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The future of leaded aviation fuel: navigating the challenges of transition

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The improvement of unleaded fuels in general aviation represents a significant milestone in the pursuit of establishing a greener and more sustainable air transportation system. Conventional aviation fuels, such as AVGAS 100LL, have TEL (Tetraethyl Lead) in their composition, which is used to increase the octane rating of fuel and improve the efficiency of piston engines used in aviation. However, these substances are considered toxic, and their emissions into the atmosphere have negative effects on the environment and human health.
Therefore, very strict air quality standards have been established by the European Union and member states. Years of research and cooperation throughout the aviation sector have contributed to the elimination of lead-containing fuels from most aircraft used in general aviation operations. Most engines have already been certified for the usage of unleaded gasoline, and so are all new engines. Nevertheless, one-third of the engines currently in use in the EU are not certified to burn unleaded fuel. Besides the lead, other toxic compounds are also being emitted with exhaust gases like CO2, NOx, and UHC. In this article, the discussion is about the profits of pursuing a zero-lead policy within General Aviation and the risks associated with introducing a leaded avgas prohibition without a valid alternative.

Key words: *emission dispersion, aviation emissions, lead, nitrogen oxides, carbon monoxides*

1. Introduction

In an era characterized by the chase of environmentally friendly technologies, every sector is actively seeking for a way to reduce its emissions. According to the ICAO, in 2022, the aviation industry accounted for 3.8–4% of total EU GHG emissions and 13.9% of all transport related emissions [21]. In addition, ICAO forecasted that by 2050, international aviation emissions could be tripled [23] due to the faster growth in comparison to other transportation methods. This motivates aviation companies to introduce modernization to their products and to conduct research to minimize the aviation industry's negative impact on air quality. Modern airframes are characterized by significantly better aerodynamic properties. New engine designs for commercial airplanes introduced plenty of features that significantly reduce fuel consumption. Geared Turbofan design enabled Low Pressure Turbines to operate at optimal rotational speed [14]. Improvement of combustion chamber of modern engines, such as Rolls-Royce Phase 5 design or General Electric TAPS II (Twin Annular Premixing Swirler) combustor, introduced a significant reduction in toxic particle emissions [3, 5, 9].

General Aviation is an isolated case. The majority of the GA propulsion systems are piston engines. Transition to unleaded gasoline was not as successful as it was in the case of the automotive industry. However, when in 2000 the leaded petrol was entirely withdrawn from the EU market, the number of cars was more than 193 million. Today, the number of general aviation aircraft in the EU is around 36.8 thousand. Going further, only one-third of them have no alternative to using leaded gasoline. Nevertheless, the general aviation sector – like the automotive industry in the past – has made efforts to identify and implement lead-free alternatives to traditional lead-containing fuels. The elimination of tetraethyl lead (TEL) from automotive gasoline began in earnest in the 1970s, driven primarily by public health concerns and the need to protect catalytic converters, which are highly sensitive to lead. Governments worldwide introduced phased regulations to limit and eventually ban TEL in road fuels. This process was supported by major advancements in fuel refining (e.g., catalytic reforming and hydrocracking), allowing the production of high-octane, unleaded fuels. Additionally, engine technologies evolved to accommodate these fuels, such as hardened valve seats to resist wear in the absence of lead lubricity. Motor Octane Number is critical in aviation. Aircraft operate under sustained high load and variable altitude, which increases knock sensitivity. The Motor Octane Number of regular automotive gasoline is in the range of 81–85. Premium automotive gasoline reaches the MON up to 90. The UL94 gasoline, very popular among lower-compression aviation engines, reaches the MON of 94. However, there is still a significant percentage of aircraft powered by high-load engines, i.e., Cessna T206 powered by Lycoming TIO540 AJ1A, which are only certified to use AVGAS 100LL, which reaches the MON of 100.

2. Aviation engine issues

Piston engines represent the majority of propulsion systems within general aviation. Due to their higher efficiency, lower cost of purchase and operation (in the range 70–370 kW), they are being used to supply small aircraft. Understanding the mechanics of these engines and the impact of their operations on emission levels is crucial for environmental management and aviation safety. Especially considering the risk associated with using non-approved fuels.

The operation and maintenance of piston engines significantly affect the levels of emitted pollutants. Key factors include fuel type, engine tuning, maintenance practices, and the condition of emission control systems. The type of fuel used in piston engines is a primary determinant of emissions. Traditionally, aviation gasoline contained tetraethyl lead (TEL), which has been used to enhance fuel performance by increasing octane rating, to prevent engine knocking, and improve efficiency. On the other side, leaded avgas is a source of lead emissions, which can pose a significant threat to human life when its concentration in the air is elevated.

To ensure optimal combustion efficiency, a proper tuning and calibration of the engine (and its components) should be provided. Non-optimal fuel-air mixtures together with incorrect ignition timing can increase emissions of CO, $NO_{x,}$ and UHC. Regular maintenance and use of diagnostic tools to fine-tune the engine are essential to minimize these emissions. Worn-off spark plugs can be a cause of incomplete combustion, which increases CO and UHC emissions. Thus, regular inspection and replacement of spark plugs is recommended. Air filters should be cleaned and replaced since clogged air filters reduce airflow, causing a low air-to-fuel ratio that increases CO and particulate emissions.

