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IMPACT OF CLIMATE CHANGE AND TRANSPORT DENSITY ON THE AIR QUALITY OF ALMATY METROPOLIS

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Abstract — This study investigates the combined impact of climate change and transport density on air quality in the Almaty metropolitan area. Due to its location in a mountainous basin, Almaty experiences a continental climate characterized by limited air circulation and frequent temperature inversions, which hinder the dispersion of atmospheric pollutants. At the same time, the rapid increase in the number of private vehicles over the past decade has significantly intensified anthropogenic emissions, making road transport one of the primary contributors to urban air pollution. These factors have led to a deterioration in environmental conditions and increased risks to public health. The research is based on the analysis of the Air Quality Index (AQI), meteorological observations, and traffic density statistics to evaluate the relationship between climatic conditions, transportation activity, and atmospheric pollution levels. Special attention is given to the influence of seasonal weather patterns, temperature inversion events, wind speed, and traffic intensity on the concentration of major air pollutants. The collected data were analyzed to identify trends and determine the relative contribution of natural and anthropogenic factors affecting urban air quality. The results indicate that climate change contributes to more frequent and persistent temperature inversions, which reduce pollutant dispersion and increase concentrations of harmful substances in the lower atmosphere. Furthermore, high transport density was identified as the dominant source of emissions responsible for deteriorating air quality. Based on the findings, practical recommendations are proposed, including the modernization of public transportation, promotion of environmentally friendly mobility, stricter vehicle emission control, and the implementation of comprehensive environmental policies aimed at improving air quality and ensuring sustainable urban development.
Keywords — Almaty, air quality, climate change, transport density, ecology, temperature inversion, atmospheric pollution.

АЛМАТЫ МЕГАПОЛИСІНІҢ АУА САПАСЫНА КЛИМАТТЫҢ ӨЗГЕРУІ МЕН КӨЛІК ТЫҒЫЗДЫҒЫНЫҢ ӘСЕРІ

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Аңдатпа — Бұл зерттеу Алматы мегаполисіндегі атмосфералық ауаның сапасына климаттың өзгеруі мен көлік ағыны тығыздығының әсерін талдауға арналған. Қаланың таулы қазаншұңқырда орналасуы және континенттік климаты ауа массаларының әлсіз айналымына және температуралық инверсиялардың жиі қалыптасуына ықпал етеді, соның салдарынан ластаушы заттардың атмосферада таралуы қиындайды. Сонымен қатар, соңғы он жыл ішінде автокөлік санының күрт артуы антропогендік шығарындылар көлемін едәуір көбейтіп, автокөлікті атмосфералық ауаны ластаудың негізгі көздерінің біріне айналдырды. Табиғи және антропогендік факторлардың бірлескен әсері экологиялық жағдайдың нашарлауына және халық денсаулығына төнетін қауіптің артуына алып келеді. Зерттеу барысында атмосфералық ауаның сапа индексі (AQI), метеорологиялық бақылау деректері және көлік ағындарының статистикасы негізінде климаттық жағдайлар, көлік қозғалысының қарқындылығы және атмосфераның ластану деңгейі арасындағы өзара байланыс бағаланды. Маусымдық өзгерістердің, температуралық инверсиялардың, жел жылдамдығының және көлік ағынының тығыздығының негізгі ластаушы заттардың концентрациясына әсеріне ерекше назар аударылды. Жиналған деректер атмосфералық ауаның

ластану заңдылықтарын анықтауға және климаттық әрі көліктік факторлардың үлесін бағалауға мүмкіндік берді. Зерттеу нәтижелері климаттың өзгеруі температуралық инверсиялардың жиілігі мен ұзақтығын арттырып, ластаушы заттардың атмосфераның төменгі қабатында жиналуына ықпал ететінін көрсетті. Сондай-ақ, көлік ағынының жоғары тығыздығы зиянды шығарындылардың негізгі көзі екені анықталды. Алынған нәтижелер негізінде қоғамдық көлікті дамыту, экологиялық таза көлік түрлерін ынталандыру, автокөлік шығарындыларын бақылауды күшейту және қаланың ауа сапасын жақсарту мен орнықты дамуын қамтамасыз етуге бағытталған экологиялық саясатты жетілдіру бойынша практикалық ұсынымдар ұсынылды.
Түйін сөздер **—** Алматы, ауа сапасы, климаттың өзгеруі, көлік тығыздығы, экология, температуралық инверсия, атмосфералық ластану.

