Review Article

Essential Tasks to Reduce Environmental Pollution in Urban Transportation Networks

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Abstract

This article reviewed the impacts of vehicle emissions in urban transportation network, the existing strategies to reduce such transportation emissions, the complexity of urban transportation environment network, and the development of vehicle emission models. The vanguard research needs are also proposed in developing emission and air quality models and simulation, and emission-oriented transportation management strategies. This requires multidisciplinary research for the expectant counter-measures for urban transportation environmental network systems. Three essential tasks are proposed including: (1) improving urban air quality monitoring networks, (2) refining field-oriented emission models to better addressing real-time transportation activities, and (3) developing efficient and smart traffic control strategies to mitigate emission and improve air quality. These tasks would address the emerging issues associated with the sustainability and reliability of urban transportation environmental network, through interdisciplinary efforts represented by Science, Technology, Engineering, and Mathematics (STEM) disciplines, which would involve the knowledge of transportation, environment, mathematics, chemistry, physics, engineering technology, and computer science.

Environmental pollution in Urban Transportation Networks

In the past decades, extensive research efforts have been made in the area of urban environment striving to improve the urban air quality and address the challenges emerged from public health and the preservation of the entire ecological system. Transportation-related emissions are the dominant source of urban air pollution, and the second largest source of carbon dioxide (CO_2) emissions in the United States, which emitted approximately 27 percent of total U.S. greenhouse gas (GHG) emissions in 2015 (Figure 1). Transportation has also been the fastest-growing source of GHG emissions. From the pre-industrial era (i.e., ending about 1750) to 2015, concentrations of the greenhouse gases (CO_2, CH_4, and N_2O) have increased globally by 44 percent, 162 percent, and 21 percent, respectively [1].

The greenhouse gas (GHG) emissions primarily come from burning fossil fuel for all modes of transportation (vehicles, ships, trains, and planes) [2]. Petroleum based fuel took over 90 percent for transportation, including gasoline and diesel fuels. Most of the transportation related

GHG emissions are carbon dioxide (CO_2) emissions resulting from the combustion of petroleum-based fuels. More than 50 percent of transportation related GHG emissions are from passenger vehicles, light-duty trucks, sport utility vehicles, pickup trucks, and minivans. Other portions of GHG emissions are from heavy-duty trucks, commercial aircraft, ships, boats, trains, pipelines, and lubricants.

In addition to GHG emissions, transposition also makes contributions to important air pollutants (68.4 percent CO, 60 percent VOCs, 49.1 percent NO_x, 5.5 percent particulates and 1.3 percent SO_2) [3-5]. Moreover, NO_x is not only a primary air pollutant, but also accounted for the production of free radicals in troposphere, which can promptly react with VOCs and lead to a large variety of secondary air pollutants that could be much more hazardous to the public health than the primary air pollutants in urban environments [3-5]. Dirty air has been linked to cancer, asthma, stroke and heart disease, among other health issues. In UK, roughly 40,000 deaths each year can be attributable to outdoor air pollution [6,7]. Curbing vehicle emissions has become an increasingly important task in urban environment.

Monitoring and Strategies to Reduce Transportation Emissions

In response to these challenges, a range of emerging technologies are adopted to reduce transportation-related emissions on urban roadway networks. Existing traffic monitoring networks enable adaptive traffic
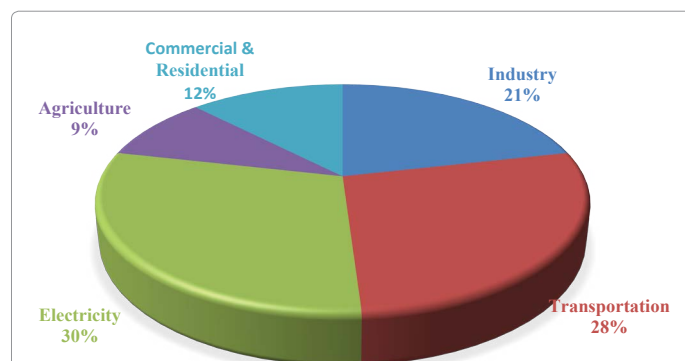

Figure 1. Total U.S. greenhouse gas emissions by economic sector in 2015 (reprinted from EPA, 2017).

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controls based on real time traffic information in order to dynamically optimize network performance to reduce delays and also possibly vehicle emissions [6]. The extension of these techniques to the simultaneous optimization of both traffic and emissions is highly desirable, which is however currently impossible because of the lack of real-time air quality data.

