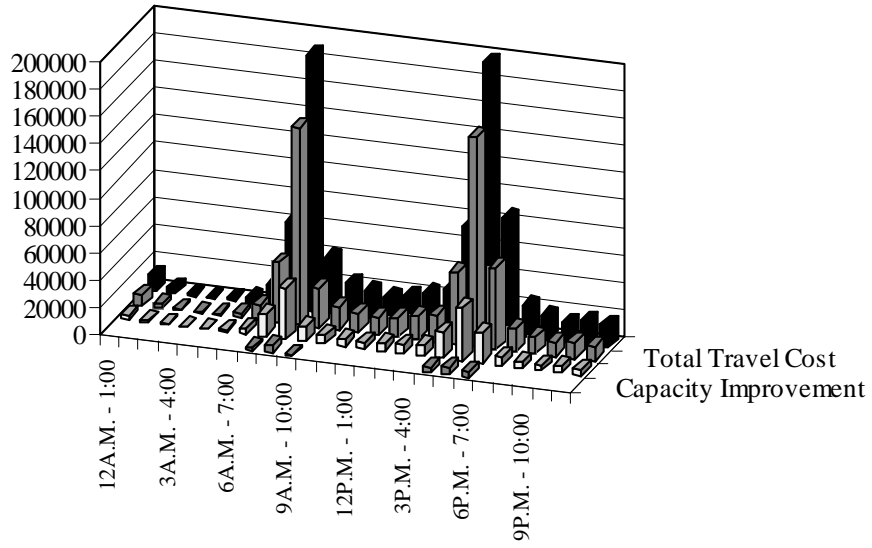


Figure 2. Cost Variations - Benchmark Analysis

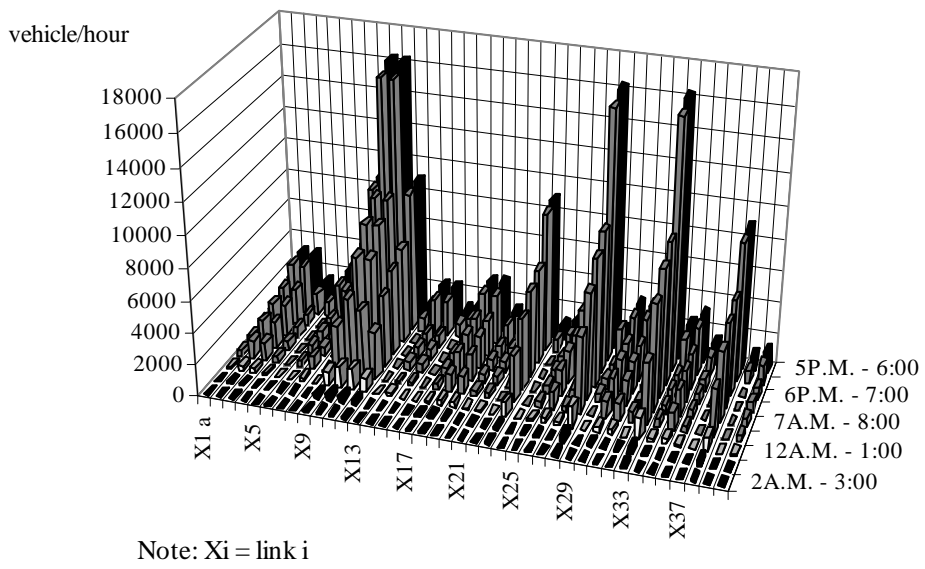


Figure 3. Optimal Link Traffic Flows - Benchmark Analysis

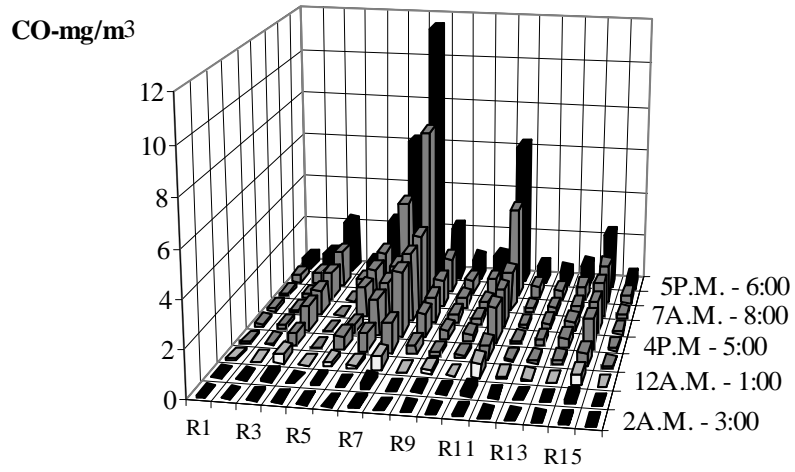


Figure 4. Spatial Variations of CO Pollution - Benchmark Analysis