Environmental Assessment of the Impact of Urban Transport on Air Pollution in Baku City

Aruz Mikayilov[1] and **Gulbasta Mammadova**[1]

[1]School of Advanced Technologies and Innovation Engineering, Department of Ecology and Environmental Sciences, Western Caspian University, Baku, AZ1072, Azerbaijan.

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Abstract

In modern times, the increase in population density in cities and the year-on-year rise in the number of cars are among the main factors negatively affecting air quality. In particular, the intensity of road traffic in Baku increases the volume of harmful substances released into the atmosphere, having a serious impact on the environmental situation and human health. This study analyses the emissions generated on the city's four main arterial roads with the highest traffic load, and their impacts on the environment and the socio-economic sphere are assessed based on international methodological approaches. The calculations applied the EMEP/EEA methodology, the World Health Organisation's 2021 air quality recommendations, and the principles for the valuation of external costs. Analyses show that most of the country's carbon monoxide emissions, approximately 71%, and 44% of its nitrogen oxides, originate from the transport sector. Much of that pollution is concentrated in Baku and has a particularly significant impact on the environment in the capital. The average annual concentration of $PM_{2.5}$ particles is estimated to range from 19 to 45 μg/m³, which is several times higher than accepted international health standards. This leads to an increased risk of heart and lung diseases in people breathing in polluted air for long periods. An economic assessment found that transport-related air pollution causes losses of over US$370 million annually, due to premature deaths, additional healthcare costs, and decreased productivity of citizens. The study recommends several measures, such as phasing out old vehicles, increasing the number of electric vehicles, improving and optimizing public transport, creating low-emission zones, implementing smart vehicle infrastructure, and improving green spaces in cities. These measures have the potential to reduce $PM_{2.5}$ emissions by 34-50% and nitrogen oxide emissions by 41-55% by 2030. The study's results show that improving air quality in Baku should not be limited to technical measures alone. Transport development and environmental policy must be integrated. These results have important implications for the development of sustainable urban transport in Azerbaijan, environmental protection, and the scientific basis for future policy decisions.

Keywords: urban transport, air pollution, emissions, environmental assessment, $PM_{2.5}$, air quality, socio-economic impacts

1.Introduction

The transport sector is one of the main contributors to air pollution. According to the World Health Organisation (WHO), each year air pollution causes more than 7 million premature deaths worldwide. A significant proportion of these deaths is due to fine particulate matter ($PM_{2.5}$ and PM_{10}), as well as various harmful gases emitted by vehicles.

Over the past two decades, Baku has undergone rapid development, and both the population and the number of vehicles in the city have increased significantly. Currently, there are more than 1.3 million registered vehicles in the country, and approximately 60%of them are concentrated in Baku. Because the number of cars has increased faster than the development of road infrastructure, traffic congestion has become a persistent problem in the city. As a result, vehicles travel at lower speeds, and the constant engine restarts lead to an increase in the emission of pollutants.

The most important air pollutants related to transportation include carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), volatile organic compounds (VOCs), and particulate matter (PM). These substances cause respiratory and heart diseases and increase the risk of certain types of cancer (Landrigan, 2017). Nitrogen oxides disrupt the balance of ecosystems and biodiversity by increasing the accumulation of nitrogen in soil and plants (Bobbink et al., 2010). Carbon particles are also known to contribute to climate change (Bond et al., 2013).

Baku's unique location, surrounded by the Caspian Sea from the east and mountains from the northwest, helps regulate the flow of rivers. This natural process prevents pollutants from accumulating and spreading in the lower atmosphere.

The main aim of this study was to assess the impact of traffic on air quality on selected main roads in Baku. During the study, the composition and dynamics of the vehicle fleet were investigated, the levels of key pollutants were analysed, and the results were compared with WHO Air Quality Guidelines (2021). In addition, the economic impact of air pollution was assessed, and potential measures to reduce greenhouse gas emissions were proposed.

The study monitored the intensity of traffic, used the EMEP/EEA method to calculate greenhouse gas emissions, and took the Air Quality Guidelines as the basis. The economic impact of pollution was assessed, and the results were compared with the environmental conditions of other cities in the region.

The data used were collected from the State Statistics Committee of the Republic of Azerbaijan, the Ministry of Ecology and Natural Resources, the Baku Transport Agency, the WHO AQG 2021 documents, and statistical indicators provided by the IQAir platform. In Azerbaijan, the protection of the atmosphere and the regulation of air quality are carried out in accordance with existing national legislative acts (Republic of Azerbaijan, 1999).

