Multipoint source method in air pollution modelling of cold start emission

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The paper presents a new method of air pollution modelling on a micro scale. For estimation of concentration of car exhaust pollutants, each car is treated as an instantaneous moving emission source. This approach enables us to model time and spatial changes of emission, especially during cold and cool start of an engine. These stages of engine work are a source of significant pollution concentration in urban areas. In this work, two models are proposed: one for the estimation of emission after cold start of the engine and another for the prediction of pollutant concentration. The first model (defined for individual exhaust gas pollutants) enables us to calculate the emission as a function of time after the cold or cool start, ambient temperature and average speed of motion. This model uses the HBEFA database. The second mathematical model is developed in order to calculate the pollutant dispersion and concentrations. The finite volume method is applied to discretise the set of partial differential equations describing wind flow and pollutant dispersion in the domain considered. Models presented in this paper can be called short-term models on a small spatial scale. The results of numerical simulation of pollutant emission and dispersion are also presented.

Keywords: engine, cold start, exhaust emission, pollution, modelling

1. Introduction

Significant emission from traffic occurs in many urban areas and causes problems with air quality. A lot of mathematical methods can be used for predicting pollutant concentrations; they differ considerably in their degree of complexity. Modelling of emission and dispersion of exhaust gases of moving vehicles is particularly complex since phenomena occurring on micro and macro levels, in space and time, are here interconnected. But it is essential to have a fairly precise evaluation of pollutant concentrations in the immediate and broader vicinity of roads and car parks. For this reason, most models of pollutant dispersion contain simplifying assumptions resulting mainly from the purpose of the models. Many studies ranging from simple analytical or empirical models to complex numerical high-order models have been reported in the literature. Mathematical models which are used to predict or evaluate air pollutant concentration near roadways are either Gaussian models, i.e., GFLSM [1], CALINE 4 [2], or numerical ones (ROADWAY-2 [3]) or stochastic. Numerous models have been formulated to predict dispersion phenomena near urban intersections where emission due to queuing, acceleration and deceleration is higher compared to single roads. Some examples of models which can be used for traffic junctions are presented in [4, 5]. Another type of dispersion models of vehicular exhaust emission is represented by models that are used for the street canyon problem Sini et al. [6] or Operational Street Pollution Model (OSPM) [7]. Despite a wide range of dispersion models, some problems are not sufficiently investigated. One of them is peak concentration of car exhaust pollutants in car parks, both above- and below-ground. In order to predict air quality in car parks, especially in underground car parks, a numerical computational fluid dynamics (CFD) model is required. It is known that a large amount of vehicle cold and cool starts in these areas is a source of significant emissions, and in some countries the concentration of carbon monoxide in closed parking areas is required to be lower than the legally prescribed limit value. On the other hand, dispersion modelling indicates that the exposure level of people living nearby can be significant [8]. Thus a numerical model for the investigation of pollutant dispersion phenomena in car parks with an appropriate emission model is proposed.

The paper discusses a dispersion model solely designed to evaluate the impact of traffic on the environment on a micro scale. Emphasis is laid on problems relating to vehicle pollutant emission and dispersion caused by cold start. The finite volume method is used to discretise the equation describing the process of pollutant dispersion, the continuity equation, and the Navier–Stokes equations determining field of air speed. Boundary conditions are taken into account from a meteorological pre-processor based on relationships resulting from the Monin–Obukhov theory. Turbulence is taken into account by using the k-ε model.

2. Description of mathematical models used

Modelling of car exhaust pollution requires a complex model. A multipoint model which allows us to solve problems regarding dispersion of pollutants produced by vehicles include the following: model of exhaust emission for different ambient and motion conditions, model of air flow in complex terrains (e.g., street canyon, single buildings) and model of pollutant transport taking into account...
advection and turbulent diffusion processes. All elements are important in micro-scale investigations, and are discussed below.

In the model local complex thermodynamic phenomena accompanying fuel combustion (change in density and temperature of exhaust gases) are omitted. This means that the equation of energy balance is not included. It is also assumed that the medium under investigation is an incompressible fluid, which results in a simpler form of equations of continuity.

