A SIMPLE MODEL FOR ESTIMATING REGIONAL AUTOMOTIVE EMISSIONS

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A simple model for estimating regional automotive emissions of carbon monoxide, hydrocarbons, and nitrogen oxides is developed. The model is designed for use when rough, low-cost pollution estimates are desired. Traffic volumes are assumed to be available. Given the characteristics of the regional highway network, the model calculates the vehicle-miles of travel over different road types in each specified subarea of the region and the vehicle speeds at which travel takes place. Then by use of emission functions that relate the output of pollutants to vehicle speeds, emission estimates are calculated for the given travel pattern. An application to the Watertown, New York, region is discussed.

•OFTEN urban and regional transportation planners want to estimate emissions of pollutants from automotive sources under different sets of assumptions (1). Several elaborate methods for producing these estimates are available (2, 3, 5, 11). But, use of these methods requires investments in time, money, and labor that can easily outweigh the value of the results that are obtained. For policy exploration, rough, low-cost emission estimates are usually all that are required so the model developed in this paper is designed for those situations where highly accurate results are not necessary. The model is for use with travel forecasts that are already available and with a dispersion model capable of translating emission quantities into air quality.

OVERVIEW OF THE MODEL

When actual or projected traffic volumes for each link in a regional highway network for a specified time period are used as input, the model will provide estimates of emissions for each subarea of the region. The model is shown schematically in Figure 1. It is assumed that the region has been subdivided into separate and adjacent subareas for which emission estimates are to be provided and that the user has a detailed map of highway links and intersections for the region to be studied.

Each element of a model run can be classified as being a fixed component, an input component, or an output component. A model run is the calculation of emission levels for a given level of traffic over a set time period. In this context, a fixed model component does not change from run to run, but input and output components do change. Inputs are provided by the user and outputs are calculations produced by the model using the input and fixed components.

The model components can be described as follows (the letter designations correspond to those in Figure 1):

Type	Designation	Description
Fixed	A	A primary link/subarea map that specifies miles of primary highway links in each subarea in the form of a primary link/subarea matrix of road mileages. (From

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		these data, it is possible to calculate total link lengths in miles and the total road mileage in each subarea.)
	B	An equivalence network/subarea map that specifies miles of secondary highway links in each subarea.
	C	A set of functions relating emissions of selected pollutants, in pounds per vehicle-mile, to vehicle speed in miles per hour with adjustments for the different emission rates of different car model years.
	D	A delay subroutine breaking down road time into idle, speed changing, and cruise time from which an average vehicle speed is calculated.
Input	E	Estimates of traffic volume on each link of the primary road network for number of vehicles using the link during a designated time period and the average freeflow speed in miles per hour per car. (It is assumed that all cars travel at the average speed and that a relationship among speed, link capacity, and traffic density has been established.)
	F	Estimates of traffic volumes and the average free-flow speed over each link in the secondary highway network for total number of vehicles using the network during a designated time period.
Output	G	Estimates of emissions of each pollutant in pounds per time period for each link of the primary highway network.
	H	Estimates of emissions of each pollutant in pounds per time period for the secondary highway network.
	I	Estimates of total emissions in pounds per time period for each subarea and for the whole region.

So highway networks are fixed components; traffic forecasts are input components; and emission estimates are output components. But, fixed components may change; for example, they may change to accommodate a new road that may need to be included in the networks. The terminology, then, derives its meaning from the context of the model run.

MATHEMATICAL DETAILS

The following representation is a link/subarea incidence matrix for road type r in the primary network.

$$A^r = \text{Links}\overset{\text{Subareas}}{\begin{bmatrix} a^r_{11} & a^r_{12} & \cdots & a^r_{1J} \\ a^r_{21} & a^r_{22} & \cdots & a^r_{2J} \\ \vdots & \vdots & \vdots & \vdots \\ a^r_{I1} & a_{I2} & \cdots & a^r_{IJ} \end{bmatrix}} \qquad (1)$$

where

A^r = an (I × J) link/subarea incidence matrix for road type $r (r = 1, 2, \ldots, R)$;
I = total number of links;
J = total number of subareas;
R = total number of road types in the primary network;
j = subarea;
i = link; and
a^r_{ij} = number of miles of road type by link in a subarea.

We partition A^r into J column vectors by writing

$$A^r = (A^{r1}, A^{r2}, \ldots, A^{rJ}) \tag{2}$$

where A^{rj} denotes the link vector for road type r in a particular subarea j (i.e., column j of A^r). Thus,

$$A^{rj} = (a^r_{1j}, a^r_{2j}, \ldots, a^r_{Ij})' \tag{3}$$

for subarea j and road type r, where prime indicates transpose.