ВЛИЯНИЕ ИЗМЕНЕНИЯ КЛИМАТА И ПЛОТНОСТИ ТРАНСПОРТА НА КАЧЕСТВО ВОЗДУХА МЕГАПОЛИСА АЛМАТЫ

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Аннотация **—** Данное исследование посвящено анализу влияния изменения климата и плотности транспортного потока на качество атмосферного воздуха в мегаполисе Алматы. Географическое расположение города в горной котловине и континентальный климат способствуют слабой циркуляции воздушных масс и частому возникновению температурных инверсий, что затрудняет рассеивание загрязняющих веществ. Одновременно стремительный рост количества автотранспортных средств за последнее десятилетие значительно увеличил объем антропогенных выбросов, вследствие чего транспорт стал одним из основных источников загрязнения атмосферного воздуха. Совокупное воздействие природных и антропогенных факторов приводит к ухудшению экологической обстановки и повышению риска для здоровья населения. Исследование основано на анализе индекса качества воздуха (AQI), метеорологических данных и статистики транспортных потоков для оценки взаимосвязи между климатическими условиями, интенсивностью движения и уровнем загрязнения атмосферы. Особое внимание уделено влиянию сезонных изменений, температурных инверсий, скорости ветра и плотности транспортного потока на концентрацию основных загрязняющих веществ. Полученные данные позволили выявить закономерности формирования загрязнения воздуха и определить вклад климатических и транспортных факторов. Результаты исследования показали, что изменение климата способствует увеличению частоты и продолжительности температурных инверсий, что приводит к накоплению загрязняющих веществ в приземном слое атмосферы. Установлено, что высокая плотность транспортного потока является основным источником вредных выбросов. На основе полученных результатов предложены практические рекомендации по развитию общественного транспорта, стимулированию экологически чистой мобильности, усилению контроля за выбросами автотранспорта и совершенствованию экологической политики для улучшения качества воздуха и обеспечения устойчивого развития города.
Ключевые слова **—** Алматы, качество воздуха, изменение климата, плотность транспорта, экология, температурная инверсия, загрязнение атмосферы.

INTRODUCTION

Almaty is the largest metropolis and economic center of Kazakhstan. Located at the foot of the mountains, the city has a continental climate, which leads to sharp temperature fluctuations and weak air circulation. In recent years, climate change has been observed at the global and local levels, increasing temperatures and changes in meteorological conditions affect the air quality of Almaty [1,2]. At the same time, the number of cars in the city will exceed 500 thousand, and daily it will be replenished with 200-250 thousand cars from other regions. This transport density increases the emission of harmful substances into the atmosphere, such as carbon

MAIN PROVISION

The air quality of the Almaty metropolis is determined by the combined influence of climatic conditions and transport density. The mountainous topography and increasing frequency of temperature inversions caused by climate change reduce atmospheric ventilation, while the continuous growth of vehicle numbers significantly increases emissions of $PM_{2.5}$, PM_{10}, CO, and NO_x. The interaction of these climatic and anthropogenic factors results in persistent air pollution, particularly during the winter season, highlighting the need for integrated environmental and transport management strategies.

dioxide (CO), nitrogen oxides (NO_x) and small particles ($PM_{2.5}$, PM_{10}). In this regard, this study aims to assess the impact of climate change and transport density on air quality in Almaty. The study seeks to determine how these two factors affect the ecology of the city and how they relate [3].

The geographical location of Almaty makes it vulnerable to air pollution. Located on the northern slope of the Trans-Ili Alatau, the city is deprived of the opportunity for natural ventilation, as the mountains block the free flow of wind. This condition causes temperature inversion to occur, especially in the winter months. During inversion, cold air accumulates in the lower layer and warm air is trapped above, resulting in pollutants not spreading in the atmosphere, forming a thick layer over the city. Climate change is further intensifying this process, as well as increasing the average temperature, making extreme weather phenomena more frequent. For example, over the past decade, there has been a gradual warming of winter temperatures and a prolongation of summer heat, which negatively affects air circulation [4].

