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Traffic control for air quality management and congestion mitigation in complex urban vehicular tunnels

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ABSTRACT

Urban vehicular tunnels, generally connected to the ground road network via on- and off-ramps, are geometrically complex with multiple entrances and exits. They are designed with in-tunnel ventilation systems and multiple pollutant discharge points for air quality control. In addition to traditional mechanical ventilation tools, traffic control has been recognized as a useful approach for air quality management and congestion mitigation in tunnels. This study aims to develop quantitative system analytic models for optimal traffic control considering both traffic and air quality improvement goals for complex urban tunnels. Moving vehicles inside the tunnel are not only the emission source, but also a key factor affecting aerodynamics in the tunnel. For a control cycle, steady-state traffic flow, aerodynamics, and pollutant dispersion models are established by tunnel segment, in which the air flow speed under a given mechanical ventilation scheme is mainly affected by tunnel traffic. An optimal time-of-day ramp traffic metering and mainline inlet traffic control model is proposed using nonlinear programming (NP) techniques to meet multiple air quality/emission as well as traffic throughput requirements. In-tunnel air quality requirements and emission limits at discharge points are modeled as nonlinear constraints for traffic control decisions. For illustration, the model was applied to an urban tunnel in Hangzhou, China for optimal traffic control to (1) assist the tunnel ventilation to meet environmental requirements under varying traffic demand; (2) provide a mechanism for tunnel air pollution control when fan operation alone is not enough during peak traffic period; and (3) maintain traffic efficiency by preventing recurrent congestion in the tunnel. The proposed tunnel traffic control method proves a useful complementary strategy to traditional mechanical tunnel ventilation for the improvement of urban tunnel transportation environment.

1. Introduction

1.1. Background

Epidemiological and toxicological studies worldwide have suggested strong association between human exposure to traffic-related air pollution and a range of adverse respiratory and cardiovascular health effects (Hoek et al., 2013; Raaschou et al., 2012). Increasing efforts are made to reduce air quality impacts of transportation by incorporating the

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Notations

n	number of segments of the mainline tunnel
I	set of mainline segments i that connect to ramps ($i \in I$)
I_C	set of mainline segments that has a converging on-ramp ($i \in I_C$)
I_D	set of mainline segments that has a diverging off-ramp ($i \in I_D$)
v_j	jet speed of the ventilating jet fans inside the tunnel (m/s)
Q'_i	air flow rate at upper vent at the end of tunnel segment i if any (m^3/s)
$c_{max\ i}$	maximum pollutant concentration in tunnel segment i (mg/m^3)
Q_i^c	discharge rate of gas pollutant c at discharge point in segment i if any (mg/s)
v_i	air flow speed in tunnel segment i (m/s)
ρ_i	traffic density in tunnel segment i (veh/m)
v_{vi}	average vehicle speed in tunnel segment i (s/m)
L_i	length of tunnel segment i (m)
q_i	traffic volume in tunnel segment i (veh/s)
r_i/s_i	the on-ramp/off-ramp traffic volumes converging to/diverging from mainline tunnel segment i if any (veh/s)
α_{ji}	the fraction of traffic that initially enters the tunnel via on-ramp at mainline segment j and stays into pass through mainline segment i
β_i	the fraction of vehicles that enter from mainline inlet and stay into pass through mainline segment i
$v_{free\ i}$	the free-flow traffic speed in tunnel segment i (m/s)
$\rho_{max\ i}$	the jam density for tunnel segment i (veh/m/lane)
T	the cycle period of the time-of-day control (s)
l_i	average vehicle queue length at origin of tunnel segment i, $i = 1$ or $(i - n) \in I_C$ (veh)
σ_k	the linearization coefficient representing the marginal contribution of q_1 to v_k
ϖ_{ki}	the linearization coefficient representing the marginal contribution of r_i to v_k
v_k^*	the base airflow velocity in tunnel segment k with no traffic (m/s)
x_i	the distance from the entrance of segment i to a point in segment i (m)
c_i	the pollutant concentration distribution in segment i (mg/m^3)
k_x	the diffusion coefficient along the tunnel ventilation direction x (m^2/s)
e_i	the pollutant emission rate from the traffic in tunnel segment i (mg/m^3/s)
f_i	the average vehicle emission factor of traffic in segment i (g/km/veh)
A_i	the cross-sectional area of tunnel segment i (m^2)
c_{0i}	the pollutant concentration at the entrance of tunnel segment i (mg/m^3)

environmental dimension into roadway design (Baldauf et al., 2009) and traffic control strategies such as intelligent transportation systems (ITS) (Zegeye et al., 2009). Urban vehicular tunnel systems (e.g., the over 48 km long tunnel networks in the underground transforming project of M-30 motorway in Madrid, Spain), for instance, have been widely adopted to help mitigate congestion on ground road networks and improve air quality nearby. How to improve air quality inside tunnels and control emissions at tunnel discharge points, in the meantime, has also raised new problems and challenges (e.g., Chen, 2011).

Urban vehicular tunnels are often built in central business districts to help ease space competition among concentrated economic activities while meeting the heavy travel demand under complex traffic organization. Some urban tunnels have complex "mainline and branches" configurations, such as slip-roads or on- and off-ramps connecting tunnel traffic to the ground road network (Meng et al., 2011). So "complex" here means complex configurations with multiple entry and exit ramps. The air flow in the ramps affects the air flow in the mainline tunnel and thus leads to complicated aerodynamics in the whole tunnel (Chen, 2011). Air quality inside the tunnel is certainly required to meet the health-based standard. To alleviate the negative impact of tunnel traffic emission on the public or residential environment near the tunnel outlets, tunnel emissions are discharged at distributed points such as the tunnel upper vents (Tan, 2013). The emission rates at these discharge points must also meet the corresponding emission requirements. As such, it is desirable to design and implement effective air quality and pollutant discharge control methods that can be adapted to complex tunnel geometry and multiple emission standards. Tunnel ventilation with jet fans has been the major tool for doing this (Tan et al., submitted for publication).

In addition to tunnel ventilation, which is passive in nature, proactive traffic control measures targeting both traffic and environment goals have become a promising area to explore. Firstly, since tunnel traffic is the dominant emission source, reducing congestion and maintaining smooth traffic speed profiles in the tunnel via ramp metering can help decrease pollutant emission rate in the first place. The overall emission reduction benefits of ramp metering that smoothes traffic and reduces bottlenecks on freeway systems are documented in many studies (Bae et al., 2012; Thornton et al., 2000; Sisiopiku et al. 2005). Secondly, due to either the outdated tunnel ventilation system or the underestimation of traffic volume in ventilation design, real tunnel traffic and pollutant concentrations (especially during peak hours) could be well beyond the