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Modelling pollution dynamics of longitudinally ventilated road tunnels

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ABSTRACT

This paper develops a mathematical model in various forms to describe the dynamic response between vehicle exhaust emissions, air flow and the resulting pollutant concentrations in a longitudinally ventilated tunnel. Starting with the well-known "advection-diffusion" partial differential equation, several innovations in analysis are presented to finally create a simple estimator usable in predictive control algorithms. These innovations include;

i) a variable time step numerical method of solution,
ii) a discrete time (z- domain) model of the system,
iii) a linear analytical solution for harmonic inputs which leads to a frequency domain description of the system dynamics for small perturbations about a mean operating condition,
iv) a continuous time (s- domain) transfer function model, derived from the frequency domain analysis.

1. Introduction

Road tunnels are often ventilated longitudinally. Fresh air Q is drawn through the upstream portal and flows along the tunnel length. Fig. 1 shows a section of tunnel, length L. Vehicle generated pollutants are diluted with the incoming air from the entry portal. Concentration of vehicle exhaust pollutants gradually increases along the length of the tunnel. The ultimate pollution level is determined by the relative rates of air flow and pollutant emissions. Instantaneous pollution concentration at a distance x from the portal is designated $C(x, t)$.

If the traffic is free flowing, the tunnel may be adequately ventilated solely by air flow Q induced by vehicle movement. However, during congested or stopped traffic the fresh air inflow may fall, causing pollution levels (principally carbon monoxide, oxides of nitrogen and particulates) to approach the upper acceptable limit. In these conditions jet fans provide thrust to augment the vehicle "piston effect".

Jet fans are axial fans which draw air from the tunnel and pass it through an impeller casing. Air from the fan is ejected at high speed V_j into the tunnel air mass which moves at a lower speed U. Thrust is imparted to the tunnel air mass through a transfer of momentum from the air jet to the tunnel air.

The decision as to when and what extent jet fans are used, is taken on the basis of in-tunnel pollution concentrations measured at the end of the tunnel, where pollutant level is highest. Pre-emptive jet fan actuation, based on traffic flow and modelled predictions of future pollutant levels, is required to achieve control actions which are both timely and energy efficient.

Two separate dynamic lags (in series) exist between the actuation of jet fans and the change in tunnel pollution level. The first lag, between the jet fan thrust and the change in tunnel air flow results from the fact that a large mass of tunnel air must be accelerated against the tunnel's aerodynamic drag. A further, much longer lived dynamic response occurs between the tailpipe emissions, change in tunnel air flow and the propagation of the pollutants down the tunnel. This paper is concerned with the modelling of the later response.

Jang and Chen (2000, 2002) give a detailed account of the interaction between traffic, airflow and resulting pollution levels in a longitudinally ventilated tunnel. The work includes a description of experimental procedures, data collected and the means by which the system parameters may be evaluated.

A variety of modelling techniques have been used to describe the pollution dynamics of road tunnels including;.

- finite difference approximations of partial differential equations (pde); (Bellasio, 1997; Ferkl and Meinsma, 2007)
- fuzzy logic; Chen et al. (1998), Karakas E. (2003), Brogdan et al. (2008), or
- neural network; Cha et al. (2006),

The aim of this paper is to develop a mathematical model in several

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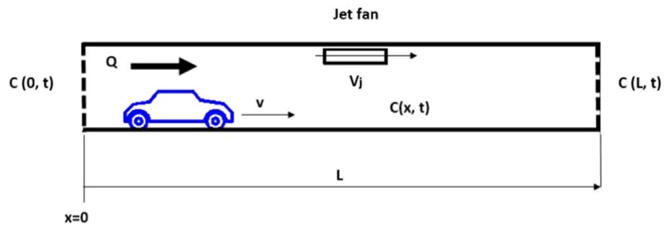

Fig. 1. Longitudinal ventilation.

forms; finite element (time domain), discrete time (z-domain), and transfer function (*s*-domain) forms, to simply describe the dynamic response between the tunnel air flow or the pollution generation rate and the resulting pollutant concentrations $C(x, t)$ in order to create a simple estimator which can be used for predictive control of tunnel pollution levels.

2. Advection-diffusion equation

In the following analysis, the assumption is made that vehicle exhaust pollutants are fully mixed into the air stream through turbulence resulting from vehicle motion and roughness of the tunnel walls.

Pollutants are predominantly transported down the tunnel with the air flow (advection) with some diffusion also occurring. The final assumptions used are that; i) because changes in air pressure are small, air flow is incompressible and ii) the air temperature is constant throughout the length of the tunnel.