2. Materials and methods

This study is based on an assessment of the current state of transport and the environment in Baku, based on practical data. During the data collection phase, traffic flow calculations were carried out, and the EMEP/EEA emission factors method was used to determine emissions to the atmosphere (European Environment Agency, 2019). In this approach, vehicle type, year of manufacture, fuel used, and operating conditions were considered as the main assessment criteria. The driving cycles were selected in accordance with the standard methodologies applied in European countries (André, 2004).

The WHO AQG 2021 was used as the main reference document during the assessment phase. Air quality indicators for individual pollutants were calculated, and the obtained results were analysed by comparison with the regulatory limits.

For the economic analysis, the external cost method was used, and health impacts were estimated using the Value of a Statistical Life (VSL) (European Parliament & Council of the European Union, 2024; Maibach et al., 2008).

In the comparison stage, Baku was compared with other cities such as Tbilisi and Yerevan.

Data were collected from three main sources: stationary air quality monitoring stations, traffic count data from the Baku Transport Agency, and open data platforms such as IQAir and OpenAQ (OpenAQ, 2024). The study covers the period 2015–2023, and forecasts were made up to 2035.

3. Analysis and Discussion

During the period 2010–2023, the total number of registered vehicles in Azerbaijan increased from 671,000 to 1.31 million, almost doubling over the period. The number of vehicles per 1,000 people also rose from 76 to 128. The vehicle fleet in Baku grew at a faster rate than the national average and exceeded 760,000 units in 2023 (Table 1)

Table 1. *Key indicators of the vehicle fleet in the Republic of Azerbaijan (2010–2023)*

İndicator	2010	2015	2019	2023	**İncrease**, %
Total registered vehicles(thousands)	671	866	1.093	1.310	+95,2
Share of Baku city (%)	54	56	58	58	–
Automobiles per 1000 people	76	98	112	128	+68,4
Trucks(thousands)	95	118	142	182	+91,6
Buses and minibuses (thousands)	43	55	68	85	+97,7

The age structure of the vehicle fleet is a concern. About 54% of vehicles are 10 years or older. The average age of vehicles had increased from 10.2 years in 2010 to 13.6 years in 2023. Older cars usually do not have modern emission control systems, so their emissions are around 8–12 times higher than the Euro 6 standard (European Parliament & Council of the European Union, 2007).

In terms of fuel use, about 82% of vehicles use gasoline, 14% – diesel, and only 4% use alternative fuels such as CNG, LPG, or electricity. Despite making up only 6% of the overall vehicle fleet, buses and minibuses produce 29% of NO_x emissions and 34% of $PM_{2.5}$ emissions, chiefly due to their old diesel engines.

In Baku, private cars make up 62% of daily trips, which is much higher than the European average of 35–40%. Between 2010 and 2023, the use of private cars increased, while public transport use decreased (Cervero, 2020). This trend is one of the main reasons for the increase in transport emissions.

According to the national report of the Ministry of Ecology of Azerbaijan, the transport sector produces 71% of the country's total anthropogenic CO emissions and 44% of NO_x emissions. Baku accounts for 62–65% of all transport emissions in Azerbaijan. The analysis of data from 2015 to 2023 shows that, after a temporary decline in 2020 due to the COVID-19 pandemic, emissions increased again during 2021–2023, exceeding pre-pandemic levels (Mammadovan & Rostamnia, 2022) and reaching new record highs (Table 2).

Table 2. *Annual Trends in Air Pollutant Emissions from the Transport Sector in Baku.*

Pollutant	2015	2018	2020	2022	2023	**İncrease**, %
CO (t/year)	48.200	56.700	52.400	58.600	61.300	+27,2
NO_2 (t/year)	14.600	17.200	15.900	18.900	19.800	+35,6
SO_2 (t/year)	3.100	3.600	3.300	3.750	3.900	+25,8
$PM_{2.5}$ (t/year)	1.840	2.210	2.050	2.380	2.480	+34,8
PM_{10} (t/year)	3.120	3.750	3.480	4.020	4.160	+33,3
CO_2 (thousand t/year)	3.840	4.520	4.180	4.780	4.970	+29,4

In Baku, traffic emissions have two peak periods during the day: 08:00–09:30 in the morning and 17:30–19:30 in the evening. During these periods, NO_x concentrations are 2.4–3.1 times higher than the daily average, showing the direct impact of traffic congestion on emissions. Field observations also show that the average speed on major roads falls to 8–12 km/h during peak hours, causing vehicles to operate under conditions that produce higher emissions. In addition, CO emissions during a cold start are 8–10 times higher than under normal driving conditions (Heywood, 2018), highlighting the effect of stop-and-go traffic in urban areas. Reducing vehicle speeds in urban areas can also contribute to improving road safety and reducing the negative environmental impacts associated with road traffic (Eastern Alliance for Safe and Sustainable Transport, 2019).