The air quality monitoring focused on measuring CO_2 and NO_x would provide sufficient assessment for the air quality in urban environments. This is due to the facts that the emissions of traffic-related primary air pollutants are always accompanied by the emission of CO_2 as a result of burning fossil fuels, and the NO_x is the sole source of the free radicals in the troposphere that are responsible for the generation of the secondary air pollutants. In general, there are two popular types of gas sensors, i.e., optical and electrochemical sensors. While the optical sensors can provide prompt signal responses for CO_2 detection, such a single-point unit would be quite costly due to the complexity of its design and operation, which requires reliable IR source and detector.

In addition, optical sensors for selective NO_x monitoring are not as matured yet as the CO_2 sensors. Regarding the electrochemical gas sensors, most of them are potentiometric type, which requires very simple equipment setting including an Ion Selective Electrode (ISE), a reference electrode (usually Ag/AgCl or saturated calomel electrode), and a potential-measuring device (a pH/millivolt meter that can read 0.2 mV resolution or better) (7). Electrochemical gas sensors usually exhibit a wide linear detection range (covering 4 orders of magnitude), are not affected by turbidity, are very flexible and very reliable in detecting different gas species, and are very simple and inexpensive. However, primarily due to the lack of intelligent materials design and engineering in the selective membrane, most of the commercial gas sensors tend to have relatively slow response time (taking several min or even longer), which is not ideal for our goals of building real-time air quality monitoring networks and correlating the air quality with traffic flows in this project.

The initiative of the Connected Vehicle (CV) program enables the development of the ecological transportation such as eco-driving, eco-signal, and eco-routing [8,9]. In August 2014, the U.S. National Highway Traffic Safety Administration (NHTSA) issued the Advance Notice of Proposed Rulemaking (ANPRM) on vehicle to vehicle (V2V) testing for light vehicles, and the test for heavy duty vehicles were scheduled in 2016. As there will be huge amount of real-time transportation and environmental data generated from the CV system, the dedicated Knowledge Discovery in Database (KDD) technology is essential for the urban transportation environmental network [9,10].

The electric vehicle (EV) technology is one of the very efficient solutions to the growing concern of urban transportation emissions. Yildiz et al. [11] suggests the implications of EV related policies until 2025. In order to embrace new technology, the United Kingdom government joined in July 2017 the other Europe countries like France to ban the sale of new diesel and petrol cars by 2040 [12]. On September 11, 2017, China as the home to the largest auto market, also mulls timetable to ban fossil fuel vehicles and promote the new energy vehicles (NEV), pledging to cut its carbon emissions per unit of GDP by 60-65 percent till 2030 from 2005 levels, and raise the share of non-fossil energy use in total consumption to about 20 percent [13]. Currently, the majority (95 percent) of electric cars are sold in 10 countries only: China, the U.S., Japan, Canada, Norway, the U.K., France, Germany, the Netherlands and Sweden [14]. The real reduction of air pollutions through the use of EV is actually depends on how the electricity is generated. The optimal use of energy storage systems (ESSs) has however, not been achieved,

with regard to their safety, size, cost, and overall management issues, which indicates the challenges that the EV systems are facing now [15].

Complex Urban Transportation Environmental Networks

By Boccalettia et al. [16], a network is called a complex one if it is often associated with a large heterogeneity in the capacity and intensity of the connections. Urban transportation environmental networks are such "complex networks" because they have the following features: (a) there are often unexpected incidents and emergencies on roadway networks causing extraordinary congestion, time delay, and thus vehicle emissions; (b) there exist nonlinear relationships between control strategies and traffic activities, and between traffic activities and vehicle emissions throughout the roadway networks as well as their influencing regions; (c) there is an ever-changing dynamic and network-wide equilibrium of travel time and vehicle emissions over the roadway networks that drives back and forth the system between ordered to chaotic systems, etc. Studies on complex networks should include not only the characterization of the topological properties of networks, but also their spatial aspects to characterize the demands and constraints within networks [16].

The connections within complex urban transportation environmental networks are first constrained by the Euclidean distances, which are associated with the network's statistical and topological properties. Further, the number of edges that can be connected to a single node (i.e., an intersection) is limited by the physical space to connect them such as the number of approaches in an intersection. Besides, the movements of traffic flow are also constrained by link (roadway segment) capacities, traffic control strategies, and other factors. All of these significantly impact traffic activities (e.g. speed, acceleration, and stops) and thus affect vehicle emissions and air quality in the region. Therefore, the network-wide transportation-related emissions are highly related to (a) roadway network topological properties, (b) traffic flow movements, and (c) network traffic control strategies. In other words, by optimizing network topological properties, and improving traffic flow movement through optimized control strategies, the regional transportation-related vehicle emissions within the urban transportation environmental network can be reduced.

To solve the air quality problems in urban transportation environmental networks requires the specific control of network-wide emissions from vehicles. In connection with real-world applications, the network controls refer to applied transportation strategies and approaches attempting to either optimize the essential network topological structure, or influence the driving behaviors of network users.

