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Health Risk Factors of Emissions from Internal Combustion Engine Vehicles: An Up-to-Date Status of the Problem

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Summary

Introduction: Motor transport with internal combustion engines powered by diesel fuel and gasoline is one of the main sources of ambient air pollution since its emissions pose an urgent medical and environmental challenge.

The objective of the study was to identify priority types of pollutants from emissions of motor vehicles powered by internal combustion engines based on the results of a systematic review in order to substantiate the main preventive strategy to mitigate the associated public health adverse effects.

Methods: We did keyword search for relevant publications in several electronic databases, such as the Russian Science Citation Index, CyberLeninka, Scopus, and WoS. Research papers published in 2000–2021 were selected for the analysis. Out of 103 topical full-text publications, 59 works met the criteria for inclusion in the systematic review.

Results: We observed that atmospheric emissions of internal combustion engines represent a complex agglomeration of gases, vapors, and particulate matter. The chemicals present in the emissions impair the oxygen transport function by inhibiting cellular respiration, cause irritation of mucous membranes, have mutagenic and carcinogenic effects, contribute to the occurrence of acid rains and to global warming. The biological effect of airborne particles largely depends on their size. It has been established that an increase in the number of airborne particles with an aerodynamic diameter less than 10 μm is associated with the risk of endothelial inflammation, thrombosis, increased cell permeability, and DNA methylation. It has been also demonstrated that a 5 $\mu g/m^3$ increment in ambient concentrations of fine particles (< 2.5 μm) causes a 7 % increase in the mortality rate. At the same time, $PM_{2.5}$ exposure-related risks of excess deaths from cardiovascular diseases are twice as high as those posed by exposure to PM_{10}.

Conclusions: Diesel and gasoline engine exhausts are a significant risk factor for human health. An effective preventive strategy should be aimed at replacing heavy hydrocarbon motor fuels by compressed gas using hydrogen cells and electric motors.

Keywords: road transport, internal combustion engine exhausts, air pollution, health risk.

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Факторы риска нарушений здоровья от транспортных выбросов двигателей внутреннего сгорания: современное состояние проблемы

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Резюме

Введение. Автомобильный транспорт с дизельными и бензиновыми двигателями внутреннего сгорания (ДВС), выбросы которых представляют актуальную медико-экологическую проблему, является одним из основных источников загрязнения атмосферного воздуха.

Целью исследования является выявление по результатам систематического обзора приоритетных видов загрязняющих веществ в выбросах автотранспорта с двигателями внутреннего сгорания с целью определения общей стратегии по снижению связанных с ними неблагоприятных последствий для здоровья населения.

Методы. Поиск релевантных публикаций осуществлялся по ключевым словам, размещенным в базах данных и информационных системах, в том числе таких электронных базах данных, как РИНЦ, КиберЛенинка, Scopus, WoS. Для анализа были выбраны научные работы, опубликованные за период 2000–2021 гг. По результатам целевого поиска выявлено 103 полнотекстовые публикации, из них 59 полностью соответствуют критериям включения в систематический обзор.

Результаты. Показано, что выбросы ДВС в атмосферу представляют собой сложную агломерацию газов, паров и взвешенных частиц. Химические вещества, присутствующие в выбросах, нарушают кислородтранспортную функцию, подавляя тканевое дыхание, вызывают раздражение слизистых оболочек, проявляют мутагенное и канцерогенное действие, способствуют возникновению кислотных дождей и глобальному потеплению. Биологическое действие взвешенных в воздухе частиц во многом зависит от их размера. Установлено, что увеличение количества частиц с аэродинамическим диаметром менее 10 мкм в воздухе связано с риском воспаления эндотелия, тромбоза, повышения проницаемости клеток, метилирования ДНК. Показано, что увеличение концентрации в воздухе частиц размером менее 2,5 мкм на каждые 5 мкг/м^3 приводит к увеличению смертности на 7 %. При этом риски дополнительных случаев смерти от сердечно-сосудистых заболеваний при воздействии этих частиц в 2 раза выше по сравнению с частицами большего размера (PM_{10}).

Заключение. Выбросы автомобилей с дизельными и бензиновыми двигателями внутреннего сгорания являются значительным фактором риска для здоровья населения. Эффективная стратегия предотвращения их неблагоприятного воздействия должна быть направлена на замену тяжелых углеводородных моторных топлив сжатым газом с использованием водородных элементов и электродвигателей для транспортных средств.

