International Journal of Physical Sciences Vol. 6(4), pp. 714-722, 18 February, 2011
Available online at http://www.academicjournals.org/IJPS
DOI: 10.5897/IJPS10.503
ISSN 1992 - 1950 ©2011 Academic Journals

Full Length Research Paper

Green transportation planning and regional sustainable development within metropolitan regions: The role of traffic pollutant inventory in decision making

Yong-gang Wang[1]*, Xu Zhu[1], Wen-sen Xiang[2] and Li-wei Hu[3]

[1]Key Laboratory for Special Area Highway Engineering, Ministry of Education, School of Highway, Chang'an University, Xi'an 710064, China.
[2]Shanghai Municipal Engineering Design General Institute, Shanghai 200030, China.
[3]Faculty of Transportation Engineering, Kunming University of Science and Technology, Kunming 150090, China.

Accepted 24 January, 2011

Increasingly, the Chinese metropolitan transportation organizations face many challenges ahead, as they try to meet the Nation's mobility requirements, decrease congestion impacts, and improve the level of air quality. However, the previous modeling tools (for example, land use, travel demand, and emission models) were not designed, nor do they generally provide visible feedback between adjacent procedures during the whole planning approach. Consequently, the preparation of a comprehensive database of traffic induced pollutant emissions in the form of an emission inventory is one of the basic tools for assessing the impact of regional development, population trends, and infrastructure improvements on air quality. The MOBILE 5 model is used to estimate emissions from both stationary and mobile motor vehicles, including: (1) identification of exhaust emission resource; (2) determination of emission index by vehicle type and size; (3) modeling the atmospheric pollutant diffuseness model across segment and intersection; (4) evaluation of traffic induced air pollution over network. The proposed approach is successfully applied to the Xi'an Metropolitan Area. The Base Case for the area generated emission estimators for hydrocarbons, particulate matter, carbon monoxide, and oxides of nitrogen. The modeled outputs provide a reasonable match for future strategies and policies in the study area, and successfully propose interventions to guide fuel consumption in planning schemes over the next five to ten years.

Key words: Transportation planning, air quality, vehicle emission index, MOBILE 5, fuel consumption.

INTRODUCTION

The assessment of vehicle pollutant emissions is important for integrating environmental issues into transportation activities, required by the Clean Air Act. Air quality in China's metropolitan areas has been improving over the past several decades, due to the strict transportation conformity strategy; that is, all the highway and transit projects must be consistent with the air quality goals. However, ozone and particulate matter are still challenging problems, especially in the western regions. Current vehicle fleets emit significant amounts of green house gas associated with climate change, such as carbon monoxide (CO), nitrogen oxide (NO_x), hydrocarbon (HC), and carbon dioxide (CO_2) etc. More importantly, particulate matter and ozone (CO, NOx and HC) are the two main pollutants causing human health damage and significant social cost (Wang et al., 2009). It is reported that traveling vehicles on highways and urban roads consumed about 60.3% of oils and it was responsible for 23.4% of greenhouse gas emissions

*Corresponding author. E-mail: sdqdwyg@163.com. Tel/Fax: +86 29 82334636.

(CO_2) in 2005 (Song et al., 2009; Boriboonsomsin et al., 2009).

Nowadays, the increasing pollution and traffic congestion in metropolitan areas have drawn numbers of concerns. Since long-term exposure to vehicle's emission pollutants could cause neurobehavioral effects, such as impaired coordination, driving inability and defective cognitive performance, the effects of air pollutant exposure on the population is assessed through ambient monitoring, models and emission inventories and then, decisions are to be made to provide a complete picture of managing and improving the environment, especially within the long term transportation planning process. For such purposes, numbers of research works have been made on the issues, integrating regional development strategies, transportation planning and future air pollution emissions (Kokaz et al., 2002; Bai et al., 2009; Karner et al., 2009; Butkevicius, 2009).