In addition, the growth of the population and the rapid development of urbanization in Almaty has increased the demand for Transport. Since the beginning of the 2020s, the number of cars in the city has been increasing annually by an average of 5-7%. [5] This includes not only cars of local residents, but also daily commuters from the Almaty region and other regions. The increase in transport density increased traffic jams on the road, which, in turn, led to the fact that emissions from cars remained in the atmosphere for a long time. Cars in which internal combustion engines are used as the main source of harmful emissions have been identified, most of which are old models. In this regard, the concentration of $PM_{2.5}$ and PM_{10} particles in the air exceeds international standards several times, which poses a threat to the health of residents.

The importance of this study lies in identifying the reasons for the deterioration of the environmental situation in Almaty and proposing measures against it. Poor air quality has been shown to exacerbate respiratory diseases, cardiovascular problems, and other chronic diseases. Therefore, the study of the influence of factors such as climate change and transport density is important not only from an ecological point of view, but also from social and medical aspects. This study aims to analyze how these two factors affect the ecology of the city and determine their relationship [6].

The main goal of the study is to assess the climatic and anthropogenic factors that affect air quality and understand how they contribute to the ecological balance in the city. To achieve this goal, specific indicators such as the air quality index (AQI), meteorological data and traffic flow statistics are used. The study also takes seasonal changes into account and compares the differences in air quality during the winter and summer periods. Thus, a complete picture of the air quality of Almaty will be formed [7].

Although climate change is a global problem, its impact at the local level varies depending on the characteristics inherent in the city. For Almaty, this feature is the mountainous relief and continental climate. The increase in temperature changes the direction and speed of the wind, reducing natural ventilation. This situation is especially noticeable in the city center and densely populated areas, where the traffic flow is also high. The effect of transport density is not limited to the volume of emissions – it increases energy consumption and excess fuel consumption through traffic jams on the road, which, in turn, leads to additional pollution.

Another important aspect of the study is the impact of air quality in Almaty on public health. According to the World Health Organization (WHO) [8], high concentrations of small particles such as $PM_{2.5}$ increase the risk of lung cancer, asthma and other respiratory diseases. Almaty has seen an increase in such diseases in recent years, which may be a direct consequence of air pollution. Therefore, this study is aimed not only at solving environmental problems, but also at improving public health.

The results of this study will serve as the basis for providing practical recommendations to the administration of Almaty, environmentalists and public organizations. For example, initiatives such as the development of public transport, the introduction of environmentally friendly technologies and measures to adapt to climate change can contribute to improving air quality. In addition, the study highlights the importance of social campaigns aimed at increasing environmental literacy among urban residents and reducing the use of private cars [10].

Research gap. Although numerous studies have investigated air pollution, climate change, or transport emissions separately, limited attention has been paid to their combined influence on the air quality of Almaty. Existing research mainly focuses on pollutant concentrations or emission inventories without integrating meteorological conditions, traffic density, and seasonal variability into a unified assessment. Furthermore, there is insufficient evidence quantifying how temperature inversion and increasing transport density jointly affect urban air pollution under the specific geographical conditions of Almaty. This study addresses this gap by

combining AQI records, meteorological observations, and transport statistics to evaluate their integrated impact on air quality.

Novelty statement. The novelty of this study lies in the integrated assessment of climate change and transport density as interacting factors affecting air quality in the Almaty metropolis. Unlike previous studies, this research combines official air quality monitoring data, meteorological parameters, and traffic statistics for the period 2020-2024 to evaluate their joint influence on seasonal pollution patterns. The study also identifies the synergistic effect of temperature inversion and transport emissions on $PM_{2.5}$ concentrations and provides practical recommendations for improving urban environmental management through sustainable transport development and climate adaptation policies.

METODOLOGY

The study was based on a mixed method: quantitative and qualitative analysis. This approach was chosen because it combines the accuracy of quantitative data and the contextual depth of qualitative analysis, allowing a comprehensive study of the impact of climate change and transport density on air quality in Almaty. In the course of the study, various data sources were used, each of which served as the basis for analyzing certain aspects. The data collection and processing process was carefully planned and relied on reliable and up-to-date information.

Data sources:

1. Air Quality Index (AQI): as one of the main sources of research AirVision.kz air quality indicators from the portal and RSE "Kazhydromet" for the period 2020-2024 were used. These data include concentrations of pollutants such as $PM_{2.5}$ (particles smaller than 2.5 micrometers in diameter), PM_{10} (particles smaller than 10 micrometers in diameter), carbon dioxide (CO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2). AirVision.kz while the portal provides real-time monitoring of air quality in various districts of Almaty, Kazhydromet has provided official statistics that allow you to analyze long-term trends. The data were collected as daily, weekly and monthly averages and formed the basis for assessing seasonal changes.