It is also preferable to make sure the exhaust system is in good condition to reduce harmful emissions. Some piston engines are equipped with advanced emission control systems such as catalytic converters and exhaust gas recirculation (EGR) systems to help reduce NO_x emissions. The effectiveness of these systems depends on regular maintenance and the quality of the fuel used.

A recent regulatory change in the European Union to restrict the distribution of leaded gasoline, and in particular avgas from TEL, has raised concerns about the potential use of unapproved fuels. The use of such fuels in reciprocating engines that are not certified for them can lead to several problems, like detonation and knock combustion. Unleaded fuels often have a lower octane number compared to leaded fuels. Using them in engines designed for high-octane leaded fuels can cause detonation, leading to knock combustion – a condition in which the fuel burns unevenly. This can result in serious engine damage, including piston and cylinder wear. Lead in fuel acts as a lubricant, protecting engine components such as valve seats. The lack of lead in unleaded fuels can cause increased wear and recession of valve seats, leading to loss of engine compression and performance. Some unleaded fuels contain ethanol, which can absorb water and cause corrosion of the fuel system and engine components that were not designed to handle alcohol-based fuels. Engines equipped with catalytic converters can be damaged if unapproved fuels clog or poison the catalytic converter, reducing the effectiveness of the system and increasing emissions.

The leaded gasoline restriction creates a scenario where pilots and operators may resort to using unapproved fuels due to availability issues, especially in critical situations such as crop dusting or emergency services. This introduces significant human factor risks. The use of unapproved fuels can compromise aircraft safety, causing unpredictable engine performance and potential failure. Operating aircraft with unapproved fuels can result in non-compliance with aviation regulations, leading to legal consequences and insurance cancellation. Increased emissions from the use of unsuitable fuels can have broader environmental and public health impacts, undermining efforts to reduce aviation's environmental footprint.

3. Pollutants' adverse influence

3.1. Air pollutants from general aviation piston engines

Piston engines, which are prevalent among smaller general aviation aircraft, can emit a variety of air pollutants that contribute to environmental concerns and air quality issues. They produce carbon monoxide as a byproduct of incomplete combustion. CO is a colorless and odorless gas that can be harmful to human health when inhaled in high concentrations. Usually, its concentration in the atmosphere is less than 0.001%. Naturally, those concentrations are higher in big cities that suffer from high traffic congestion. Carbon monoxide is mostly exhaled from the lungs as unchanged gas. Less than 1% of it is oxidized to carbon dioxide. Ten to fifteen percent is bound to proteins. It competes with oxygen for binding with hemoglobin and, as a result, leads to hypoxia. [7] It can be dangerous during engine start-ups in enclosed and non-ventilated areas.

Nitrogen oxides are produced when nitrogen in the air reacts with oxygen at high temperatures during combustion. Nitrogen oxides react further with oxygen and within a few hours, Nitrogen dioxide marks its peak in a range of dispersion. In the third step, the level of NO_2 declines and the concentration of ground-level ozone increases, which is a key component of smog, and can also contribute to acid rain. Ozone compounds damage plants and their fruits and irritate the human respiratory system. [19] Figure 1 shows the pattern of how the ground-level ozone concentration increases during the day [13].

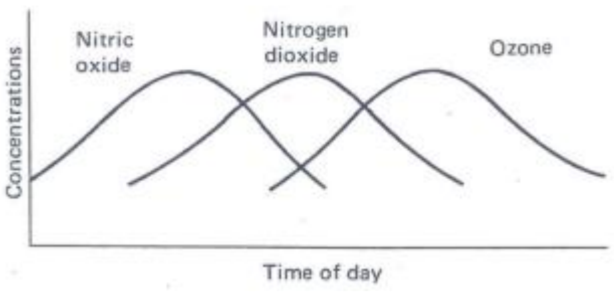

Fig. 1. Graphic describing the nitrogen oxides and ground-level ozone concentrations [19]

Hydrocarbons are unburned fuel molecules that are released into the atmosphere when combustion is not complete. In the sunlight, they react with nitrogen oxides and can contribute to the formation of ground-level ozone and have adverse effects on air quality [13]. In the literature, direct measurements of general aviation aircraft emission under various loads are presented [16].

Combustion engines emit particulate matter, tiny airborne particles that can have adverse health effects when inhaled. These particles can include soot, metal particles, and other combustion byproducts. In the upper atmosphere, it modifies Earth's radiation characteristics, impacts the formation of clouds, and catalyzes secondary pollutant formation. In the lower atmosphere, it affects atmospheric visibility and has a negative impact on human health, such as congenital heart defects, ischemic heart disease, respiratory and circulatory mortality, preterm birth risk, or abnormal fetal growth [17, 22].

