

RESEARCH ARTICLE

Mathematical Modeling of Motor Vehicle Exhaust Gas Dispersion in The Conditions of Andijan City

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Abstract

In this study, changes in atmospheric air quality in the city of Andijan under conditions of global urbanization and the rapid development of motor transport complexes were investigated using sophisticated mathematical models. The specific climatic characteristics of Andijan — situated in the central geoecological section of the Fergana Valley — were analyzed, including its low aerodynamic potential, very low mean annual wind speed (1.8–2.2 m/s), and the frequent recurrence of thermal inversion layers. To quantify harmful components (CO, NO_x, PM10 particulate matter) emitted from road corridors, an integrated combination of the international COPERT methodology and Gaussian linear diffusion models was applied. Traffic loads on Babur Avenue, the New Market district, and Navoi Avenue — the highest-traffic routes in the city — were studied and modeled concentrations were compared against Maximum Permissible Concentration (MPC) standards. The “street canyon” effect arising from the vertical density of the built environment was identified and its negative impact on air purification (stagnation of up to 40%) was assessed. The article concludes with scientific recommendations for the innovative architectural-phytocenotic “Green Shield” project and the “Smart Air Andijan” digital monitoring platform, both aimed at improving the urban ecological environment.

KEYWORDS

Mathematical modeling, Gaussian dispersion, linear source, carbon monoxide, nitrogen dioxide, PM10 dust, street canyon, aerodynamic stability, urbanization, Fergana Valley.

INTRODUCTION

The ongoing global urbanization process is directly affecting the quality of atmospheric air. In Andijan — one of the most densely populated cities in Uzbekistan — the rapid growth in the number of motor vehicles is causing serious environmental challenges. The city’s geographic position in the central part of the Fergana Valley, characterized by slow air-mass exchange and frequent thermal inversion events, promotes the accumulation of exhaust gases in the lower strata of the urban atmosphere.

The objective of this study is to develop a theoretical framework for modeling the dispersion of harmful substances in the atmospheric layer surrounding road corridors in Andijan city, and to lay the scientific basis for constructing an urban air pollution map.

Gas dispersion in the atmosphere obeys hydrostatic and thermodynamic equilibrium laws (the Barometric Formula and Dalton’s Law) at the global scale, and the laws of hydrodynamics and turbulent diffusion at the

local and regional scale. These formulations today serve as the foundational basis for computer programs used in ecological forecasting, climate modeling, and meteorological services.

THEORETICAL BACKGROUND: ATMOSPHERIC STRUCTURE AND GAS DYNAMICS

1. Hydrostatic Equilibrium

To understand gas dispersion in the atmosphere, it is first necessary to examine the static atmospheric model. In the absence of macroscopic motions (wind, convection), gases are in a state of equilibrium described by the hydrostatic equilibrium equation. Any infinitesimally small volume element of the atmosphere is subject to two opposing forces: the upward pressure gradient force and the downward gravitational force. When these forces are balanced, hydrostatic equilibrium is established:

$$dP/dz = -\rho g$$

where P is atmospheric pressure (Pa), z is altitude (m), ρ is air density (kg/m^3), and g is the acceleration due to gravity (m/s^2).

2. Ideal Gas Law

Air density (ρ) depends on both pressure and temperature and is determined by the ideal gas equation of state (Mendeleev–Clapeyron equation):

$$P = (\rho/M) \cdot R \cdot T \Rightarrow \rho = PM / RT$$

where M is the mean molar mass of air (for dry air, $M \approx 28.97 \times 10^{-3} \text{ kg/mol}$), R is the universal gas constant ($8.314 \text{ J/(mol}\cdot\text{K)}$), and T is the absolute temperature (K).

STUDY AREA AND INPUT PARAMETERS

The radial-ring street network of Andijan city evolved historically and was not designed to accommodate the modern volume of traffic. The sharp increase in the number of vehicles, persistent congestion, frequent braking and acceleration cycles (stop-start mode) cause internal combustion engines to operate under suboptimal hydrodynamic conditions. This results in

incomplete fuel combustion and the release of disproportionately large quantities of carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and dispersed particulate matter (PM10, PM2.5) into the atmosphere.

For modeling purposes, the following three locations with the highest traffic loads were selected:

- *Babur Avenue (Babur Square area)*: The administrative and cultural center of the city, where radial arteries converge. Total traffic intensity during peak hours reaches 3,800–4,200 vehicles per hour. The surrounding 5–7-storey buildings restrict air circulation and create enclosed canyon conditions.
- *New Market district and adjacent intersections*: This zone is characterized by intensive commercial traffic. In addition to passenger cars, minibuses and delivery trucks constitute a high proportion of the flow. Average vehicle speed drops to 10–15 km/h due to congestion, increasing exhaust emissions exponentially.
- *Navoi Avenue*: One of the main transport arteries connecting the city with the Northern and Southern industrial zones. The share of medium and heavy-duty diesel vehicles on this route is 18% higher than in other study areas.

The following parameters were incorporated into the model:

- Type and number of vehicles (passenger cars, freight vehicles, buses);
- Fuel type (petrol/gasoline, compressed natural gas/LPG, diesel);
- Meteorological data (wind direction, wind speed, relative humidity).