2. meteorological data: to study the impact of climate on air quality in Almaty, temperature, wind speed and humidity indicators for the period from 2020 to 2024 were analyzed. These data were obtained from Kazhydromet Weather Stations and contain information collected from stations installed at various points in the city [1]. To determine temperature inversion, daily temperature profiles were studied and how wind direction and speed affect air circulation were assessed. Humidity data were taken into account as an additional factor related to the distribution of pollutants and the formation of atmospheric fog.

3. transport density: to assess the impact of transport flows on air quality, transport statistics of the mayor's office of Almaty and traffic police reports were used. This data includes the number of registered cars in the city, the volume of daily traffic and the frequency of traffic jams on the main highways. In addition, the number of cars arriving in the city from outside (up to 200-250 thousand) and the time of their movement (morning and evening hours) were taken into account. In order to more accurately determine the effect of transport density, various zones such as the city center, outskirts and industrial zones were considered separated.

Analysis methods. In the course of the study, several analytical methods were used, each of which was aimed at testing a specific hypothesis. Correlation analysis was chosen as the main method, which made it possible to quantify the effect of temperature inversion and transport flow on air quality. By calculating the correlation coefficient (r), the relationship between climatic factors (temperature, wind speed) and air pollution ($PM_{2.5}$, No. 2) and transport density was determined. For example, studying the correlation between PM2.5 concentration and transport flow density during temperature inversion helped determine the joint effects of these two factors.

In addition, the seasonal comparison method was used to determine the differences in air pollution in the winter and summer periods. In winter, the effects of temperature inversion and the heating season were taken into account, and in summer, a decrease in pollution due to wind activity and high temperatures was assessed. This comparison made it possible to understand the impact of seasonal fluctuations on air quality and the relationship with climate change.

As an additional method, regression analysis was used, which was aimed at assessing the cause-effect relationship between transport density and air pollution. For example, the relationship between the volume of daily traffic flow (number of cars) and the concentration of CO or PM_{10} on the same day was checked using a regression model. This model helped determine how much vehicle emissions contribute to the deterioration of air quality.

As part of the qualitative analysis, the opinions of local residents and expert assessments regarding the air quality in Almaty were taken into account. This data was collected from open access forums, social networks and reports from environmental organizations. Qualitative analysis supplemented quantitative data and allowed a deeper understanding of the social and environmental consequences of air pollution.

Data collection process. The data collection process covered the period from 2020 to February 2025. This five-year period allowed us to assess the long-term trends in climate change and transport density. Air quality data was taken from daily monitoring stations, and meteorological data was recorded every hour. Transport statistics were collected on the basis of monthly reports, and as an addition, data from cameras that monitor the traffic flow on the road were used.

Several measures have been taken to ensure the accuracy of the data. For example, the calibration of air quality stations was checked, and the correct operation of meteorological instruments was confirmed by Kazhydromet specialists. To reduce possible errors in transport statistics, the data of the akimat and the traffic police were compared, and common values were taken as a basis.

Scope and limitations of the study. The study was limited to the administrative boundaries of the city of Almaty, but the impact of vehicles coming to the city from outside was also taken into account. However, the study had some limitations. First, due to the limited number of air quality stations, it was not possible to fully cover all areas in the city. Secondly, meteorological data was taken only from official stations, and climatic differences in micro-regions were not taken into account. Thirdly, the flow on small streets was not fully covered, as the transport density data was mainly focused on the main roads and highways.

Research hypotheses. The study focused on testing the following hypotheses:

1. temperature inversion increases air pollution in Almaty, especially in winter. 2.transport density is the main factor in the deterioration of air quality.

3.climate change (rising temperature, weakening wind) and transport flow act together, increasing pollution.

The above methods and data sources were used to test these hypotheses. The results of the study were aimed at confirming or refuting the validity of these hypotheses, and also served as the basis for the development of practical recommendations regarding air quality in Almaty.

Data processing and analysis tools. Modern software was used for data processing and analysis. Correlation and regression analysis was carried out using the SPSS and R statistical programs. Excel and Tableau tools were used to visualize seasonal comparisons, which made it possible to present data in the form of graphs and charts. Qualitative data analysis was processed through the nvivo program, which helped to identify key topics from opinions and reports.