The following are matrices of (I × 1) vectors. $T^r = (T^{r1}, T^{r2}, \ldots, T^{rJ})$ gives subareal link trips for road type r, and $V^r = (V^{r1}, V^{r2}, \ldots, V^{rJ})$ gives subareal average link speeds for road type r. The partitions are constructed to correspond to Eqs. 2 and 3 for link mileages.

$$T^{rj} = (t^r_{1j}, t^r_{2j}, \ldots, t^r_{Ij})' \tag{4}$$

and

$$V^{rj} = (v^r_{1j}, v^r_{2j}, \ldots, v^r_{Ij})' \tag{5}$$

where

t^r_{ij} = traffic volume, in vehicles per day, on link i of road type r in subarea j, and
v^r_{ij} = average speed on link i of road type r in subarea j.

Assume that there are K pollutants of interest. We establish a set of pollution functions in the form

$$p(k) = f(v) \tag{6}$$

where

p(k) = pounds of pollutant k emitted per vehicle-mile;
f(v) = function of vehicle speed, in miles per hour; and
K = total number of pollutants.

We can construct a partitioned emissions matrix for each pollutant for each road type by using Eq. 6:

$$P^r(k) = \left[P^{r1}(k), P^{r2}(k), \ldots, P^{rJ}(k)\right] \tag{7}$$

where each partition (column) of the matrix $P^r(k)$ represents the pounds of pollutant k emitted per vehicle-mile at the corresponding average speed and highway links of road type r.

To calculate $m^r_{ij}(k)$—pollutant k emissions on a per mile basis for each link i of road type r in subarea j—we multiply corresponding elements of vectors T^r and $P^r(k)$:

$$m^r_{ij}(k) = (t^r_{ij}) \left[P^r_{ij}(k)\right] \tag{8}$$

for $i = 1, 2, \ldots, I$; $j = 1, 2, \ldots, J$; $k = 1, 2, \ldots, K$; and $r = 1, 2, \ldots, R$. The partitioned matrix $M^r(k)$, $[M^{r1}(k), M^{r2}(k), \ldots, M^{rJ}(k)]$ represents pollutant k per mile of each link of road type r for the traffic volumes in each subarea.

Total emissions of pollutant k for each road type r in each subarea j are then given by

$$E^{rJ}(k) = \left[M^{rJ}(k)\right]' A^{rJ} \tag{9}$$

for j = 1, 2, . . ., J; k = 1, 2, . . ., K; and r = 1, 2, . . ., R.

Finally, total emissions of pollutant k on primary networks are given by

$$E^J(k) = \sum_{r=1}^{R} E^{rJ}(k) \tag{10}$$

for k = 1, 2, . . ., K; and j = 1, 2, . . ., J.

This procedure estimates emissions over the R road types in the primary highway network. Slightly different calculations are carried out for the network of secondary roads. Because all secondary roads are considered collectively we have a link/subarea matrix

$$A^S = \left(a^S_{11}, a^S_{12}, \ldots, a^S_{1J}\right) \tag{11}$$

where S = total number of secondary roads. The $(1 \times J)$ vector $T^S_1 = (t^S_{11}, t^S_{12}, \ldots, t^S_{1J})$ gives subarea secondary traffic volumes, where t^S_{1J} represents the number of vehicle trips made per time period over secondary roads in subarea j. The corresponding $(1 \times J)$ vector giving average speeds is $V^S = (v^S_{11}, v^S_{12}, \ldots, v^S_{1J})$. The pollution functions given by Eq. 6 are the same for secondary networks.

We calculate pollutant k emissions on a per mile basis for the secondary network by the following equation:

$$m^S_{1J}(k) = (t^S_{1J})\left[p^S_{1J}(k)\right] \tag{12}$$

where $m^S_{1J}(k)$ represents the pounds of emission per vehicle-mile of pollutant k in subarea j over secondary links. The emissions vector for pollutant k is $M^S(k) = [m^S_{11}(k), m^S_{12}(k), \ldots, m^S_{1J}(k)]$. Total emissions of pollutant type k in each subarea of secondary links are then given by

$$E^{SJ} = M^S(k)(A^S)' \tag{13}$$

Total emissions, in pounds per time period, of each pollutant in each subarea are obtained by adding contributions from primary and secondary network sources (i.e., Eqs. 10 and 13).