A vehicle emission inventory (VEI) is a general database of all directly or potentially harmful pollutants released from all motor vehicle substances (stationary, mobile and area sources) to the atmosphere, including the emission rates and source detection data. Despite being an air quality assessment tool itself, a VEI is a key component of modeling that is essential for an air quality management intervention. Harrington et al. (2007) have argued that such efforts (for example, as smart growth policies, traffic demand management (TDM) strategy, etc.) may help reduce if not completely internalize the congestion externality, so as to improve the air quality for a long term. Chi et al. (2005) used an ecological footprint based methodology to estimate the change of land, for building county highways and remediating annual vehicle exhausted emissions through forest carbon sequestration in 10 years interval. Kear et al. (2008) pointed out in their research that emission inventory models could compare the gaps between on-road vehicle emissions and drafted air quality plans, to ensure continuous improvement efforts in air quality, while preventing unintended disruption of transportation planning.

Nowadays, the high levels of pollution and traffic congestion in Chinese metropolitans are linked to their fast rate of growth and spectacular economic success story. However, the cities have been becoming "congestion and poisonous zones" that demands to put a system involving resources - financial, human and time -in place as quickly as possible (Jarzemskiene, 2009). A full implementation of the clean air practice and sustainable development strategy (or any other model) requires statistically robust procedures for verifying the gap between expectations in planning program and observed emission pollutants (Kiss et al., 2009). Therefore, the main objective in this study would be to verify the mobile source emission factors embedded in the MOBILE 5 model, locally, using vehicle emissions (mobile sources) from the Xi'an metropolitan database and considering Xi'an as the study area. From the list of vehicle pollutants emitted (e.g., CO, NO_x, HC, SOx's, PM, and Pb, etc), this study will focus on CO, NO_x and HC. In Section 2 and 3, this research focuses on the modeling motor vehicle emission methodology and tries to estimate the quantity of motor vehicle emission pollutants using MOBILE 5 procedure.

VARIABLES

Emission index of vehicles

To quantify the vehicle emission under different traffic conditions, we choose the emission index of vehicles (gas pollutant emitted/kg of fuel burned) that is defined as, the average pollutant emission per kilometer for the type of vehicle, and total vehicle emissions in a given area, are the sum of emissions from each type of pollutants from different vehicles.

Actually, in - use pollutant emission rates from motor vehicles is affected by many factors, ranging from vehicle / engine type, oil-type fuels (gasoline, diesel), exhaust and control etc., to traffic flow state and environmental condition (Singh et al., 2006). Therefore, the above defined emission index is really the estimated average emission rate for a given pollutant, for a given category of motor vehicles (Boudebbouz et al., 2009).

Driving performance of vehicles

The systemic procedure of vehicle driving, cycles, from hot or cold start, idling and acceleration, to deceleration and cruise that behaves complex and different in different inputs (types of road, pavement, environment, vehicle, driver, and city, etc.). To estimate the pollutant emission factor of single vehicle, driving cycle is conducted, considering motor vehicles in Chinese cities, as claimed in previous researches (Wang et al., 2008; Lin et al., 2003).

The experimental test is carried out with typical motor vehicles on typical roads and on both work day and off-work day (Fontaras et al., 2008; Yu et al., 2009), using vehicle speed sensor, engine rotating speed sensor, fuel consumption sensor, vehicle exhaust analyzer and other digital data recorder, etc. The test variables include speed and distance of driving, engine rotating speed, fuel consumption, exhaust emission, etc. Through the test of start and brake cycle of vehicles, the driving performance of typical motor vehicles are measured.