In conclusion, this methodology made it possible to comprehensively study the impact of climate change and transport density on air quality in Almaty. The combination of quantitative and qualitative methods served as the basis for obtaining specific results and developing recommendations aimed at solving environmental problems. The next section discusses the results of the study in more detail.

RESEARCH RESULTS AND DISCUSSION

In this section, the results of the study on the impact of climate change and transport density on air quality in the Almaty metropolis are fully considered. The study focused on determining how climatic and anthropogenic factors affect the ecology of the city, their relationship and the role of seasonal changes. The results showed that the problem of air pollution in Almaty is complex and an integrated approach is needed to solve it.

Climate change and temperature inversion. According to the results of the study, temperature inversion is most often observed in Almaty in winter. This phenomenon is characteristic of the mountainous terrain and is closely related to the location of the city on the northern slope of the Trans-Ili Alatau. During temperature inversion, cold air accumulates in the foothills and warm air is trapped in the upper layer, resulting in a significant decrease in air circulation. This situation inhibits the spread of pollutants in the atmosphere, causing them to accumulate over the city.

It was found that in the winter period 2023-2024, the concentration of $PM_{2.5}$ exceeded an average of 150 mcg/m^3 and reached dangerous levels. This figure is six times higher than the safe limit (25 mcg/m3) established by the World Health Organization (who). Temperature inversion is especially strong on windless and cold days, when the wind speed does not exceed 1-2 meters per second. In such conditions, pollutants, including $PM_{2.5}$, PM_{10} and No. 2, remain in the city's atmosphere for a long time, without being naturally purified.

Climate change further exacerbates this process. Over the past decade, Almaty has seen a gradual increase in average temperatures, which has affected the duration and intensity of winter inversion. For example,meteorological data from 2020 to 2024 showed an increase in the average winter temperature by 1-1.5°C. This change was accompanied by a weakening of the wind and an increase in humidity, as a result of which the frequency of atmospheric fog and smog formation increased. During the study, it was recorded that during temperature inversion, the daily maximum of $PM_{2.5}$ concentrations exceeded 200 μg/m^3, which was especially pronounced in the city center and in areas near the mountains.

Climate change is not limited to the winter period. In summer, extreme temperature increases (35-40°C) and changes in wind direction negatively

affect air circulation. However, due to the greater possibility of natural ventilation in the summer period than in the winter inversion, the level of pollution is relatively reduced. Thus, climate change affects air quality in Almaty in different ways, depending on seasonal features, but temperature inversion in the winter period remains the most important factor.

Influence of transport density. Transport density has been identified as the main anthropogenic cause of air pollution in Almaty. According to the results of the study, the time of peak traffic flow – 07:00-09:00 AM and 17:00-19:00 PM – directly coincides with a sharp deterioration in air quality. At this time, traffic jams are formed on the main highways in the city, and emissions from cars spread into the atmosphere for a long time. For example, in January 2024, the level of carbon dioxide (CO) exceeded 5 mg/m^3 per hour and was 1.5 times higher than the permissible limit (MPC-3 mg/m^3).

The study confirmed that emissions from cars account for more than 80% of air pollution. This indicator mainly includes substances such as CO, NO_x and $PM_{2.5}$, which come from internal combustion engines. The average age of cars in Almaty is more than 10-15 years, which indicates that they do not meet environmental standards (for example, Euro-4 or Euro-5). At the same time, most of the 200-250 thousand cars coming to the city from outside ha e diesel engines, which increases the concentration of PM10 and No. 2.

The study revealed a direct relationship between traffic flow and air pollution. For example, during traffic jams on the central streets of Almaty (Abay Avenue, Al-Farabi Avenue), the $PM_{2.5}$ level exceeded 100 μg/m^3 and was twice as high as in relatively quiet areas on the outskirts of the city (40-50 μg/m^3). This difference clearly shows the effect of transport density at the local level. In addition, excessive fuel consumption during traffic jams and idling of engines further increase the volume of emissions.

The effect of transport density also depends on seasonal factors. In winter, along with temperature inversion, an increase in the number of vehicles on the road (an increase in visitors to the city due to the heating season) leads to a sharp deterioration in air quality. Although vehicle flow is relatively uniform in summer, high temperatures increase fuel evaporation and ozone formation, which creates an additional environmental risk.