In 2023, the transport sector in Baku emitted 4.97 million tonnes of CO_2, accounting for 18% of the country's energy-related emissions. Between 2015 and 2023, transport-related CO_2 emissions increased by 29.4%, indicating a trend that is not consistent with Azerbaijan's Nationally Determined Contribution (NDC) commitments (International Energy Agency, 2023).

In 2023, the annual average $PM_{2.5}$ concentration in busy traffic areas of Baku ranged from 19 to 45 µg/m³, which was 3.8 to 9 times higher than the DST standard (5 µg/m³). The annual average NO_2 concentration ranged from 32 to 68 µg/m³, exceeding the DST standard (10 µg/m³) by 3.2 to 6.8 times. None of the six monitoring sites met the WHO Air Quality Guidelines (Table 3).

Table 3. *DST Air Quality Standards and Air Pollution Levels in Baku (2023)*

Pollutant	WHO Guideline	Baku 2023 Average	Exceedance factor
$PM_{2.5}$ (µg/m³, annual)	5	35	7,0×
PM_{10} (µg/m³, annual)	15	58	3,9×
NO_2 (µg/m³, annual)	10	54	5,4×
SO_2 (µg/m³, 24-hour)	40	48	1,2×
O_3 (µg/m³, 8-hour)	60	112	1,9×

According to seasonal analysis, air pollution is most severe during the winter months (December–February). The higher frequency of temperature inversion events during this period promotes the accumulation of pollutants close to the ground. As a result, the average $PM_{2.5}$ concentration in winter is 2.3 times higher than that recorded in summer. Elevated ozone levels during summer months also pose risks to vegetation and crops (Mills et al., 2011). Compared with other cities, Baku's annual average $PM_{2.5}$ concentration (29 µg/m³) is similar to that of Ankara (24 µg/m³) but considerably higher than the level observed in Tbilisi (17 µg/m³). The existing network of seven permanent air quality monitoring stations is not sufficient to provide adequate coverage of the city. By comparison, Warsaw, which has a similar population density, operates 28 monitoring stations, whereas Istanbul has 44.

The results obtained using the external cost methodology indicate that the annual social cost of transport-related emissions in Baku exceeds USD 370 million (Table 4). Calculations show that the largest share of the total economic loss – 38.4% – is associated with the probability of premature death resulting from the impact of $PM_{2.5}$ particles on human health. Expenditure on treatment and hospital care accounts for 18.2% of the total damage. Reduced work attendance and interruptions to work due to illness make up 14.6% of the economic loss. Overall, the costs associated with adverse health effects account for approximately three-quarters of the total economic loss.

Table 4. *Annual External Costs of Transport Emissions in Baku (2023, USD)*

Damage category	Damage (mln $)	Share (%)
Premature Mortality Risk ($PM_{2.5}$)	142,0	38,4
Hospital Expenditures	67,5	18,2
Workday loss	54,2	14,6
Category of loss	**Damage (mln $)**	**Share (%)**
Medical Examination and Treatment Costs	38,4	10,4
Building and Infrastructure Corrosion	24,6	6,6
Agricultural Losses	18,7	5,1

Calculations show that the annual external economic loss per vehicle in Baku is approximately 1,520 US dollars. This figure is higher compared to Tbilisi (USD 1,240) and Yerevan (USD 1,380). The main reasons for this are the high level of traffic congestion in the city, the ageing vehicle fleet, and the high population density. Analyses also show that every US$1 invested in transport infrastructure can generate an economic benefit of approximately US$3.20–6.30 in the future.

The assessment shows that the BakuBus compressed natural gas (CNG) programme is the most successful currently existing initiative. It has earned an efficiency score of 4.25 out of 5. Conversely, fuel quality efforts scored 2.25, and the minibus emissions management system scored just 2.00. These low scores show the necessity of immediate reform.

Our SWOT analysis identified key structural strengths. These include Baku's metro network, large natural gas reserves, and financial backing from institutions like the Green Climate Fund and the European Bank for Reconstruction and Development (EBRD). Reliance on high-sulfur fuel and the limited capacity of the air quality monitoring system were identified as key weaknesses.

To address these issues, the study compared three policy approaches: the business-as-usual (BAU) baseline, the minimal action package, and the comprehensive strategic plan. The minimal action package combines fuel upgrades, expanded CNG programmes, and the replacement of older vehicles. The comprehensive strategic plan combines ten different measures (C40 Cities, 2022). Estimates show that the minimal action package can reduce $PM_{2.5}$ emissions by 34% and NO_x emissions by 41% by 2030. This strategy requires a phased investment between US$430 million and US$630 million. Ultimately, it represents a highly efficient choice, yielding an estimated benefit-cost ratio of 3.2 to 4.4.