Vehicle population by size and age

The car population is divided into three size classes: (1) mall cars have engine displacement below 1400 cc;(2) medium cars have engine displacement between 1400 cc and 2000 cc; (3) large cars have engine displacement above 2000 cc. In order to estimate the overall emission index, the percentage of vehicles is classified by type j and licensed age i as:

$$R_{ij} = \frac{V_{ij}}{\sum_{i=1}^{N_j} V_{ij}} \tag{1}$$

where R_{ij} is the vehicle distribution of type j in licensed year i, V_{ij} is the number of new vehicles registered in year i that could be referenced by the statistics report of motor vehicle management department or estimated through the samples registered in year i, and N_j is the expired year of vehicles of type j that ranges from 8 years to 10 years according to types (Yoon et al., 2004).

Distribution of annual vehicle mileage traveled by vehicle types is annually average estimated driving distance through survey a**s**:

$$AAL_j = \sum_{i=1}^{N_j} R_{ij} \cdot L_{ij} \tag{2}$$

Where $AADD_j$ is the annual average driving distance of type i, V_{ij} is vehicle's distribution estimated by Eq(1), N_j is the vehicle's expired year of type j, L_{ij} is the statistical driving mileage of type j in year i.

Moreover, other mobile and environmental factors are derived from motor vehicle inspection and maintenance program (I/M program) (Wang et al., 2010). For this proposed MOBILE 5, the required parameters are derived from both annual inspection records and unscheduled on-road inspection (Wang et al., 2011) including geographic factor (for example, altitude, environment temperature, speed and direction of wind, air pressure, etc.) and traffic related topographical features (e.g., speed, number of vehicle lane, width of vehicle lane, width of non-motor vehicle lane, and surrounded buildings on both sides, etc.).

METHODOLOGY

Model choice and resource consideration

Usually, motor vehicle's emission index is generally estimated by experiment, respective to driving cycle and MOBILE 5 model (Tsai et al., 2005; Wang et al., 2009). Here, we also consider the later method, average speed is treated as the independent variable, and for HC emission index, motor vehicles are categorized into three groups: (1) natural gas powered car, mini-vehicle, medium-sized vehicle and jeep; (2) heavy-duty gas or diesel powered vehicle; (3) motorcycle. Thus, exponential function, rank function, and hyperbolic function are introduced to describe these vehicles mentioned above, respectively. Moreover, CO emission index satisfies hyperbolic distribution, and NO_x emission index complies with three-rank function.

Since pollutant emission is related to traffic volume, we have to predict the number of motor vehicles in future planning year, following the general sequential four-step procedure (Rasa et al., 2009). In this research, passenger car unit (PCU) is taken as the traffic unit of motor vehicle and then the emission index of pollutant type p is the equivalent emission of PCU, as estimated by Equation(3).

$$E_{PCUi}(p) = \frac{\sum_{j=1}^{k} b_{ij} E_{ij}(p)}{\sum_{j=1}^{k} \alpha_j b_{ij}} \tag{3}$$

Where $E_{ij}(p)$ is the emission index of vehicle type j in link i for pollutant type p [g/veh·km]; α_j is equivalency factor of vehicle type j; b_{ij} is the surveyed or predicted percentage of traffic volume type j in link i [%]; k is the total number of vehicle types.

If we get V_{PCUi} as traffic volume measured in PCU in link i [PCU/h], thus, we could calculate the corresponding emission intensity $Q_i(p)$ of pollutant type p as:

$$Q_i(p) = \frac{V_{PCU_i} E_{PCU_i}(p)}{3600} \tag{4}$$

According to location types of roads, diffusing model of traffic pollutants is divided into segment model and intersection model (Berkowicz et al., 2006; Broderick et al., 2007). During the process of transportation planning, it is unnecessary and impossible to make microcosmic design of traffic projects (e.g., segment type and size, intersection geometry, etc), which causes the lack of some essential parameters in simulating the diffusing features of different traffic pollutants (Gualtieri, 2010).