APPLICATION

The emissions model was applied to the Watertown region (Jefferson County) in upstate New York. The region was subdivided into six subareas, each made up of one or more townships (Table 1). The goal was to estimate emissions of carbon monoxide (CO), nitrogen oxides (NO_x), and hydrocarbons (HC) in a subarea from automotive sources for one day in 1970.

Four road types were used (Table 2). Limited-access expressways, main arterials, and subordinate arterials formed the primary highway network, and township roads formed the secondary network.

To summarize the calculation procedure, subarea estimates are made of total vehicle-miles of travel in an average day for each road type. Travel on each road type is assumed to be at the speed limit (i.e., free-flow speed) adjusted downward for congestion, traffic signals, and other delays. Emissions per vehicle-mile of CO, NO_x, and HC are estimated by referring to emission functions that relate emission rates to

Figure 1. Schematic model.

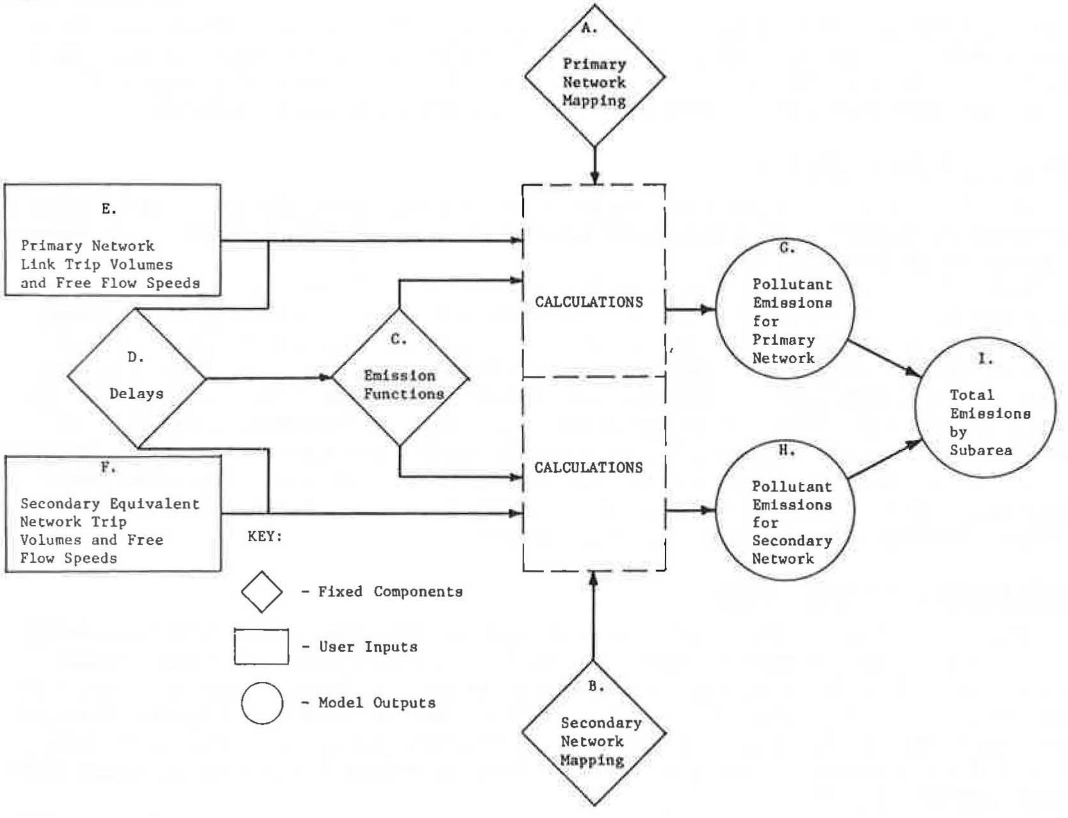

Table 1. Subarea composition.

Subarea	Townships	Subarea	Townships
1	Alexandria Cape Vincent Clayton Lyme Orleans	3	Pamelia Watertown
		4	Brownville Hounsfield
2	Antwerp Champion LeRay Philadelphia Rutland Theresa Wilna	5	Adams Ellisburg Henderson Lorraine Rodman Worth
		6	Watertown City

Table 2. Road types.

Road Type	Description	Watertown Region Example
1	Limited-access expressway	Interstate 81
2	Main arterials	State routes
3	Subordinate arterials	County routes
4	Tertiary roads	Township roads

Table 3. Dimensions of Watertown region highway networks.