With these approximations, solution of a second order partial differential equation gives the time-space distribution of pollutant concentration $C(x, t)$ a distance x from the start of the test section at time t;

$$\frac{\partial C(x, t)}{\partial t} + \frac{\partial U(x, t)C(x, t)}{\partial x} = D(v)\frac{\partial^2 C(x, t)}{\partial x^2} + \frac{p(x, v, t)}{A(x)} \tag{1}$$

- $Q(t)$ is the longitudinal airflow down a tunnel. Airflow is determined by the combination of forces acting on the tunnel air mass. These forces are due to; vehicle motion, differential portal wind pressure and jet fans.
- $A(x)$ is the cross sectional area of the tunnel. In most road tunnels the cross sectional area is constant over the majority of the total length. Changes in cross section are localised to merge and de-merge sections as well as on and off-ramps.
- $U(x, t) = \frac{Q(t)}{A(x)}$ is the tunnel airspeed. Time varying airspeed inputs are not widely discussed in the literature. Scullen (1992) and Noye (2000) have published research in this area, however not in the areas not relevant to this paper.
- $D(f, r, U, v)$ is the turbulent diffusion coefficient and is a function of tunnel roughness with friction factor f and vehicle speed v. For turbulent flow in a pipe of radius r, Taylor (1954) determined the diffusion coefficient $D = 10.1\ r\ U\sqrt{\frac{f}{8}}$ [m^2/s]. However, the diffusion coefficient in a road tunnel may well exceed these values due to the turbulent mixing of pollutants by fast moving vehicles.
- Pollution generation rate per unit length $p(x, v, t)$ varies along the length of the tunnel due to changes in road gradient. Vehicle density and hence pollution generation is also a function of traffic speed. Traffic mix (vehicle type, age, size and fuel type) is time dependent. For a fixed traffic fleet composition, constant gradient roadway, with traffic flowing at constant speed; the average pollution generation rate is essentially constant. The PIARC World Road Association Technical Committee Report [2012] is an industry accepted guideline which tabulates typical pollution generation rates for various vehicle classes, traffic speeds and road gradients.
- The initial boundary condition may be fixed or variable. Where clean air flows into the entry of the test section (for example at an entry portal) the boundary condition $C(0, t) = 0$ over the time range $0 < t < \infty$ applies.
- A time varying initial boundary condition results in a pollution profile (smeared by diffusion) passing down the tunnel. This profile appears at the end of the test section after a transport delay. This pollution profile is superimposed onto that created by vehicle exhaust emissions created within the test section.
- When diffusion is considered, a second boundary condition exists at the end of the tunnel. If the ambient air is perfectly clean, the boundary condition $C(L, t) = 0$ over the time range $0 < t < \infty$ applies.

3. Steady state solution

Eq. (1) can be solved for a steady state solution, assuming zero initial conditions at the entry portal;

$$C(x, \infty) = \frac{pL}{Q}\left\{\frac{x}{L} - \left(1 + \frac{C(L, \infty)Q}{pL}\right)\left[\frac{1 - \exp(\frac{Qx}{AD})}{1 - \exp(\frac{QL}{AD})}\right]\right\} \tag{2}$$

For all realistic cases; $\exp\left(\frac{QL}{AD}\right) >> 1$. Hence, excluding the zone very close to the exit portal, the steady state solution is unaffected by either diffusion or end conditions and;

$$C(x, \infty) \approx \frac{px}{Q} \tag{3}$$

4. Finite element model

Ewing and Wang (2001) and Bouche et al. (2003) describe the various numerical techniques by which the advection-diffusion has been solved. Eq. (1) is based on the assumption that the flow is viewed from a fixed (*Eulerian*) frame of reference. The alternative (*Lagrangian)* approach to solving this problem is to set up the equation relative to a frame of reference which moves with the flow; effectively decoupling advection and diffusion.

In numerical solutions the *Courant* number $Cr = \frac{U\Delta t}{\Delta x}$ represents the portion of the cell that the pollutant stream will traverse by advection in one time-step. *Peclet* number $Pe = \frac{U\Delta x}{D}$ is the ratio of the rate of advection to the rate of diffusion. Pure advection occurs when $Pe = \infty$.

Price et al. (1966) show that for Eulerian, constant time step methods, the space centred formulation for approximating the second derivative leads to stable (but oscillatory) solutions in time only when

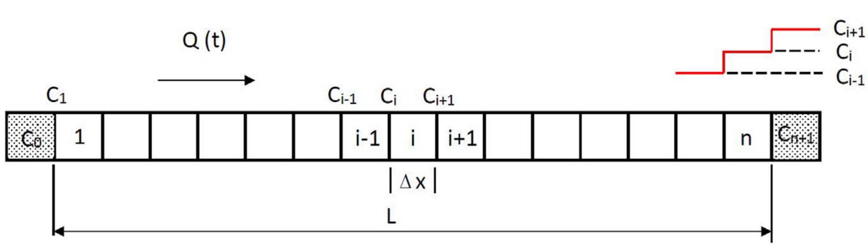

Fig. 2. Finite element model of the tunnel, divided into equal volume elements.

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