Quantity estimation of pollutants

Since traffic network in planning is composed of segment and intersection, the overall pollutants that motor vehicles emit is the sum of vehicle pollutant at segments and pollutant emission at intersections, respectively. Namely, the total type p pollutant emission $Q(p)$ [t/h] could be measured as $Q(p) = Q_s(p) + Q_{in}(p)$, and here $Q_s(p)$ and $Q_{in}(p)$ are estimated by Equations (5) to (7), respectively.

$$Q_s(p) = \sum_{i=1}^{N_1} V_{PCUi} L_i E_{PCUi}(p) \times 10^{-6} \tag{5}$$

$$Q_{in}(p) = \sum_{j=1}^{N_2} \sum_{l=1}^{M} \frac{N_{jl} D_{jl} EI_{PCUjl}(p)}{3600} \times 10^{-6} \tag{6}$$

$$EI_{ilPCU}^{p} = \frac{\sum_{k=1}^{K} b_{ilj} EI_k(p)}{\sum_{K=1}^{K} b_{ilj} \alpha_j} \tag{7}$$

Where L_i is the length of segment i [km]; N_1 and N_2 are the amount of segments and intersections, respectively; M is the number of entrances to intersection j; K is the number of vehicle types; $EI_{PCUjl}(p)$ is the emission index of traffic pollutant type p measured in PCU at entrance l to intersection j [g/(pcu·h)]; $EI_k(p)$ is the emission index of traffic pollutant type p emitted from type k vehicle in idling [g/veh·km]; b_{ilk} is the proportion of type k vehicles at entrance l to intersection i [%]; N_{il} is the simulated volume of motor vehicle in queue at

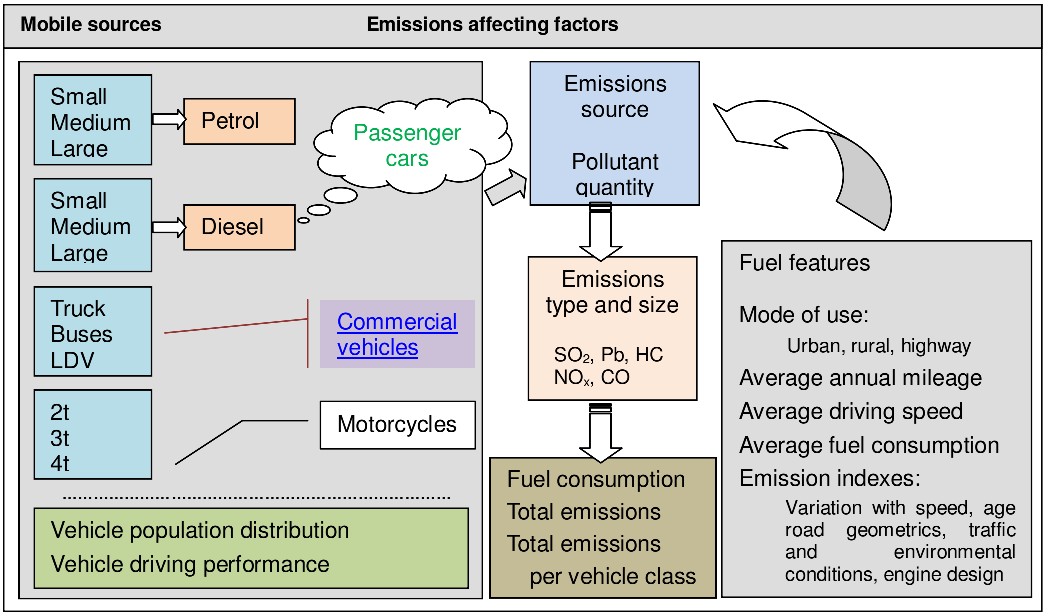

Figure 1. Procedure for estimating motor vehicle emission index.

entrance l to intersection i [pcu/h]; D_{il} is the average simulated delay at entrance l to intersection i [s].