	I-81		State Routes		County Routes		Township Roads		Total	
Subarea	Links	Miles	Links	Miles	Links	Miles	Links	Miles	Links	Miles
1	6	16	46	103	96	156	195	246	343	521
2	2	3	62	143	87	139	237	241	388	526
3	7	19	29	63	17	32	48	56	101	170
4	1	1	25	54	25	43	83	98	134	196
5	8	17	46	105	91	139	213	224	358	485
6	0	0	13	13	15	13	30	35	53	51
Total	24	56	221	481	331	522	806	900	1,377	1,949

Note: 1 mile = 1.6 km.

speed for the vehicle year under consideration. Then the emissions of each pollutant per vehicle-mile are multiplied by total vehicle-miles to give total emissions in each subarea for primary and secondary networks. The main elements of this procedure with particular reference to the Watertown region are described as follows.

Traffic Volume Estimates

The dimensions of the primary and secondary highway networks are given in Table 3. Information identifying each link in the highway system by location, length, and capacity were compiled in matrix form.

In developing estimates of average daily 1970 traffic volumes for each link of the primary road network and for all secondary network roads collectively, we were provided the following data by the Region 7 Office of the New York State Department of Transportation: statewide traffic volume reports for state routes, 1964-1971; traffic counts on Jefferson County roads and selected township roads, 1959-1967; TOPICS data for Watertown city, 1971; origin-destination study data for Watertown city, 1961; and special traffic counts performed on an irregular basis. Because these sources pertain to activity in different regions at different times; the estimates for regionwide travel activity in 1970 were put together from the information available for 1970 and other years. Traffic volume data are given in Table 4.

Calculation of Emission Factors

The emission rate for any pollutant is a function of vehicle speed. While traveling over any particular stretch of road, a driver may change vehicle speed many times—the vehicle may start, idle, alternately accelerate and decelerate, come to a partial or full stop for a traffic light, start again, accelerate and decelerate, and so on. Because emissions vary nonlinearly as the vehicle changes from one driving state to another, the emission estimation technique must take this variability into account to obtain realistic emission factors.

For this model, travel is divided into two categories: travel at free-flow speed and travel delay. The average delay on any road link is a function of the road type and the volume-to-capacity ratio. Once an estimate of average delay is obtained for each road link in the highway network, it is proportioned into two subcategories—speed-changing delays and standing delays. Emission rates are, in the end, calculated for cruising at free-flow speeds, speed changing, and standing.

Figure 2, developed from information in the Highway Capacity Manual (4), shows average delay for each road type; capacity is defined as that traffic volume at which traffic is at a standstill because of congestion. This underestimates true delay because it is assumed that no vehicle starts its trip on the road link in question (e.g., there is a zero average delay at low volume-to-capacity ratios) and it is also assumed that no travel takes place above free-flow speed when in reality high-speed travel does take place.

Table 5 gives the proportions used to separate delay time into standing and speed-changing components for each road type. These proportions are an extension of factors developed by the New York State Department of Transportation in connection with the development of a pollution emission model and described in unpublished material as "[developed from] theoretical considerations of the probable number of stops, stop durations, acceleration rates, deceleration rates and speed limits."

Emission functions that relate emissions, in pounds per vehicle-mile, to vehicle speed were developed from data collected from six sources (6, 7, 8, 9, 10). Figure 3 shows the function for carbon monoxide; Figure 4, for hydrocarbons; and Figure 5, for nitrogen oxides. These functions apply to 1970 and any years when emissions were uncontrolled. Adjustments of these functions for the effects of emission-control devices can be made by applying uniform percentage reductions of emissions on the vertical axis at the corresponding point for speed on the horizontal axis. The U.S. Environmental Protection Agency has published data to calculate these adjustments (10, Table 3.1.1-1).

Table 4. Estimated average daily vehicle-miles of travel, 1970.

Subarea	I-81	State Routes	County Routes	Township Roads	Total
1	20,000	215,000	38,000	16,000	289,000
2	8,000	459,000	45,000	21,000	533,000
3	54,000	202,000	15,000	8,000	279,000
4	10,000	178,000	13,000	13,000	214,000
5	64,000	91,000	27,000	19,000	201,000
6		130,000	70,000	35,000	235,000
Total	156,000	1,275,000	208,000	112,000	1,751,000

Note: 1 mile = 1.6 km.

Figure 2. Average delay function.