The solutions would embrace multidisciplinary knowledge such as environmental science and toxicology, transportation studies, mathematics, chemistry, physics, computer science, electronics, communications and information technologies. Techniques should include Operations Research (OR), Knowledge Discovery in Database (KDD), computational algorithms, probability analysis, statistics, digital signal processing, and even the adaptive and post-modern control theory. The optimized tools would advance the implementation of air quality monitoring, emission modeling, and pollution mitigations within urban transportation environmental networks.

Vehicle Emission Model Development

Vehicle emission models are the key in developing network control

strategies for complex urban transportation environmental networks, which can bridge traffic flows to air quality. The development of suitable emission models has been a fast evolving and demanding research area, which involves complicated facets of data [17], mathematical [18] and computational issues [19,20]. The most popular macroscopic level emission models include MOBILE, EMFAC [21], COPERT [22] and IVE [23], which are widely used to assess numerous air quality planning functions but request only average speed as the indication of traffic conditions. This input requirement of average speed corresponds to a specific series of pre-defined driving cycles used in an in-laboratory environment [24]. These models, however, are insensitive to the distribution of vehicles' instantaneous modal events, which are needed when network control strategies are to be developed. To address this deficiency, various microscopic level modal emission models have been developed [17,25,26]. The new generation of emission modeling system MOVES2010 integrated both macroscopic and microscopic level modeling concepts using a newly adopted parameter called vehicle specific power (VSP) and its distribution models [27]. On another front, since the emergence of remote emission sensing (RES) and portable emission measurement systems (PEMS) technologies in late 1990s, various research efforts have been made to develop advanced emission models based on either RES [28] or PEMS [29-31]. These efforts have significantly advanced the state-of-the-art in the way that emissions are modeled. However, due to the mathematical and computational complexity in dealing with the massive real-world second-by-second data, the research gap still exists in terms of determining comprehensive emission characteristics of idling, heavy-diesel vehicles, and under various traffic network and management scenarios. It is our belief that both macroscopic and microscopic level emission models are needed but should be further advanced in order for them to be adopted in developing various control strategies for complex urban transportation environmental networks.

The network control models are needed in developing strategies for maintaining the urban network in an environmentally optimal state. The network control models for urban networks involve the development of traffic flow theories and various transportation network optimization models [32], with an objective to mitigate vehicle emissions. In recent years, transportation network control and modeling has been one of the most demanding and attractive research fields that have experienced substantial advancement in both theory and applications [33]. However, the research effort made particularly for application to optimizing environment has not made too much progress. In the early years of this type of research, Yu et al. [34] proposed traffic optimization models and algorithms based on a generalized cost function that includes both travel-time variables and environmental variables. In the recent decade, numerous research results have demonstrated that practical transportation management strategies and intelligent transportation systems have significant impacts on network vehicle pollutants and GHG emissions, such as signal coordination [35], electronic toll collection (ETC) systems [36], roundabout operations [37,38], and public transport priority strategies [39], thus such controls are successful in reducing the network vehicle emissions. However, most of existing studies were conducted by using either traffic simulation models [40] or portable emission measurement systems [19] for a specific roadway segment (the link) with a particular control strategy. There is still a lack of network control models that can effectively associate network-wide traffic control or management strategies with the total network vehicle emissions and the resulting air quality measurements. The newly developed Vehicle Specific Power (VSP) based modeling approaches have demonstrated the capabilities and potential of modeling network

transportation management scenarios and the resulting emissions in a large-scale network [41]. VSP (kW/ton) is the instantaneous tractive power per unit vehicle mass, as illustrated in Equation (1), which can be derived from the instantaneous vehicle speed and acceleration [42].

$$VSP = \frac{\frac{d}{dt}(KE+PE) + F_{rolling}v + \frac{1}{2}\rho_a C_D A(v+v_w)^2 v}{m} \tag{1}$$

where KE and PE are the kinetic and potential energies of the vehicle, $F_{rolling}v$ is the rolling resistance, $\frac{1}{2}\rho_a C_D A(v+v_w)^2 v$ is the aerodynamic drag, and v is the vehicle speed.

Furthermore, the increased availability of floating car data (FCD) in urban transportation networks presents a unique opportunity to develop integrated vehicle emission and network control models [43].

Essential Tasks to Reduce Vehicle Exhaust Emissions

While many models and theories are either directly or indirectly associated with the modeling and control of urban transportation environmental networks, there are three essential tasks to reduce vehicle exhaust emissions: (1) improving urban air quality monitoring networks, (2) refining field-oriented emission models to better addressing real-time transportation activities, and (3) developing efficient and smart traffic control strategies to mitigate emission and improve air quality.