For Equation (3), different grade roads have different volumes of daily traffic and thus the corresponding pollutant emissions differ significantly on different grade roads, which are determined by following expression, respectively.

$$Q_n(p) = \sum_{m=1}^{D} V_{PCUmn} L_{mn} E_{PCUn}(p) \quad (9)$$

Where $Q_n(p)$ is the emission of type p pollutant in grade n road [t/h], here n = 1, 2, …, 5 for Highway, expressway, major arterial, minor arterial, and branch road, respectively; V_{PCUmn} is traffic volume measured in PCU on road m graded n [PCU/h]; L_{mn} is the length of road m graded n [km]; D is the number of grade d road.

Urban traffic network air pollution

Traffic pollutant emission rate η_p [%] is the percentage of type p pollutants $Q_t(p)$ from motor vehicles to the total type p pollutants $Q(p)$. In the same way, we define the traffic air pollution rate $\eta_r(p)$ from different grade roads as the percentage of traffic pollutants $Q_{tr}(p)$ in overall traffic pollutants $Q_t(p)$. Thus we get $\eta_p = Q_t(p) / Q(p) \times 100\%$ and $\eta_r(p) = Q_{tr}(p) / Q_t(p) \times 100\%$. The proportion of vehicle mileage w_r from different grade roads is the mileage percentage on highway, expressway, major arterial, minor arterial and branch roads, respectively, to total vehicle mileage, as described in Equation (8).

$$w_r = \frac{\sum_{m=1}^{n} L_{mn} V_{PCUmn}}{\sum_{n=1}^{4}\sum_{m=1}^{n} L_{mn} V_{PCUmn}} \times 100\% \quad (8)$$

The grade of traffic pollution (λ_{rp}) is the ratio of $\eta_r(p)$ to w_r that reflects the seriousness of air pollution under different geometric and environmental conditions.

$$\lambda_{rp} = \frac{\eta_r(p)}{w_r} \quad (9)$$

Since urban traffic network consists of segments and intersections, the air quality around these two critical locations should be considered separately, and thus the transportation planning program could be further optimized.

The MOBILE 5 model uses standard procedures for estimating mobile source emissions, and the procedure for estimating mobile source emissions is summarized in the flowchart, Figure 1.

CASE APPLICATION

Scenario of vehicle type and road network

Vehicle emission pollution of Xi'an metropolitan area is considered in the procedure of urban transportation planning. Xi'an lies in the northeast of China mainland with the population of 8, 370,000 in 2009. As one of the oldest cities in Chinese history, Xi'an city is now experiencing a rapid development in economy and society. Unfortunately, the congestion situation as well as vehicle population problem is also more and more serious.

To provide the strategy and guide for future sustainable development, the Third Urban Transportation Planning of Xi'an City has been drafted since 2008 and has been approved in June, 2010, in which vehicle emission population problem is systemically and seriously treated with through quantity estimation by MOBILE 5 and specific demand supply. In this research, we only consider 6 districts in the key metropolitan area, with 668 traffic zones, as shown in Figure 2, and road network consists of 17260 segments and 10054 road links (also known as intersections). In the planning scenario (Figure 3), the