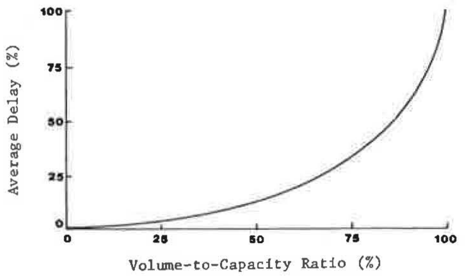

Table 5. Percentage of traffic standing still at various volume-to-capacity ratios.

Volume-to-Capacity Ratio	I-81	State Routes	County Routes	Township Roads
0.1	0	0	0	1
0.2	0	4	5	7
0.3	5	12	14	17
0.4	8	19	25	30
0.5	15	30	36	42
0.6	26	45	50	60
0.7	50	61	65	80
0.8	85	87	88	93
0.9	98	98	98	99
1.0	100	100	100	100

Figure 3. Emission function for CO.

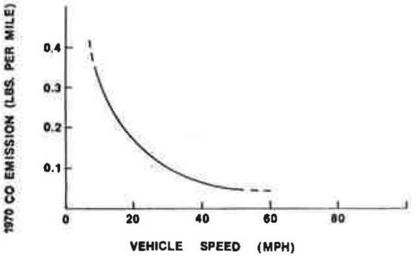

Figure 4. Emission function for HC.

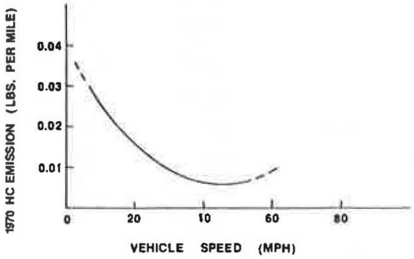

Figure 5. Emission function for NO_x.

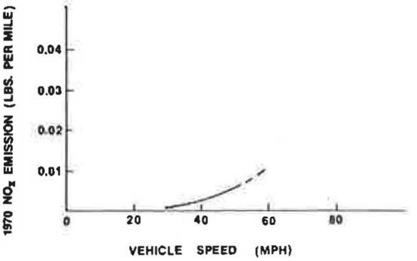

Table 6. Emission factors.

Driving Condition	CO (lb/vehicle-hour)	HC (lb/vehicle-hour)	NO_x (lb/vehicle-hour)
Standing	0.2	0.10	0.00
Speed-changing	4.3	0.53	0.25
Cruising			
20 mph	3.9	0.34	0.00
30 mph	3.4	0.32	0.00
40 mph	3.3	0.33	0.10
50 mph	3.8	0.38	0.10
60 mph	4.6	0.52	0.26
70 mph	5.9	0.69	0.35

Note: 1 lb = 0.4536 kg.

Table 7. Estimated subarea transportation emissions.

Road Type	Subarea	CO (lb/day)	HC (lb/day)	NO_x (lb/day)
I-81	1	1,600	500	500
	2	640	200	200
	3	4,320	1,350	1,350
	4	800	250	250
	5	5,120	1,600	1,600
	6	0	0	0
	Subtotal	12,480	3,900	3,900
State routes	1	19,305	3,861	2,574
	2	41,310	8,262	5,508
	3	18,135	3,627	2,418
	4	16,065	3,213	2,142
	5	16,830	3,366	2,244
	6	17,940	2,080	0
	Subtotal	129,585	24,409	14,886
County routes	1	3,915	783	522
	2	5,508	1,102	734
	3	1,576	315	210
	4	1,170	234	156
	5	2,649	530	353
	6	9,660	1,120	0
	Subtotal	24,478	4,084	1,976
Township roads	1	1,670	334	223
	2	2,570	514	343
	3	864	173	115
	4	1,125	225	150
	5	1,913	383	255
	6	2,760	320	0
	Subtotal	10,903	1,949	1,086
	Total	177,446	34,342	21,848

Note: 1 lb = 0.4536 kg.

Using this information, it is possible to develop emission factors for the three travel categories. Table 6 gives the factors that are stored in the computer as functions.

The estimates the model produced of subarea and regional emissions of CO, HC, and NO_x from transportation sources for an average 1970 day are given in Table 7.

One of the problems with judging the usefulness of the model presented in this paper is the lack of a suitable procedure for testing its accuracy or validity. For example, it would be desirable to compare the pollution estimates obtained from this model with the quantities of pollutants that are actually emitted in a region. But for many reasons this kind of testing is impractical, so when using this model one must keep in mind the restrictions that accompany the use of any untested procedure.

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