The development of an optimal air quality monitoring system in a network is necessary to measure spatially distributed air quality indexes in order to provide critical assessment of the effectiveness and validity of emission models and network control strategies. The development of traffic activity-incorporated emission models is to provide suitable emission predictions, through maximizing the use of on-road emission measurements, real-time vehicle activity information, Geographical Information Systems (GIS), and Global Positioning System (GPS). Traffic control strategies are aiming to mitigate the GHG and pollutant emissions from vehicles and improve air quality on real-time basis via optimizing the network structure with environmental constrains and developing relevant dynamic transportation management strategies. These will require the multidisciplinary support such as environmental toxicology, KDD, Operations Research (OR), computational algorithms, probability analysis, statistics, digital signal processing techniques, and adaptive and post-modern control theory.

In order to develop and implement vehicle emission models and real-time intelligent network control methods to reduce GHG and pollutant emissions, thereby improving air quality in the complex urban transportation environmental networks, the following steps are essential:

- **Developing comprehensive transportation and environmental data bank:** This includes collecting large amount of real-time transportation activity data (e.g. volume, speed, acceleration, occupancy) as well as GPS data, and the resulted VSP distribution from various types of vehicle conditions in urban areas. This will construct a VSP distribution data bank for the use in developing vehicle emission models.

- **Developing traffic activity based vehicle emission models for urban networks:** This is to develop VSP-based vehicle emission models for urban networks. The models to be developed in this task will take the full advantage of the urban transportation environmental data bank.

- **Refining vehicle emission dispersion model by incorporating the air quality monitoring data:** This is to develop vehicle emission dispersion model. The vehicle emission dispersion model should incorporate the optimized geographical distribution of air quality monitors in urban environment networks, and the gas sensing function that is integrated into the network infrastructure for monitoring traffic flows. The collected data bank such as the emission data, VSP distribution data, and real-time traffic activity data, as well as the established emission models could also be used in developing the vehicle emission dispersion model. Such emission dispersion model is essential in understanding the impacts of vehicle activities and the resulted emissions to the entire air quality.

- **Developing models that optimize network topological structures to improve urban air quality:** This is to develop models to optimize network topological structures so as to mitigate GHG and pollutant emissions for urban networks and improve air quality. The objective to optimize the network topological structures is to determine the optimal topology and appropriate link and node parameters of the network which minimize the total network emissions with a given traffic demand. The network topological structures that can be optimized include network framework and layout, link directions and capacities and nodes connections and turning rules. This will thus develop theoretical and applied models for optimizing the network topological structure with environmental and economic constrains so as to reducing GHG and pollutant emissions.

- **Developing models that optimize traffic controls to improve urban air quality:** Since network transportation problem is actually a demand vs. supply problem, the optimization models of network transportation management strategies could thus include two possibilities. One is to optimize the network supply in which the traffic facilities like roads and signals are coordinated to provide an optimal service, thus influencing vehicles' driving behaviors such that GHG and pollutant emissions are reduced over the network with given traffic demands. Another one is to optimize the network demand through the environment-oriented dynamic traffic assignment and navigation models, which change vehicles' route choices. Many existing studies have provided that transportation management strategies like signal synchronization [44,45] and Intelligent Transportation System (ITS) technologies (e.g. advanced toll collection technology) are able to reduce emissions effectively with possibly a slight trade-off of travel times.

- **Developing simulation tools and models incorporating real-time traffic data to support decision-making.** From the systems engineering perspective, the emission dispersion model for air quality prediction gives the feedback to the network traffic control model and may provide alternative control objectives by identifying the vulnerable locations, such as residential or school areas, where the network control model can effectively reduce the emissions by various network traffic control strategies. Taking the advantage of the dynamic nature of the network control model by integrating the multi-level emission model, real-time traffic and air quality data, and the air quality prediction model, the research team will develop integrated simulation tools that provide an effective approach to support decision-making with the capability to maintain the urban network in environmentally optimal state.

Summary

This article summarized the serious urban transportation related environmental problems, as well as the strategies to reduce their adverse impacts on public health. Based on the analyses of the complexity of urban transportation environmental network, and the development of vehicle emission models, three essential tasks are proposed including: (1) improving urban air quality monitoring networks, (2) refining field-oriented emission models to better addressing real-time transportation activities, and (3) developing efficient and smart traffic control strategies to mitigate emission and improve air quality. These tasks would address the emerging issues associated with the sustainability and reliability of urban transportation environmental network, through interdisciplinary efforts represented by Science, Technology, Engineering, and Mathematics (STEM) disciplines, which would involve the knowledge of transportation, environment, mathematics, chemistry, physics, engineering technology and computer science.

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