Seasonal differences. Air quality in Almaty is strongly dependent on seasonal changes. The results of the study showed that in summer, due to wind activity and high temperatures, pollution levels are relatively low. For example, in July-August 2023, the concentration of PM10 was on average around 50 μg/m^3, which is only slightly higher than the WHO allowable limit (50 μg/m3). The average wind speed was 3-5 meters per second, contributing to the spread of pollutants.

On the contrary, in winter, due to temperature inversion and the heating season, the level of pollution increases 3-4 times. In January-February 2023-2024, the concentration of PM10 reached 150-200 μg/m^3, and $PM_{2.5}$ exceeded 150 μg/m^3. During this period, the coal burning of private houses and small enterprises in the city was an additional source of pollution, but transport emissions still played a dominant role. In the winter period, the weak wind (0.5-1 meter per second) and the accumulation of cold air on the slopes almost completely stopped the natural cleaning of pollution.

The analysis of seasonal differences made it possible to identify the joint impact of climate change and transport density. For example, the appearance of winter smog is not limited to coal burning or inversion – a high traffic flow intensifies this process. Although pollution is low in summer, climate warming leads to the formation of additional pollutants such as ozone (O_3), which in the long term can pose new environmental risks.

Correlation. The study found that there is a strong positive correlation ($r = 0.87$) between temperature inversion and transport density. This indicator confirms that the combined effect of both factors has a significant negative impact on air quality. During the correlation analysis, it was found that wind weakness and high transport flow during temperature inversion are directly related to a sharp increase in $PM_{2.5}$ and CO levels.

For example, in the winter period, on days when the temperature was below -10°C and the traffic flow exceeded 1000 cars per hour, the concentration of $PM_{2.5}$ reached an average of 180 μg/m^3. This indicator is significantly higher than the values on days when there is no inversion and the traffic flow is low (50-60 μg/m^3). Regression analysis showed that when the vehicle density effect was assessed individually, each additional 100 vehicles increased $PM_{2.5}$ levels by about 5-7 μg/m^3.

Additional observations. The study also looked at the reduction of green areas in the city and the role of industrial emissions. It was observed that the ability of green spaces to absorb pollution decreased, but their share was small compared to transport and climatic factors. Although industrial emissions were significant in areas on the outskirts of the city, the impact on air pollution in general did not exceed 10-15%.

The results of the study showed that the deterioration of air quality in Almaty is caused by the complex effects of climate change and transport density. While temperature inversion exacerbates winter pollution, traffic flows pose a constant threat throughout the year. This is due to the fact that there

is a strong correlation between seasonal differences and correlative relationships. The next section presents practical recommendations based on these results.

CONCLUSION

Air quality in the Almaty metropolis is deteriorating due to the complex effects of climate change and transport density. As it turned out in the course of the study, these two factors are closely related and pose a serious threat to the ecology of the city. While temperature inversion increases the accumulation of pollutants during the winter period, the abundance of cars remains a constant source of danger throughout the year. In this regard, it is necessary to take concrete measures to improve the environmental situation in Almaty and protect the health of the population. Based on the results of the study, the following recommendations were developed, which are aimed at improving air quality in the short and long term.

First, the development of public transport and the restriction of the use of private cars is proposed as an important measure. Transport density in Almaty is the dominant source of air pollution, especially during traffic jams, the volume of emissions increases sharply. Modernization of the public transport system – increasing the number of buses, optimizing routes and introducing electric buses – can reduce the demand for private vehicles. For example, expanding the metro network and developing alternative systems such as light rail transport can be a long-term solution. In addition, measures such as restricting the entry of private cars in the city center or introducing a congestion charge (congestion charge) will help regulate the flow of transport. These approaches have been successfully used in megacities such as London or Singapore and can also be adapted to Almaty.

Secondly, encouraging environmentally friendly fuel types (gas, electricity) is an effective way to reduce air pollution. Currently, most cars in Almaty run on gasoline or diesel, which leads to the release of such harmful substances as $PM_{2.5}$, NO_x and CO. To encourage the use of electric vehicles, government subsidies, tax breaks and the expansion of the network of charging stations are needed. In addition, the development of natural gas vehicles (CNG) can reduce emissions in the short term, as gas fuel produces fewer pollutants than diesel. An important step will also be the mandatory introduction of environmental standards for vehicles (for example, Euro-5 or Euro-6) and the implementation of decommissioning programs for used cars.