Volatile organic compounds (VOCs) are a diverse group of carbon-based chemicals that readily evaporate at room temperature, contributing significantly to air pollution and posing various health risks. Among them, 1,3-butadiene, toluene, and benzene deserve special attention due to their widespread presence and harmful effects. 1,3-butadiene, a colorless gas with a mild gasoline odor, plays a key role in the production of synthetic rubber, essential for tires, auto parts and various industrial products. However, 1,3-butadiene is also a known carcinogen, and exposure to it is associated with an increased risk of leukemia and other cancers. Its reactivity in the atmosphere further contributes to the formation of ground-level ozone and secondary organic aerosols, worsening air quality. Butadiene has many environmental sources, in addition to those previously mentioned; it is worth adding car exhaust and tobacco smoke, pointing out that 78.8% of its emissions are caused by the combustion of fuels in a reciprocating engine, and another 19.6% by other combustion processes (such as cooking) [6].

Toluene and benzene, significant components of fossil fuel emissions, pose serious health risks, especially to gas station workers. Toluene, a clear liquid with a sweet, pungent odor, is widely used as a solvent in paints, thinners, adhesives, and chemical intermediates. Exposure to toluene, whether by inhalation, ingestion, or skin contact, can cause dizziness, headaches, and respiratory problems in the short term, while long-term exposure can lead to severe neurological damage, liver and kidney dysfunction, and developmental damage in fetuses. Benzene, a colorless or light yellow liquid with a sweet odor, is a natural component of petroleum and a byproduct of combustion processes, including automobile emissions and industrial activities. Benzene is highly carcinogenic, and long-term exposure to it is strongly associated with leukemia and other blood disorders. Even low concentrations can affect the bone marrow, leading to anemia and a weakened immune system. The combustion of fossil fuels, especially in piston engines used in general aviation, contributes significantly to the release of these volatile organic compounds. Piston engines, commonly used in small aircraft, rely on the combustion of aviation gasoline, which contains high levels of toluene and benzene. This not only poses a risk to pilots and ground personnel but also contributes to broader environmental pollution. Emissions from these engines include significant amounts of volatile organic compounds, which worsen air quality and threaten the health of surrounding communities.

Joint statement of the world's largest organizations within general aviation, one-third of piston engines in the EU used in general aviation have no alternative to leaded gasoline, such as avgas 100LL [10]. As a result, lead emissions are a serious problem, as lead is a potent neurotoxin that can harm both the environment and human health [20, 25].

Although general aviation emits these pollutants, quantitatively these emissions are much lower than those of commercial aviation, not to mention the automotive, energy or heavy industry. Nevertheless, the cumulative impact of general aviation on air quality and the environment can still be significant. Especially near the most popular airports.

3.2. International regulations

In the European Union, the air quality standards are defined in Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe. In the US the Environmental Protection Agency (EPA) releases National Ambient Air Quality Standards (NAAQS). Those standards are presented in the Table 1.

Table 1. EU and USA air quality standards

Pollutant	Measurement averaging time	UE Standard [μg/m^3]	USA Standard [μg/m^3]
Carbon monoxide	1 hour	N/A	40750
	8 hours	10000	10480
Lead	Rolling three months average	N/A	0.15
	1 year	0.5	N/A
Nitrogen dioxide	1 hour	200	188
	1 year	40	100
Ozone	1 hour	240*	N/A
	8 hours	N/A	137
Particulate matter (PM_{10})	24 hour	50	150
Sulfur dioxide	1 hour	350	
	24 hours	125	200
*Alert level			

4. Modeling approach

4.1. Modeling and management of aviation emissions

Emission dispersion modeling plays an important role in managing the environmental impact of the aviation industry. Precise information on the number of harmful pollutants emitted and their spatial distribution allows us to better understand what the final environmental impact of planned activities within the airport will be. Thus, it can be used to effectively manage traffic at the airport to reduce environmental impact. Emission dispersion modeling is a useful method that helps airport operations meet regulatory requirements for protecting public health and the environment. Dispersion modeling should also be used to support measurement units. A dense grid of measurement points would be very expensive to implement, however, a hybrid approach where a limited number of measurement points are supported by dispersion models seems to be an appropriate approach. Analysis of different flight routes, taxiing procedures and fuel-saving measures can lead to significant reductions in emissions. These optimizations improve air quality and increase the efficiency of flight operations. In the context of global climate change, emissions dispersion modeling is expanding to quantify emissions of greenhouse gases, such as carbon dioxide (CO_2), from aviation operations. Such comprehensive emissions inventories help evaluate strategies to reduce the aviation sector's carbon footprint.

4.2. Emission calculations

The Aviation Environmental Design Tools (AEDT) program was used to modelling emissions and dispersion of aircraft engines. AEDT uses the Emission and Dispersion Modeling System (EMDS) algorithm for emission and dispersion calculations. The aircraft engine's emissions are calculated including their landside and airside operations among which the EDMS defines four modes: Taxi/Idle, Takeoff, Climb out and Approach. Aircraft operates in each mode for specific amount of time (TIM – Time in Mode). In Table 2 the default TIM for various aircraft is presented.