2.1. Cold start emission modelling

In order to exactly define the amount of exhaust gas pollutants emitted by vehicle engines, it is necessary to specify two sets of data: data concerning conditions of vehicle motion and data concerning exhaust gas pollutants produced under those conditions. Vehicles differ in features such as type of engine, emission standards met by the vehicle, and engine capacity. These parameters also have a decisive effect on the amount of exhaust emissions, which makes it necessary to gather and use sets of data containing a very large quantity of data and parameters. As a result, defining emissions as a function of all these parameters presents a considerable problem.

Since it is not possible to carry out tests for the whole car population and for different conditions of vehicle motion, interpolation and extrapolation methods related to the existing database containing experimental results have to be used to estimate emission. Due to lack of data on emission as a function of vehicle speed and acceleration, an approach in which emission depends only on average vehicle speed is often used. This average emission factor method is a widespread method of estimating traffic emissions and is based on emission values generated under various conditions of vehicle motion [9,10]. Because average speed is the only decisive parameter used in estimating emission values for a given category of vehicles, vehicle dynamics is only indirectly taken into account.

The average speed method of estimating exhaust emissions from vehicle engines can also be applied to model emission of exhaust gases in the initial start phase, which is mainly determined by the thermal state of the engine, trip length and mean vehicle speed during the heating up period [11,12]. The concept of cold start (phase of cold work) covers both the ‘start’ of an engine, which has an ambient temperature at this time, and its heating up until working temperature of engine and catalyst is reached. The method of utilising cars in Europe is chiefly characterised by short trips with a series of engine starts since cars are mainly used under urban conditions. Hence a large percentage of starts are with a cold or insufficiently heated engine. Since the phase of engine heating has a significant influence on pollutant emissions, this has to be taken into account in the model of emission [13–16]. The dependence of exhaust emissions on the thermal state of the engine is most obvious for spark ignition cars. For this reason, such cars are the basic category where thermal state is included in emission modelling. Thermal state can also be taken into consideration when modelling emissions from compression ignition cars.

Besides the type of vehicle (engine type, engine capacity, etc.), the main parameters for a given vehicle category which influence the total amount of additional cold start emission are as follows: engine and catalyst temperature, ambient temperature, and the driving pattern following engine start. The influence of those parameters on emission was the subject of several reports [17–21]. Saxer et al. [17] and Ludykar et al. [18] reported measurement data obtained for cold start emission of some exhaust gas components that are dependent on ambient temperature. The results clearly show that emission increased when the ambient temperature dropped, and this relation is not uniform for analysed exhaust components. Heeb et al. [19] disclosed results which showed how cold distance influenced methane, benzene and alkyl benzene emission, according to different vehicle technology (Euro-0 to Euro-3) for vehicles with spark ignition engines. Further data that show the time dependency of additional cold start emission (for different ambient temperature, including vehicles with compression ignition engines) are presented in [20]. In their report, Weilenmann et al. [21] showed an impact of driving pattern (cycle) on total additional emission. Their results also showed the influence of vehicle technology on emission after cold start.

The problem in estimating pollutant emission from vehicles during cold start and motion while engine and catalyst are heating up has been variously reflected in computational methods. Methodology based on the average emission factor includes algorithms which enable cold start and heating engine to be taken into account in calculations. Of interest in this regard is the methodology in the COPERT program, HBEFA database and the approach of Institut National de Recherche sur les Transports et leur Sécurité (INRETS) [22–24]. The emission caused by cold start and motion with an unheated engine is defined as additional average emission factor during the cold drive cycle, cold/heat emission ratio or total emissions during the cold drive cycle.

For the multipoint model presented in this paper, the above definitions of emission after cold start are insufficient, because additional emissions on a micro scale have to be known with respect to time after the engine start (in the model, cars are moving in time). In order to obtain approximation of additional emission for a given vehicle category in the multi-point model, one ought to consider some simplifications. Hence, we assume only pure cold start condition, which means that engine and catalyst temperature before engine start is equal to the ambient temperature. This assumption does not exclude the possibility of modelling emission after cool starts (not equal ambient and engine temperature), because emission under that condition can be described by the correlation coefficient (see HBEFA database [22]) defined on the basis of emission in