Ключевые слова: автомобильный транспорт, выбросы двигателей внутреннего сгорания, загрязнение воздуха, риск для здоровья.

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The use of mineral fuel in internal combustion engines (ICE) of motor vehicles is the largest source of air pollution [1–3], which is a major public health concern worldwide [4–8]. Emissions from road transport account for at least 60 % of the total air pollution in the United States, Germany and France. Annual combustion of 31.2 billion tons of motor fuel in 106 billion tons of atmospheric oxygen generates 137.2 billion tons of additional waste [9]. Cars and trucks contribute major percent to road transport exhaust [10].

Exhaust fumes contain from 200 to 300 pollutants and their compounds [11, 12]. At the same time, the term “exhaust fumes” cannot be considered completely correct, since engine emissions include both gases (gas phase) and fine particulate matter (particulate phase).

The objective of the study was to identify, based on the results of a systematic review, priority types of pollutants from emissions of motor vehicles powered by internal combustion engines in order to substantiate the main preventive strategy to mitigate the associated public health adverse effects

Methods. We searched for publications on emissions from internal combustion engine vehicles in several electronic databases, such as the Russian Science Citation Index, CyberLeninka, Scopus, and WoS using the following keywords and phrases: "road transport", "internal combustion engines", "air pollution", and "health risks".

The main criteria for including the results of published works into the systematic analysis were:

– a detailed description of research objects and methods, a quantitative assessment of exposure to the key components of hazardous emissions of internal combustion engine vehicles;

– compliance of the study design and findings to our research objective, and

– statistical significance of values showing the intensity of exposure to certain ICE exhaust pollutants and distribution of related harmful effects.

Research papers published in 2000–2021 were selected for the analysis, and 59 of 103 topical full-text publications met the criteria of inclusion in the systematic review.

Results. Emissions produced by internal combustion engines powered by hydrocarbon fuels, such as gasoline, diesel, and fuel oil, are a complex mixture of gas-, vapor-, and fine particulate-phase materials. Their major pollutants include carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), hydrocarbons, fine, ultrafine and nano-sized carbonaceous particulate matter (PM), hydrofluorocarbon-134a (HFC-134a), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and other chemicals classified as "hazardous air pollutants" [13, 14].

To date, characteristics of the major types of airborne contaminants coming from internal combustion engines utilizing fuels produced from heavy hydrocarbon raw materials, products of their transformation in atmospheric air, and types of exposure-related adverse human health effects have been established (see Table).

Judging by the results of recent national and international research, special attention is paid to aerosol particulate matter (PM) when analyzing ICE emissions [15, 16]. This is due to the fact that numerous

Table. **Components of internal combustion engine emissions and their potential adverse human health effects**
Таблица. **Эмиссионные компоненты двигателей внутреннего сгорания и их возможные вредные эффекты на организм человека**