Table 2. Default time-in-mode for various aircraft categories [24]

Aircraft category	Taxi/idle	Takeoff	Climb out	Approach
Commercial				
Jet-airliner	26	0.7	2.2	4
Turbo-prop	26	0.5	2.5	4.5
Transport/piston	13	0.6	5	4.6
General Aviation				
Business jet	13	0.4	0.5	1.6
Turbo-prop	26	0.5	2.5	4.5
Piston	16	0.3	5	6
Helicopter	7	–	6.5	5.6

The emission sources of the specific airframe are its Engines, Auxiliary Power Units (APU), and Ground Support Equipment (GSE). The engine emissions are calculated using equation 1.

$$E_{ij} = \sum(TIM_{jk}) \cdot \left(\frac{FF_{jk}}{1000}\right) \cdot (EI_{ijk}) \cdot (NE_j) \tag{1}$$

where: E_{ij} – total emission of pollutant I, in pounds, produced by aircraft type j for one LTO cycle, TIM_{jk} – time in mode for mode k, in minutes, for aircraft type j, FF_{jk} – fuel flow for mode k, in pounds per minute, for each engine used on the aircraft type j, EI_{ijk} – emission index for pollutant I, in pounds of pollutants per one thousand pounds of fuel, in mode k for aircraft type k, NE_j – number of engines used on aircraft type j.

Emission index for various pollutants and engine types are sourced from the International Civil Aviation Organization (ICAO) Engine Emissions Databank and other databases. These factors are specified for different phases of flight, such as idle, takeoff, climb, cruise, and descent. During the LTO Cycle, those Emission indices are fixed. For mission calculations that go beyond the LTO cycle, various scaling methods like Boeing Fuel Flow Method 2 can be used.

GSE emission factors contained in the EDMS database are derived from the document "Technical Data To Support FAA's Advisory Circular On Reducing Emissions From Commercial Aviation" [1, 24]. Those factors are based on brake horsepower, load factor, fuel type, and coolant type. In EDMS GSE emission factors are given in kilograms per hour. With an operation time per LTO cycle given in minutes, the calculation for emissions generated per LTO cycle is the product of the emission factor and operation time.

4.3. Emission dispersion modelling in AEDT

Once emissions are quantified, AEDT employs advanced dispersion modeling techniques to predict the distribution and concentration of pollutants in the atmosphere. The dispersion modeling is based on principles of atmospheric physics and chemistry, involving complex equations that describe the transport, diffusion, and chemical transformation of pollutants.

A primary approach used in AEDT for near-field dispersion (close to the emission source) is the Gaussian Plume Model. This model assumes that pollutants disperse in the atmosphere following a Gaussian distribution, influenced by wind speed, atmospheric stability, and other meteorological conditions. The general form of the Gaussian plume equation for a continuous point source is:

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

where: $C(x, y, z)$ is the concentration of the pollutant at location (x,y,z), Q is the emission rate (grams per second), σ_y and σ_z the dispersion coefficients in the horizontal and vertical directions, respectively, u is the wind speed (meters per second), H is the effective source height (meters), which accounts for the initial plume rise.

For more comprehensive and regulatory-compliant assessments, AEDT integrates the AERMOD (American Meteorological Society/Environmental Protection Agency Regulatory Model). AERMOD is a steady-state plume model that simulates the dispersion of pollutants by considering both simple and complex terrain and a wide range of meteorological conditions. AERMOD requires detailed input data, including:

- Meteorological data: wind speed and direction, temperature, humidity, atmospheric pressure, and solar radiation
- Terrain data: elevation profiles and land use categories
- Emission data: source characteristics such as emission rates, stack heights, and exit velocities.

5. Results and discussion

The area of Warsaw-Babice Airport and its vicinity was selected for emission concentration assessment due to the relatively high number of operations and unique localization in the middle of the highly urbanized province of Warsaw. In the direct vicinity of the airport, there are multifamily houses and family allotment garden areas where people have a rest and grow food plants (Fig. 2).

Airplane Cessna T206 powered by Lycoming TIO540 AJ1A engine was selected due to its popularity and the fact that TIO540 AJ1A is not certified to use any unleaded gasoline. In Table 2, Lycoming TIO540 AJ1A emission indexes (by default implemented in the AEDT based on ICAO Aircraft Emission Data Bank) are presented.

Table 3. Lycoming TIO540 AJ1A engine emission indexes for different LTO cycle phases in grams per kilogram of fuel.

	Takeoff	Climb out	Approach	Taxiing
Carbon monoxide	1442.0	1470.9	1261.6	1293.7
Nitrogen oxide	0.362	0.235	1.388	0.387
Lead	0.7766	0.7766	0.7766	0.7766

Lead emission index was calculated using the upper lead content per liter of Avgas 100LL, which is 0.56 g/dm^3, and its density is equal to 0.7211 kg/ dm^3. Some of the lead compounds, like lead oxides, can be sintered on the exhaust

Fig. 2. Area of Warsaw-Babice Airport with the direct vicinity of family allotment gardens and multi-family houses