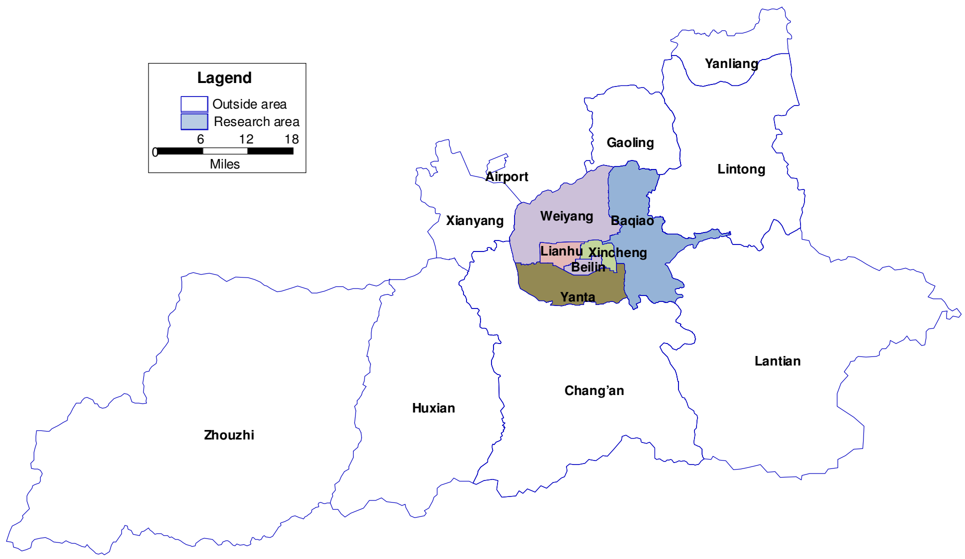

Figure 2. Research location in Xi'an Metropolitan area.

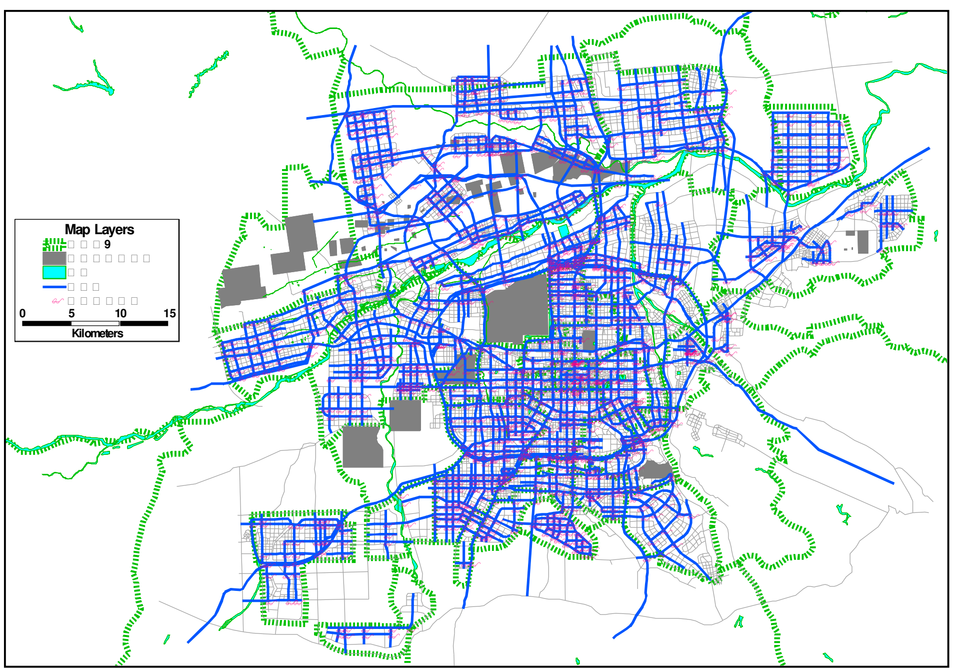

Figure 3. Distribution of road network structure in modeling process.

analysis model is composed of highway, expressway, arterial road, sub-arterial road, branch and minor streets. Through the traffic survey, passenger car covers 52.6% of all motor vehicles and the second is motorcycles with 29.2%. The percentage of motor bicycles, buses and trucks are 7.4%, 0.6% and 2.4%, and the others are different types of Lorries. Tables 1 and 2 present the distribution of traffic volume and mileage on simulation road network, respectively. As a specific type of traffic bottleneck, the mean traffic volume, capacity and *v*/*c* of intersections are 1673 pcu/h, 3217 pcu/h and 0.583. The traffic volume per hour in intersections is mainly less than

Table 1. Distribution of traffic volume in mileage.

Volume ($pcu \cdot h^{-1}$)	Mileage (km)	Percentage
< 500	2103	89.76
500-1000	116	4.95
1000-2000	71	3.03
2000-5000	37	1.58
> 5000	16	0.68

Table 2. Vehicle mileage distribution by road type.

