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Urban Air Quality Monitoring and Modelling: A Comprehensive Review

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Abstract: *Road transport is one of the dominant contributors to carbon monoxide (CO) pollution in urban areas. Exposure to CO poses serious health risks, and because CO behaves as a relatively inert pollutant near roadways, it is frequently used as a tracer for understanding the dispersion of traffic-related emissions. The increasing scale and severity of traffic-induced air pollution has prompted extensive research focused on monitoring and modelling pollutant concentrations in urban roadside environments. This review presents a comprehensive synthesis of air quality monitoring techniques and dispersion modelling approaches used in urban settings. Special attention is given to CO dispersion in near-road microenvironments, including road corridors bounded by high-rise buildings that form street canyons, as well as signalized intersections where congestion and idling are prevalent. The review highlights the evolution, applicability, and limitations of various air quality models and discusses their relevance for urban planning and pollution mitigation strategies.*
Keywords: *Urban traffic, air pollution, carbon monoxide, air quality monitoring, dispersion modelling*

I. Introduction

Motor vehicles are a major source of carbon monoxide (CO) emissions in urban environments, particularly gasoline-powered light-duty vehicles. Rapid urbanization and increased vehicle ownership have made traffic emissions a dominant contributor to urban air pollution, resulting in adverse public health outcomes. Numerous studies have identified road transport as a primary pollution source in cities, with strong associations between traffic-related pollutants and respiratory as well as cardiovascular illnesses.

Carbon monoxide is produced through incomplete combustion of fuel and is characteristic of mobile sources. Because it undergoes minimal chemical transformation in near-road environments, CO serves as a useful indicator for assessing the dispersion and transport of primary vehicular emissions. Over the past few decades, extensive research has focused on measuring and predicting CO concentrations in urban areas, especially near busy roads and intersections. Given the growing magnitude of the problem, it is essential to critically review existing air quality monitoring methods and modelling frameworks.

This review provides an overview of urban air quality, summarizes key monitoring studies, examines major dispersion models, and evaluates their suitability for different urban scenarios. Particular emphasis is placed on modelling CO concentrations in complex microenvironments such as street canyons and intersections, where pollutant accumulation is often severe.

II. Urban Air Quality

Urban air pollution is composed of a mixture of gaseous and particulate contaminants originating primarily from combustion processes. Suspended particulate matter (PM) consists of solid particles and liquid droplets that vary in size and composition. Fine particles generated by combustion activities are of particular concern because they can penetrate deep into the respiratory system, bypassing the body's natural defense mechanisms. Health impacts associated with PM exposure depend on particle size, chemical composition, and duration of exposure.

Carbon monoxide is a localized pollutant, with elevated concentrations occurring primarily near emission sources such as busy roads. As a colorless and odorless gas, CO poses significant health risks by binding with hemoglobin in the blood and reducing oxygen delivery to vital organs. High exposure levels can aggravate cardiovascular conditions, impair neurological functions, and reduce exercise tolerance.

Ozone is a secondary pollutant formed through photochemical reactions involving nitrogen oxides (NOx) and volatile organic compounds under sunlight. Although not directly emitted, ozone is a powerful respiratory irritant that damages lung tissue and exacerbates asthma and bronchitis. Nitrogen oxides themselves originate mainly from fuel combustion and contribute to smog formation, acid rain, and reduced atmospheric visibility.

Sulfur dioxide (SO_2), primarily emitted from fossil fuel combustion, undergoes atmospheric oxidation to form secondary pollutants such as sulfur trioxide and sulfate aerosols. Diesel exhaust is another critical concern, containing numerous toxic gases and fine particles. Diesel particulate matter is particularly hazardous due to its small size and carcinogenic properties, and mobile sources remain the largest contributors to diesel emissions in urban areas.

III. Air Quality Monitoring Studies

Field measurements conducted near major roadways consistently reveal elevated concentrations of traffic-related pollutants, including CO, NOx, PM_{10}, $PM_{2.5}$, ultrafine particles, black carbon, polycyclic aromatic hydrocarbons, and benzene. These concentrations are often significantly higher than background urban levels. Monitoring studies demonstrate that pollutant levels exhibit strong spatial and temporal variability, influenced by traffic volume, meteorological conditions, and road geometry.

Diurnal patterns are commonly observed, with peak CO concentrations occurring during morning and evening rush hours. Spatial variations are also pronounced, with intersections and congested road segments exhibiting the highest pollutant loads. Research has shown that pollution levels decrease with increasing distance from roadways, although this gradient depends on wind speed and direction.

Comparisons between fixed-site monitoring stations and passive sampling techniques have generally demonstrated good agreement, validating the reliability of different monitoring approaches. However, recent studies emphasize that traditional urban background monitoring stations may underestimate exposure levels experienced by populations living or commuting near busy roads.

IV. Air Quality Models

Air quality models are essential tools for predicting pollutant dispersion, assessing exposure, and supporting environmental decision-making. Atmospheric dispersion models mathematically simulate the transport, diffusion, and transformation of pollutants based on emission characteristics and meteorological conditions. Modern models are typically computer-based and involve multiple stages, including data input, dispersion calculations, concentration estimation, and result analysis.