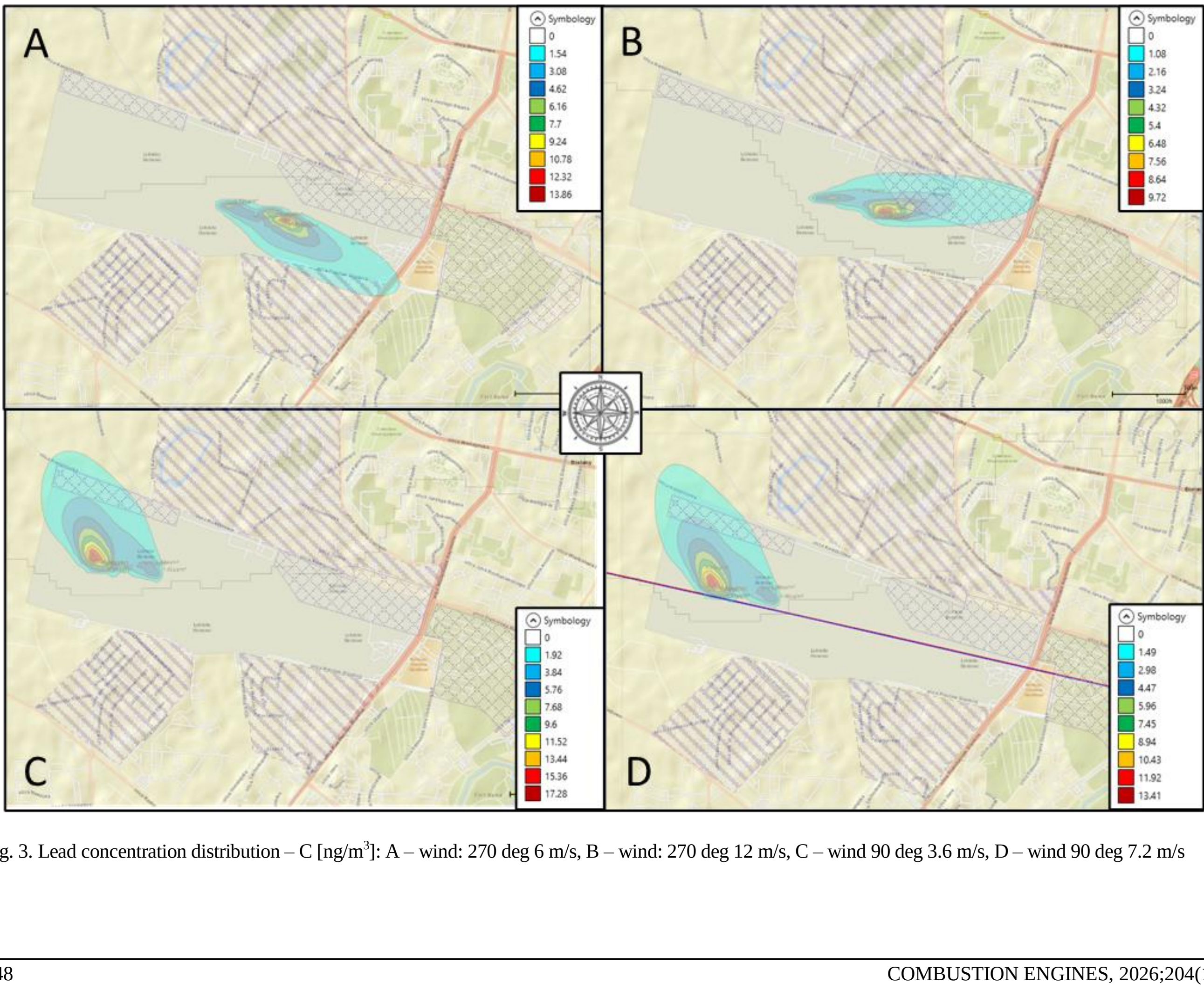

Fig. 3. Lead concentration distribution – C [ng/m^3]: A – wind: 270 deg 6 m/s, B – wind: 270 deg 12 m/s, C – wind 90 deg 3.6 m/s, D – wind 90 deg 7.2 m/s

system of the engine; however, this is negligible since the addition of ethylene dibromide in the leaded fuels significantly limits this process.

On the Warsaw-Babice, there are environmental limitations on the number of operations per hour and daily, 10 and 100 operations, respectively. Figures 3–5 show the concentration of lead, nitrogen oxides, and carbon monoxide for 4 days in June 2022 with different wind directions and/or wind speeds. Aircraft approach and departure flying in a direction opposite to the wind. For each hour of each day, 5 arrival and 5 departure operations were modelled. All presented values correspond to 1-hour averaged, tier 1 values. The meteorological data used in the modeling were obtained from the publicly available repository of the Institute of Meteorology and Water Management (IMGW).

The concentration distribution maps A and B in Fig. 3 show lead concentration for westerly winds of 6 m/s and 12 m/s, respectively. Westerly winds are particularly unfavorable for people resting in nearby allotments. However, even for that wind direction, the estimated lead concentrations resulting from the Warsaw-Babice airport's operations rank between 0 and 0.00648 ng/m^3 within the allotments area. In the case of easterly winds (maps C and D), this impact is limited to people working in the Warsaw-Babice airport area itself and people resting within allotment gardens on the north-west side of the airport. The lead concentration ranks there between 0 and 0.00384 ng/m^3. Although there is no limit to the hourly concentration of lead in the air specified in both European and US regulations, it should be remembered that 1-hour averaged values will have significantly higher values than values after annual averaging. This is due to the lack of flight operations during nighttime hours.