Vehicle type	Vehicle mileage		Mean speed ($km \cdot h^{-1}$)
	Thousand (pcu·km)	Percentage	
Expressway	465	27.39	77.18
Major arterial	479	28.21	64.72
Minor arterial	154	9.07	44.65
Branch and minor street	82	4.83	20.82
Suburb highway	57	3.36	27.58
Suburb freeway	461	27.15	91.64
Total	1698	100	——

Table 3. Distribution of estimated vehicle pollutants at typical locations.

Location	HC ($t \cdot h^{-1}$)	CO ($t \cdot h^{-1}$)	NO_x ($t \cdot h^{-1}$)
Segement	6.080	37.260	3.658
Intersection	0.206	2.120	0.041
Total	6.287	39.380	3.699

Table 4. Macro-distribution of estimated emission pollutants by road type.

Road type	HC		CO		NO_x	
	Count ($t\text{-}h^{-1}$)	Percent	Count ($t\text{-}^{h-1}$)	Percent	Count ($t\text{-}^{h-1}$)	Percent
Expressways	1.283	21.15	7.030	18.91	1.026	28.07
Major arterial	1.452	23.93	8.988	24.17	0.920	25.17
Minor arterials	0.859	14.15	5.857	15.75	0.342	9.35
Branch roads	0.407	6.71	2.222	5.98	0.077	2.11
Suburb highways	0.922	15.19	7.143	19.21	0.318	8.70
Suburb freeway	1.146	18.88	5.942	15.98	0.972	26.59
Total	6.069	100.00	37.182	100.00	3.654	100.00

2000 pcu (about 71.2%).

ESTIMATION AND FINDINGS OF EMISSION POLLUTANTS

In this research, traveling speed is the independent variable in modeling MOBILE 5 procedure. As shown in Tables 3 and 4, the result shows that more exhaust pollutants have been emitted while traveling on segments, and three typical emissions (HC, CO and NO_x) cover 95.68, 95.42 and 98.65%, respectively. Fewer pollutants have been released at inters, because much more additional exhausts have been produced at indling.

Obviously, the proportion of passenger car emission pollutants is relatively higher, namely, 33.26, 57.32 an 32.17%, respectively, especially CO related pollutants. Trucks have produced more nitrogen oxide emissions with

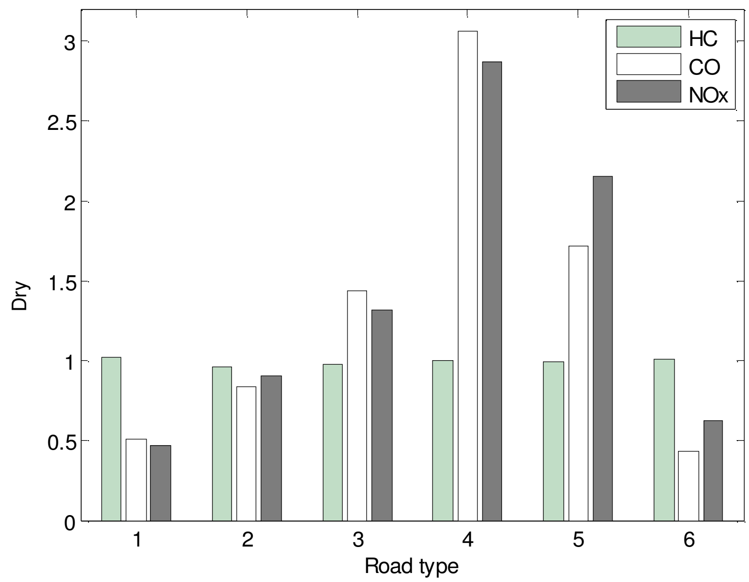

Figure 4. λ_{rp} determination as grade ratio of traffic air pollution. Notation for road type: 1: expressway; 2: major arterial; 3: minor arterial; 4: branch and minor street; 5: suburb highway; 6: suburb freeway.