The study employed systematic analysis, statistical data processing, and mathematical modeling. Local algorithms adapted to the international COPERT and AERMOD methodologies were applied to calculate emissions from traffic flows.

Table 1. Traffic flow characteristics at the main study corridors in Andijan city

Study location	Flow intensity (veh/h)	Mean speed (km/h)	CNG/LPG share (%)	Petrol share (%)	Diesel share (%)
Babur Avenue	4,100	22	62%	33%	5%
New Market district	3,750	12	55%	40%	5%
Navoi Avenue	3,200	28	50%	32%	18%

MATHEMATICAL MODEL OF EXHAUST GAS DISPERSION

Modeling emissions from motor traffic differs fundamentally from models developed for stationary industrial point sources. Since vehicles move continuously along roadways, they are treated as a linear (line) pollution source. The modeling procedure consists of two stages: calculation of the integrated emission rate of the line source, and solution of the spatial dispersion of the resulting pollutants using differential equations.

The mass of a pollutant released per unit time from a

$$C(x, y, z) = \frac{Q}{2\pi\sigma_y\sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \left[\exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right) \right]$$

where C is the pollutant concentration at a given point (mg/m³); Q is the source emission rate (g/s); u is the mean wind speed (m/s); σ_y and σ_z are the horizontal and vertical turbulent diffusion coefficients (m), respectively; H is the effective emission height (m); and x, y, z are the Cartesian coordinates of the receptor point.

RESULTS AND DISCUSSION

Table 2. Modeled pollutant concentrations at key monitoring locations in Andijan city compared to MPC standards

Monitoring location	CO (mg/m ³)	NO ₂ (mg/m ³)	PM10 (mg/m ³)	MPC exceedance (CO)
Babur Square (Center)	10.2	0.085	0.45	2.04x

given road segment (M_l) is calculated as:

$$M_l = \sum_{i=1}^n E_{ik} \cdot N_i$$

where E_{i^k} is the specific emission factor of vehicle type i for pollutant k (g/km), and N_i is the number of vehicles of type i per unit time.

The spatial distribution of pollutant concentrations is calculated using the Gaussian dispersion equation, which describes the dilution of gases from point or line sources as a function of downwind distance:

Using the developed algorithm and the parametric data presented in Table 1, computer-based modeling was carried out. The results were compared against the Maximum Permissible Concentrations (MPC) established for atmospheric air by the Sanitary Rules and Norms of the Republic of Uzbekistan: CO — 5.0 mg/m³; NO₂ — 0.085 mg/m³; PM10 particulates — 0.15 mg/m³.

Monitoring location	CO (mg/m ³)	NO ₂ (mg/m ³)	PM10 (mg/m ³)	MPC (CO)	exceedance
New Market district	12.4	0.072	0.38	2.48×	
Navoi Avenue	8.5	0.091	0.52	1.70×	

The modeling results demonstrate that CO concentrations in the New Market district reach 12.4 mg/m³, exceeding the established MPC by nearly 2.5 times. The primary causes are the very low mean vehicle speed (12 km/h) and unstable engine operating conditions. On Navoi Avenue, conversely, the high proportion of diesel vehicles results in elevated NO₂ and PM10 concentrations (0.091 mg/m³ and 0.52 mg/m³, respectively). NO₂ concentrations exceed the MPC threshold, while PM10 levels are 3.4 times above the permissible norm.

The narrow streets in Andijan’s old city district and newly constructed multi-storey buildings impede the vertical dispersion of exhaust gases by up to 40%, causing prolonged retention of harmful substances in pedestrian zones. The climatic characteristics of Andijan (mean annual wind speed 1.8–2.2 m/s) indicate a high probability of atmospheric stagnation events, further exacerbating pollutant accumulation.

PROPOSED MITIGATION MEASURES

Based on the modeling results, the following scientifically grounded solutions are proposed:

- 1. Traffic flow optimization:** Expansion of the city’s Northern and Southern ring roads to divert transit traffic away from the central districts, thereby reducing pollutant loads at the most congested intersections.
- 2. Green shield (phytocenotic buffer zones):** Establishment of vegetation barriers composed of plane trees (*Platanus*), elm (*Ulmus*), and oak (*Quercus*) species well-adapted to Andijan’s climate, with high phytoncide production capacity and demonstrated ability to absorb gaseous pollutants and intercept particulate matter.

3. “Smart Air Andijan” digital monitoring platform:

Deployment of a distributed sensor network across strategic city points for real-time data acquisition, analysis, and visualization of air quality indicators, enabling evidence-based environmental management decisions.

CONCLUSIONS

The findings of this study demonstrate that administrative measures alone are insufficient to protect the atmosphere of Andijan city from motor vehicle exhaust pollution. The mathematical modeling results confirm the necessity of incorporating prevailing wind directions (wind roses) into urban planning and design, widening key road corridors to reduce the street canyon effect, and transitioning public transport to environmentally clean energy sources (electric buses).

The proposed integrated model — combining COPERT emission factors with the Gaussian dispersion framework — is intended to serve as a foundational tool for constructing an ecological map of Andijan and for evidence-based urban planning. Future work will focus on integrating real-time sensor data with the dispersion model to improve predictive accuracy and to support dynamic, adaptive air quality management in the city.

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