The NO_x concentration level presented in Fig. 4 is lower than the expected lead concentration, and this is a direct result of the lower NO_x emission index. In comparison to the emissions allowed by regulation, the resulting concentration presented in the figure below can be considered as negligible.

Compared to jet engines, the NO_x emission index of piston engines is significantly lower. This, combined with substantially lower airflows, results in considerably lower nitrogen oxide emissions from aircraft powered by piston engines. The NO_x emission index in piston engines is lower due to the fact that combustion in piston engines occurs in a confined space with a relatively short duration for NO_x formation, as the high-pressure and high-temperature conditions are transient. Jet engines have a continuous combustion process, allowing more time for NO_x formation due to prolonged exposure to high-temperature conditions in the combustion chamber. For comparison, the NOx emission index of the CFM56-7B26 engine, which is used to power Boeing 737-800 aircraft, is equal to 23.94 g/kg fuel, whereas for the Lycoming TIO540 AJ1A, it is equal only to 0.362 g/kg fuel.

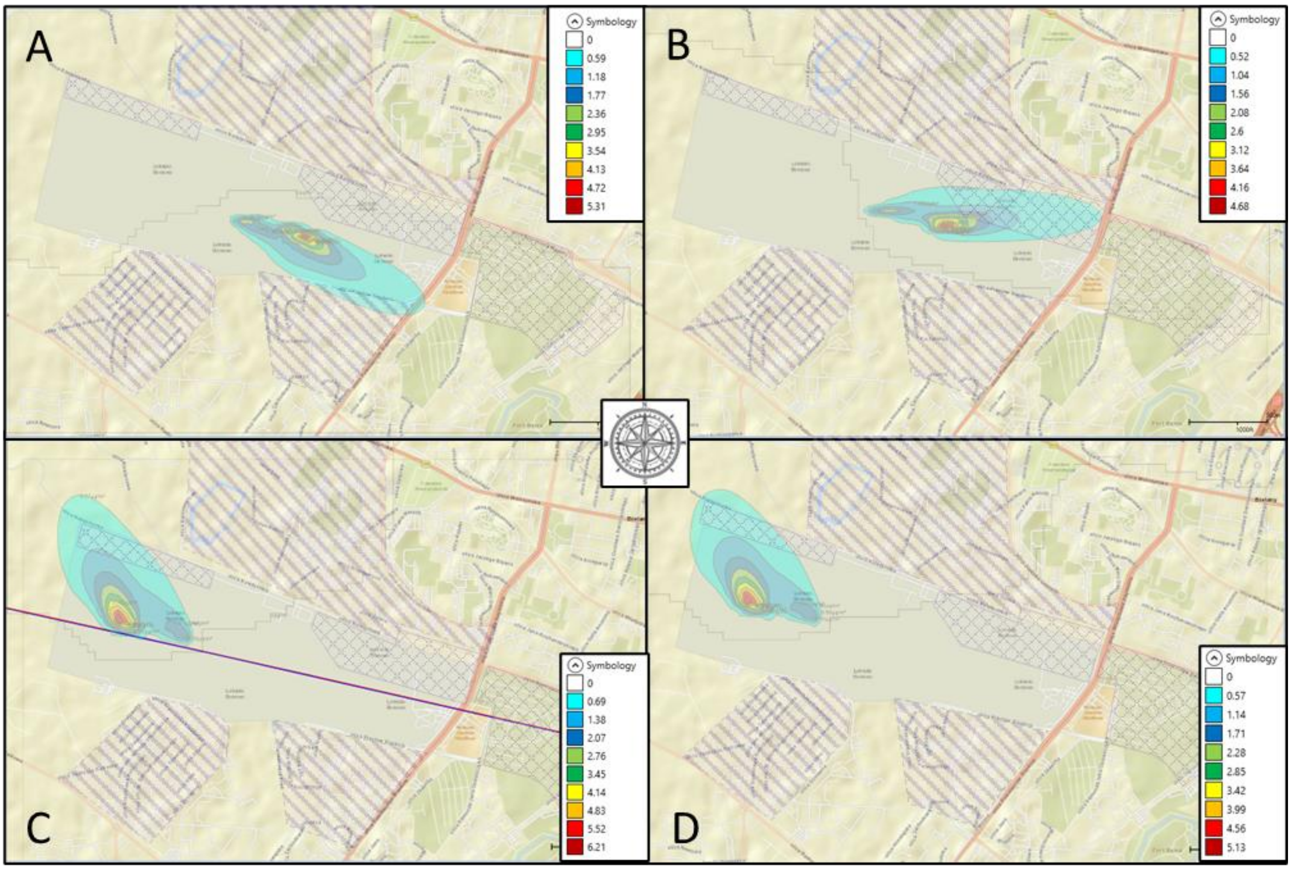

Fig. 4. Nitrogen oxides concentration distribution – C [ng/m^3]: A – wind: 270 deg 6 m/s, B – wind: 270 deg 12 m/s, C – wind 90 deg 3.6 m/s, D – wind 90 deg 7.2 m/s