Advancements in atmospheric science have led to improved representations of turbulence and diffusion processes, allowing models to better handle complex terrain, urban structures, and long-range transport.

4.1 Major Types of Air Quality Models

Plume-rise models estimate the initial vertical rise of pollutant plumes due to thermal buoyancy and momentum, particularly relevant for emissions from stacks and chimneys.

Gaussian models are among the most widely used dispersion models. They assume pollutant concentrations follow a Gaussian distribution in both horizontal and vertical directions. These models are commonly applied for steady-state conditions and are recommended by regulatory agencies.

Semi-empirical models rely on simplified formulations and empirical parameters, making them suitable for practical applications when data availability is limited. Examples include box models and parametric approaches.

Eulerian models solve mass conservation equations on a fixed spatial grid and are often coupled with meteorological models. These are particularly useful for regional-scale simulations and complex chemical interactions.

Lagrangian models track individual pollutant parcels or particles as they move with the airflow, accounting for both mean wind and turbulence. These models are effective in simulating dispersion under variable atmospheric conditions.

Chemical modules simulate pollutant transformation processes, ranging from simple first-order reactions to complex photochemical mechanisms.

Receptor models work backward from observed concentrations to identify and quantify contributing sources based on chemical composition.

Stochastic models use statistical techniques to analyze trends and forecast pollution episodes, though they do not explicitly represent physical cause-effect relationships.

4.2 Suitability of Air Quality Models

The appropriateness of a model depends on several factors, including terrain complexity, meteorological variability, data availability, required accuracy, computational resources, and user expertise. Models requiring detailed inputs should only be applied when reliable data are available. Generally, models that incorporate finer spatial and temporal resolution provide more accurate assessments of source impacts and control strategies.

4.3 Applications of Air Quality Models

Air quality models are used for regulatory compliance, policy development, public information dissemination, and scientific research. Regulatory applications include emission permitting and environmental impact assessments. Policy-oriented modelling supports evaluation of pollution control measures and long-term planning. Models also play an increasing role in providing real-time air quality information to the public and forecasting pollution episodes. In research, advanced models help improve understanding of atmospheric processes and guide future model development.

V. Urban Roadway Dispersion Models

Vehicular emissions are influenced by complex factors such as driving behavior, traffic flow, vehicle composition, and roadway conditions. Turbulence generated by moving vehicles enhances mixing, allowing roadway emissions to be represented as line sources in dispersion models. Due to variability in emissions during acceleration, deceleration, idling, and cruising, roadway modelling often requires integration with detailed emission models.

5.1 CALINE-4 Model

CALINE-4 is a Gaussian line-source dispersion model developed for evaluating air quality impacts of roadway traffic. It incorporates a mixing zone concept and can simulate various roadway configurations, including intersections, street canyons, parking facilities, and bridges. The model is widely used for predicting short-term CO and NO_2 concentrations and is recommended by regulatory agencies for roadway impact assessments. However, certain legacy features, such as outdated modal emission assumptions for intersections, limit its applicability without appropriate adjustments.

5.2 Urban Roadway Dispersion Modelling Studies

Numerous studies have evaluated the performance of CALINE and other line-source models under diverse traffic and meteorological conditions. Improvements in emission modelling have enhanced representation of real-world driving patterns. Comparative studies demonstrate that simple Gaussian-based models can produce reliable predictions when properly calibrated, even in complex urban settings. Other approaches, including finite line-source, Lagrangian, and empirical models, have also been successfully applied to roadway pollution studies.

5.3 Street Canyons with High-Rise Buildings

Urban streets flanked by tall buildings often experience severe air pollution due to restricted ventilation. Several models have been developed to simulate airflow and pollutant dispersion within street canyons, ranging from simplified operational models to more complex numerical approaches. Operational models such as OSPM strike a balance between accuracy and data requirements, making them suitable for routine assessments. Comprehensive reviews have demonstrated that canyon geometry, wind direction, and traffic intensity are key determinants of pollutant accumulation.

5.4 Urban Roadway Intersections

Intersections are pollution hotspots due to frequent vehicle idling and stop-and-go traffic. Studies consistently report higher CO concentrations near intersections compared to roadway links. Hybrid modelling approaches combining traffic flow analysis and dispersion modelling have been developed to address these conditions. Among these, CAL3QHC has demonstrated strong performance in predicting intersection-level CO concentrations. Research also indicates that intersection geometry, orientation, and traffic volume significantly influence pollutant levels beyond traditional traffic performance indicators.

VI. Conclusions

Urban air quality studies consistently identify vehicular emissions as a dominant source of carbon monoxide pollution. High traffic density, frequent congestion, poor traffic management, unfavorable meteorological conditions, and low wind speeds contribute to pollutant accumulation and limited dispersion.

Advancements in emission modelling have improved representation of real-world vehicle behavior, enhancing prediction accuracy. In street canyons, pollutant concentrations are strongly influenced by wind speed, street width, and building height. At intersections, fluctuating driving modes significantly affect emission rates and resulting concentrations.

Overall, effective assessment of urban traffic pollution requires integrated approaches combining accurate emission estimates, appropriate dispersion models, and detailed local meteorological data. Such efforts are essential for informed urban planning, policy formulation, and public health protection.

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