37.08%, due to the fuel of diesel oil. Furthermore, the highest proportion of hydrocarbons is emitted by motor bicycles. In contrast, the emitted pollutants by buses and channel buses are much less. The estimated result also shows that emitted pollutants are concentrated on major arterials and suburb freeways, because more traffic volumes have increased on these type of roads.

The variable λ_{rp} reflects the relative relation of level of air pollution caused by vehicle emissions and endurable capacity, whose ideal value is 1, meaning a dynamic balance. As shown in Figure 4, the λ_{rp} of NO_x is about 1 and this means the emission of NO_x is within the scope of permissible. However, the indexes of HC and CO derived from branch and minor streets and suburb highways are both far beyond 1. The reasons may lie in the idling in traffic flow and frequent breaking, off the procedure.

Air quality evaluation within metropolitan area

Through the overall research and modeling result, it is found that the air quality of planning road network is satisfied. Since the average traveling speed on expressway and suburb freeway is both lower than expected (less than 70km/h), and the proportion of mileage traveling on these two types of roads (LOS of grade C) is respectively 27.16 and 25.34%, the nitrogen oxide emission is much more under this critical velocity.

Fortunately, the air of major arterial is of good quality, partially contributing to the higher level of service (grade B), under bigger proportion of traffic volume (26.47%). Moreover, the fine grade of atmosphere quality is mainly in minor arterials and this is mainly due to fewer traffic volume (less than 10%) and higher level of service (grade A or B).

The general air quality of intersection is unsatisfied, only 32.1% in good grade and 52.6% in medium or poor grade. It is detrimental for pollutants to diffuse across intersections due to surrounding buildings and complex traffic environment.

CONCLUSION

The MOBILE 5 model provides a promising tool, for the estimation of a regional motor vehicle emission inventory, along transportation planning process. A major benefit of using this proposed model capable of accounting for fuel specification and traffic patterns, is that the benefit of various control strategies and policies for vehicle pollutant emission may be explored using the model. The trends in this research indicate that the Xi'an Metropolitan Planning has been successful in generating a mobile source emission inventory that reflects the air quality phase in planning procedure, the need of reducing sulphur in fuels and introducing cleaner converters. This tendency is one possible explanation for the persistent resilience of the idea that transit and smart growth of transportation planning will solve urban pollution and congestion problems in China, in spite of the evidence that it does not work for most high density cities.

Further validation of the approach’s emission factors is planned in the Xi’an Metropolitan Rail Transit Project. However, the physical environment and human oriented transportation issue have been neglected for so long, just as in the Xi’an metropolitan area. Although it may be one of the most challenging issues to solve, it is apparent that the authority to implement the projects must be better understanding with their emphasis in improving emission standards and enforcing them strictly for the reduction of vehicle emission pollution. At this stage, the most pressing need is to make stronger connections between transportation and clean air protection that has still not been accepted by national metropolitan planning organizations, state transportation agencies, and local counties in China.

There are some important notes from this study, useful for the real application along transportation planning. It is very important, but very difficult, to choose and process the effective performance variables over a long period of time for trends. Thus, it is recommended that future research lies in exploring an intelligent data processing technique.

How can bridge transportation planning and clean air environment be re engineered to be conducted within a multi disciplinary set of perspectives (for example, energy use, traffic equity, community development)? There is a need for continued or more in-depth discussion in certain topics.

ACKNOWLEDGEMENTS

This project is supported by the Special Fund for the Basic Scientific Research of Central Colleges, Chang’an University (No. CHD2010JC019). Here, we also wish to thank editors and anonymous reviewers, for their detailed suggestions, precise comments and continuous helps, which lead to the belief that their dedication contributes to this research work and it would not have been feasible without their support.

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