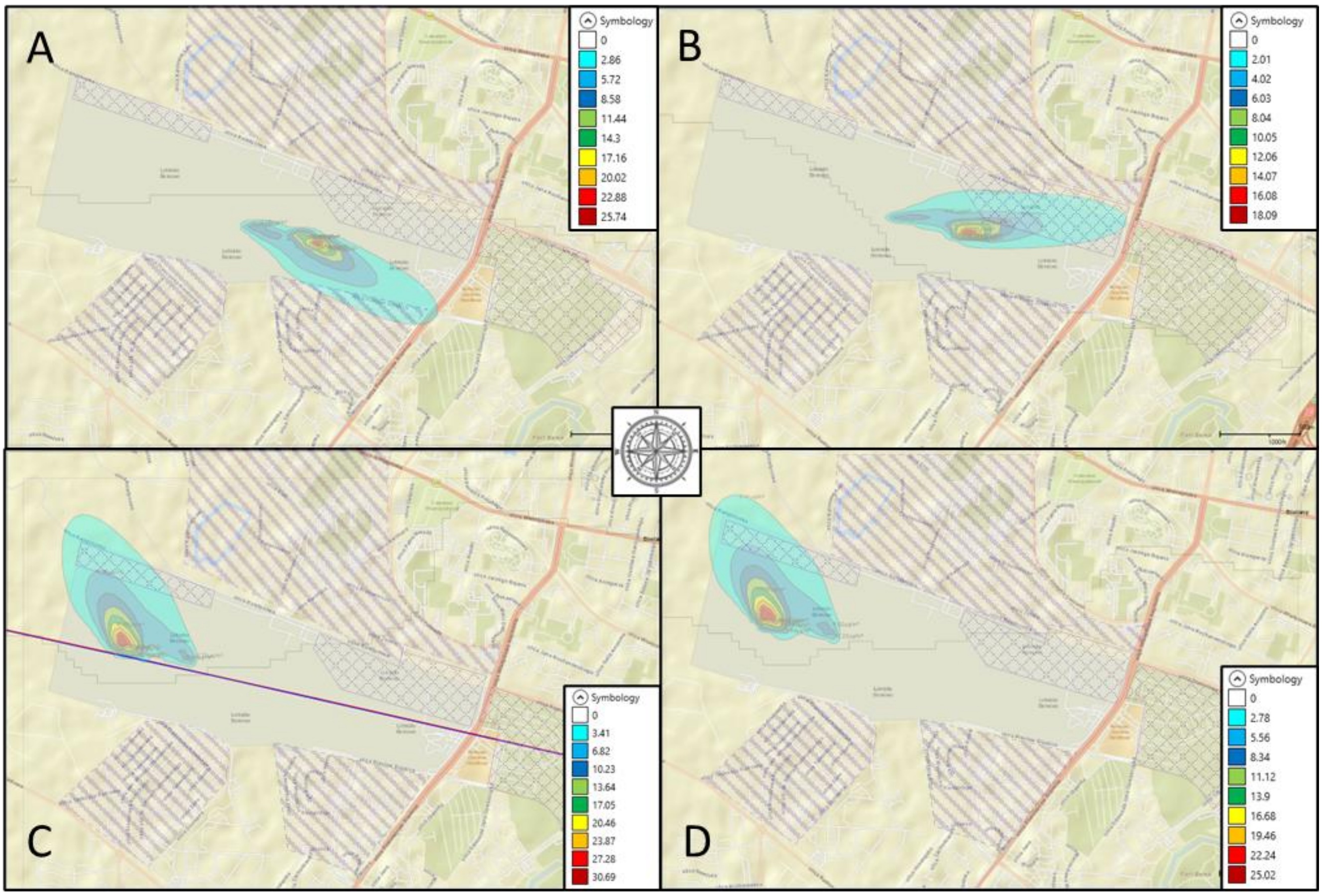

Fig. 5. Carbon Monoxide concentration distribution C [μg/m^3]: A – wind: 270 deg 6 m/s, B – wind: 270 deg 12 m/s, C – wind 90 deg 3.6 m/s, D – wind 90 deg 7.2 m/s

Figure 5 shows the CO concentration distribution. Carbon monoxide emissions result from the incomplete combustion process. In the case of jet engines, which operate with a high air-fuel ratio across most operating ranges, the majority of CO emissions and the highest concentrations are observed along taxiing routes. For piston engines, which typically operate near stoichiometric mixtures (or richer), the CO emission factor remains relatively constant across all flight phases. Richer mixtures also lead to increased CO emission factor; thus, piston engine-propelled aircraft are a significant source of that pollutant. Similar to nitrogen oxides and lead emissions, the highest concentrations of carbon monoxide are found near the end of the runway.