The full implementation of the strategic measures could reduce $PM_{2.5}$ emissions by 67% and NO_x emissions by 74% by 2035. The highest economic efficiency among the proposed measures is attributed to the implementation of a congestion charge system in the city centre (6.3). This is followed by improving fuel quality (3.75) and expanding the CNG programme (3.25).

International experience also confirms the effectiveness of these approaches. In London, after the implementation of the Ultra Low Emission Zone (ULEZ), roadside NO_2 concentrations decreased by 44%. In Seoul, the combined implementation of bus rapid transit (BRT) and an urban road charging system reduced PM_{10} levels by 32%. For Baku, priority measures include converting 8,000 minibuses to run on CNG. The proposal includes switching to cleaner fuel, the creation of three new BRT corridors, the implementation of a subsidy programme for the scrapping and renewal of old vehicles, as well as the introduction of a congestion charging system in the city centre. According to the developed monitoring plan, the primary objective is to reduce $PM_{2.5}$ concentrations to 18 $\mu g/m^3$ and NO_2 concentrations to 24 $\mu g/m^3$ by 2030. The promotion of electric mobility and the expansion of EV charging infrastructure are also important measures for reducing transport-related carbon emissions and supporting the transition to low-carbon urban transport (Green Climate Fund, 2022).

Table 5. *A Four-Block System of Transport and Environmental Recommendations for Baku City.*

Block	Specific recommendation	Target	Timeframe	Responsible İnstitution
Regulatory and legal measures	1. Fuel sulfur limit: 50 ppm in 2026, 10 ppm in 2028.	SO_2: -85%	2025-2028	Ministry of Energy SOCAR
	2. A complete ban on the import of vehicles below Euro 4.	Average fleet age -2,5 years	2026	Customs Committee
	3. Conduct quarterly emission inspections for minibuses using camera-based monitoring systems.	Nonconformity 60%	2026	Ministry of Transport BNA
Technology upgrade	4. Low-interest financing scheme for converting 8,000 minibuses to CNG over five years	NO_x: -68%, PM: 79%	2025-2028	Ministry of Finance
	5. Build three dedicated Bus Rapid Transit (BRT) routes	Shift toward public transport +18%	2025-2030	BNA, Urban planning
	6. Establish 500 EV charging points through cooperation between the public and private sectors	EV Share: +10%	2025-2027	Ministry of Energy
	7. Expand the metro system by adding four new stations	Modal shift +10%	2027-2033	Baku metropolitan area
Economic incentive	8. Financial incentives (4-6AZN per day)	Traffic: -22%	2027	BNA, Ministry of Finance.
	9. City centre access feevehicles:5000AZN	Fleet renewal+15%	2025-2030	Ministry of Finance
Public behavior	10. Addition of an eco-driving module to the driver's licence exam	Fuel -8%	2025	Ministry of Transport
	11. School zones around schools designated as car-free- 20 schools pilot	School NO_2: 40%	2025-2026	Ministry of Education BNA
	12.5% tax relief for businesses implementing remote work	Pik traffic: -14%	2025	Ministry of Finance

This table presents a set of recommendations for the transport and environment sector in Baku, identifying specific actions, implementation timelines, and expected outcomes in four main blocks: regulatory and legal measures, financial resources, technological infrastructure, and public behavior. The actions within each area clearly complement each other and create a synergistic effect. This shows that a systemic approach is more effective than a fragmented approach. Therefore, this four-block matrix of recommendations constitutes a practical implementation plan for decision-makers.

4. Conclusion

In conclusion, the study shows that the transport sector is the main source of air pollution in Baku. The number of vehicles has almost doubled between 2010 and 2023, with 54% of them being over a decade old. In addition, 62% of all city trips are made by private car, which is a major structural factor in the increase in greenhouse gas emissions.

Air pollution on Baku's main roads frequently violates the 2021 WHO Air Quality Guidelines. Levels of $PM_{2.5}$, NO_2, and ozone remain dangerously high, which increases risks for public health and creates severe economic losses, estimated at US$370 million per year.

This study demonstrates that an integrated package of regulatory, technological, and economic measures can substantially reduce transport-related air pollution in Baku while improving public health and supporting sustainable urban development.

The BakuBus programme achieved the highest efficiency score at 4.25/5. In contrast, fuel quality efforts scored the lowest at 2.25/5. A baseline package of fuel reform, CNG adoption, and vehicle replacement requires a phased investment of US$430 to US$630 million. However, despite the cost, this package will reduce $PM_{2.5}$ and NO_x emissions by 34% by 2030. The estimated cost-benefit ratio is between 3.2 and 4.4. More broadly, if the entire strategic package of 10 steps were implemented by 2035, particulate matter ($PM_{2.5}$) emissions could be reduced by 67% and nitrogen oxide emissions (NO_x) by 74%.

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