Thirdly, the expansion of green areas to improve air circulation in the mountainous area contributes to reducing the impact of climate change and temperature inversion. The location of Almaty at the foot of the mountains naturally worsens air circulation, and the process of urbanization has led to a decrease in green spaces. The results of the study showed that green areas have the ability to absorb pollutants, but the current volume is insufficient. Therefore, it is necessary to expand parks and tree planting projects on the outskirts of the city and in the central areas.

Fourth, strengthening local climate change adaptation policies will ensure long-term sustainability. Climate change increases the intensity of temperature inversion in Almaty and leads to a weakening of the wind. Given this situation, local authorities should develop a strategic plan that will assess the impact of climate change and ensure adaptation to it. For example, the strengthening of meteorological monitoring and the introduction of a system for predicting the deterioration of air quality will make it possible to warn the population in a timely manner. In addition, additional sources of pollution, such as coal burning, can be reduced by improving energy efficiency and developing renewable energy sources (solar, wind).

In conclusion, the problem of air quality in Almaty is caused by the complex interaction of factors such as climate change and transport density. This study fully analyzed the impact of these factors and offered practical solutions. For the implementation of the above measures, cooperation between local authorities, business and society is necessary. And the expansion of green areas and the strengthening of climate policy will be effective only with the support of the city's residents.

As a result of the implementation of these measures, Almaty can get access to fresh air and become an environmentally sustainable metropolis. This allows not only to preserve the health of the current generation, but also to leave a decent living environment for future generations. The results and recommendations of the study will give a clear direction to the city administration, environmentalists and public organizations and will serve as the basis for improving the environmental future of Almaty.

CONFLICT OF INTEREST

The author claims that there is no conflict of interest in the implementation of this study and the publication of the article.

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REFERENCES

[1] RSE "Kazhydromet," "Annual Report on Atmospheric Air Pollution in Almaty", 2024. [Online]. Available: https://kazhydromet.kz. [Accessed: Dec. 28, 2024].

[2] Akimat of Almaty City, "Transport Infrastructure and Statistics", 2023. [Online]. Available: https://almaty.gov.kz. [Accessed: Jan. 18, 2025].

[3] AirVision.kz, "Air Quality Index (AQI) Data for Almaty", 2024. [Online]. Available: https://airvision.kz. [Accessed: Jan. 15, 2025].

[4] United Nations Development Programme (UNDP), "Report on Climate Change and Air Quality", 2024. [Online]. Available: https://undp.org. [Accessed: Jan. 10, 2025].

[5] A. Asylbekov, "Ways to Improve Almaty's Ecology", *Egemen Qazaqstan*, 2019. [Online]. Available: https://egemen.kz. [Accessed: Jul. 10, 2025].

[6] R. Mukhtarov, O. P. Ibragimova, A. Omarova, M. Tursumbayeva, K. Tursun, A. Muratuly, F. Karaca, and N. Baimatova, "An episode-based assessment for the adverse effects of air mass trajectories on $PM_{2.5}$ levels in Astana and Almaty, Kazakhstan", Urban Climate, vol. 49, Art. no. 101541, May 2023, doi: 10.1016/j.uclim.2023.101541.

[7] K. Tursun, A. Omarova, O. P. Ibragimova, B. Bukenov, M. Tursumbayeva, R. Mukhtarov, I. Radelyuk, S. Yenisoy, D. Karakaş, H. Ergin, F. Karaca, and N. Baimatova, "Dominant sources of $PM_{2.5}$ in Kazakhstan's urban cities: A PMF and HYSPLIT-based study for air quality management in Central Asia", Urban Climate, vol. 64, Art. no. 102706, Dec. 2025, doi: 10.1016/j.uclim.2025.102706.

[8] World Health Organization, "WHO Global Air Quality Guidelines: Particulate Matter ($PM_{2.5}$ and PM_{10}), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide." Geneva, Switzerland: WHO, 2021. [Online]. Available: https://www.who.int/publications/i/item/9789240034228. [Accessed: Jan. 20, 2025].

[9] Intergovernmental Panel on Climate Change (IPCC), Climate Change 2023: Synthesis Report. Geneva, Switzerland: IPCC, 2023. [Online]. Available: https://www.ipcc.ch/report/ar6/syr/. [Accessed: Jan. 20, 2025].

[10] United Nations Environment Programme (UNEP), "Actions on Air Quality," 2024. [Online]. Available: https://www.unep.org/explore-topics/air. [Accessed: Jan. 20, 2025].