The global shift away from leaded gasoline in the automotive sector has resulted in an increase in the relative contribution of general aviation and stationary industrial sources. Cho highlights it in the research, indicating that roughly 50% of Pb emission comes from aviation emissions [6]. However, the high mobility of an aircraft as a source does not result in a high contribution to local lead concentration in the air. Mutlu and Lee state in their research that measurements show the highest long-term means of lead concentration in the highly industrial South Korean cities like Ulsan, Incheon, or Busan [18]. The largest annual mean Pb concentration level was recorded in 2004 in Incheon and was equal to 136 ng/m^3. Statistical analysis also showed that the highest concentration could be observed from December to May. Since General Aviation activity is the most intensive during the summer season, it might indicate that aviation is not a major contributor to the local pollution. Winter and spring seasons, however, are the times of specifically extensive energy consumption, which can be associated with increased Pb concentration. Lower lead concentration during the cold and dry winter/spring season is also reported by Feinberg on the Centennial Airport [8]. According to the FAA, roughly 1000 takeoff and landing operations are being held on the Centennial Airport, of which 89% are General Aviation operations.

Measurements within this airport show that the monthly averaged lead concentration within the airport varies from 7 to 30 ng/m^3 from month to month. In the cited research, similar tools and methodology were used. Comparison of model results to measurements showed that the approach and results presented in this research are also overestimated. Carr et al in their research from 2011 presented AERMOD model results for comparison with measurements based on the Santa Monica Municipal Airport, on which 200–300 landing and takeoff operations are held every day [4]. The results obtained in this study are similar, keeping in mind that the intensity of air traffic is almost three times higher.

6. Conclusions

The presented results of calculations indicate that the concentration of lead compounds in the air is approximately three orders of magnitude lower than the allowable threshold within the airport area. In addition, analysis shows the surroundings are not exposed to any significant lead concentration in the air. Also taking into consideration the analysis of NO_x and CO, the concentration is very limited and might only gain in importance when added up to the car traffic ingestion emissions. Nearby family allotment gardens are not exposed to the high concentrations of harmful pollutants emitted by the operations of Warsaw-Babice airport. However, the analysis does not consider concentrations resulting from traffic on Warsaw's streets. While this study focuses on airborne lead emissions due to their direct impact on human inhalation exposure, it is important to note that long-term accumulation of lead in soil near airports also poses significant environmental and health risks.

From a sociological point of view, the sudden blocking of the possibility of using traditional lead fuels can be perceived as arbitrary behavior by decision-makers who do not consider the situation of a significant number of aircraft and helicopter users. Usually, such bans are much better received when viable alternatives are pointed out at the same time.

The effects of the human factor will also be a major threat. In the absence of alternatives, some aircraft and helicopter owners will use unsuitable fuel, increasing the likelihood of failure of power units and, as a result, endangering not only the pilots but also their passengers and people/infrastructure on the ground.

Studies using a similar methodology have shown that using the AEDT model to estimate lead concentrations in the vicinity of a local airport leads to results that may be overestimated compared to actual measurements reported in the literature. This indicates that the methodology adopted may be conservative, which is an important aspect in the context of environmental risk assessment. The pollutant concentration values obtained in this research are comparable with those obtained by other researchers [4, 6, 8, 18].

However, an important limitation of the present study is the lack of consideration of emissions associated with the aircraft run-up mode, which, as Carr has shown, can significantly affect local air lead concentrations. Including this stage in future analyses could allow for a more precise assessment of the impact of aviation activities on air quality in the airport environment. Another limitation of this study is the lack of consideration for the actual durations of the individual flight phases. Current research shows significant differences between the real durations of flight phases and those defined in the LTO regulations [12, 15].

The ban on the use of fuel containing TEL will negatively affect the training of airplane and glider pilots. This should be considered in view of the growing shortage of personnel in aviation. The need to replace power units in many airplanes and helicopters will exceed the financial capacity of many aeroclubs, resulting in their demise, entailing restrictions on access to flight schools.

It seems that a good solution would be to ban the production of power units requiring leaded gasoline. There should be a transition period during which the currently used engines of this type would be taken out of service due to normal wear and tear.

In view of the rapid development of unleaded aviation fuels in recent years, the abrupt withdrawal of leaded fuels from the European market, without providing access to an alternative, is clearly premature and will have a negative impact on the owners of 16,000 aircraft. It is important to keep in mind the even larger number of European Union citizens whose business activities are based on the logistical, recreational, and sporting aspects of general aviation.

The development of G100UL fuel offered the possibility of eliminating leaded gasoline in general aviation. After more than a decade of research, it received FAA approval. It is currently the only certified lead-free substitute for high-octane fuel. There is growing interest in this fuel in the US [2, 11]. Despite this success, the problem of its availability has yet to be solved. Distributors declare that U.S. demand will not be met until 2026, which allows us to tentatively assume that G100UL will not be available in the European market before 2030. An incentive for a dynamic entry into the European market would be the interest of users in purchasing a supplemental type certificate, the possession of which authorizes the aircraft owner to use G100UL fuel.

Wind speed has a significant impact on local concentrations of harmful compounds at airports. Higher wind speeds enhance the dispersion of pollutants, leading to lower localized concentrations, while lower wind speeds contribute to the accumulation of emissions in the vicinity of their sources. This effect underscores the importance of considering meteorological conditions when assessing air quality and pollutant dispersion around airport environments.

The carbon monoxide emission index of reciprocating engines is significantly higher than that of turbine engines. This is a direct result of richer mixtures. Nevertheless, the negative effect that could result from this is significantly reduced by significantly lower mass flow rates through the cylinders.

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