Exhaust pollutants / Эмиссионные компоненты	Products of their transformation in the atmosphere / Продукты их превращения в атмосфере	Adverse human health effects / Вредное воздействие на организм человека
Gaseous phase / Газовая фаза		
Carbon monoxide / Монооксид углерода, CO	–	Highly toxic to humans: blocks oxygen saturation of hemoglobin, thus preventing its transport; affects cytochrome oxidase, thus impeding tissue respiration; as part of Haldane effect, hampers oxygen release by hemoglobin in tissues / Сильно токсичен для человека: блокирует насыщение гемоглобина кислородом, препятствуя его переносу; воздействует на цитохромоксидазу, затрудняя тканевое дыхание; в рамках феномена Холдена нарушает отдачу кислорода гемоглобином в тканях
Nitrogen oxides / Оксиды азота, NO_x	Nitric acid, ozone / Азотная кислота, озон	Nitrogen dioxide is an airway irritant and a major precursor to ozone. Nitric acid contributes to acidification of air and precipitation (acid rains) / Двуокись азота является раздражителем дыхательных путей и основным предшественником озона. Азотная кислота способствует закислению атмосферных осадков (кислотные дожди)
Sulfur dioxide / Диоксид серы, SO_2	Sulfuric acid / Серная кислота	Sulfur dioxide is an airway irritant. Sulfur acid contributes to acidification of air and precipitation (acid rains) / Диоксид серы является раздражителем дыхательных путей. Серная кислота способствует закислению атмосферных осадков (кислотные дожди)
Carbon dioxide / Углекислый газ	–	Major factor of global warming / Главный фактор глобального потепления
Saturated hydrocarbons (alkanes, < C19) / Насыщенные углеводороды (алканы, < C19)	Aldehydes, alkyl nitrates, ketones / Альдегиды, алкилнитраты, кетоны	Respiratory tract irritation; reaction products are ozone precursors (in the presence of $NO_{x)}$ / Раздражение дыхательных путей. Продукты реакции – предшественники озона (в присутствии NO_x)
Unsaturated hydrocarbons (Alkenes, < C5) / Ненасыщенные углеводороды (Алкены, < C5)	Aldehydes, ketones / Альдегиды, кетоны	Respiratory tract irritation; some alkenes are mutagenic and carcinogenic; reaction products are ozone precursors (in the presence of NO_x) / Раздражение дыхательных путей. Некоторые алкены обладают мутагенными и канцерогенными свойствами. Продукты реакции — предшественники озона (в присутствии NO_x)
Formaldehyde / Формальдегид	Carbon monoxide, hydroperoxyl radicals / Окись углерода, гидропероксильные радикалы	Formaldehyde is a probable human carcinogen and ozone precursor (in the presence of NO_x) / Формальдегид является вероятным канцерогеном для человека и предшественником озона (в присутствии NO_x)
Higher aldehydes (e.g. acrolein) / Высшие альдегиды (напр., акролеин)	Peroxyacyl nitrates / Пероксиацилнитраты	Respiratory tract and eye irritation; impairs immunity / Раздражение дыхательных путей и глаз; снижение иммунитета
Monocyclic aromatic compounds (e.g. benzene, toluene) / Моноциклические ароматические соединения (напр., бензол, толуол)	Hydroxylated nitro derivatives / Гидроксилированные нитропроизводные	Benzene is toxic and carcinogenic to humans; some reaction products are mutagenic for bacteria (Ames test) / Бензол токсичен и канцерогенен для человека. Некоторые продукты реакции являются мутагенными для бактерий (анализ Эймса)

Exhaust pollutants / Эмиссионные компоненты	Products of their transformation in the atmosphere / Продукты их превращения в атмосфере	Adverse human health effects / Вредное воздействие на организм человека
PAHs (< 5 rings) e.g. phenanthrene, fluoranthene) / ПАУ (< 5 колец) (например, фенантрен, фторантен)	Nitro-PAHs (< 5 rings) / Нитро-ПАУ (< 5 колец)	Some of these PAHs and nitro-PAHs are mutagenic and carcinogenic to humans / Некоторые из этих ПАУ и нитро-ПАУ являются доказанными мутагенами и канцерогенами
Nitro-PAHs (2 and 3 rings) (e.g. nitronaphthalene) / Нитро-ПАУ (2 и 3 кольца) (напр., нитронафталины)	Quinones and hydroxylated nitro-derivatives / Хиноны и гидроксилированные нитропроизводные	Some reaction products are mutagenic (Ames test) / Некоторые продукты реакции обладают мутагенными свойствами (анализ Эймса)
Solid phase / Фаза твёрдых частиц		
Elemental carbon / Элементарный углерод	–	Nuclei absorb organic compounds; the aerodynamic size of less than 1 micrometer allows deep penetration of particles into the lungs (alveoli), while the size of < 100 nm allows penetration through the walls of blood vessels directly into the blood flow / Ядра адсорбируют органические соединения; аэродинамический размер частиц менее 1 мкм позволяет проникать глубоко в легкие (альвеолы), а при размере менее 100 нм проникают через стенки сосудов непосредственно в кровоток
Magnetite / Магнетит		Plays a role in the development of Alzheimer's disease / Влияет на развитие болезни Альцгеймера
Inorganic sulfates / Неорганические сульфаты	–	Respiratory tract irritation / Раздражение дыхательных путей
Aliphatic hydrocarbons / Алифатические углеводороды (C14–C35)	They are oxidized in the air as a result of photochemical reactions in the presence of nitrogen dioxide, forming toxic oxygen-containing compounds; possibly aldehydes, ketones and alkyl nitrates. They are the components contributing to smog / Окисляются в воздухе в результате фотохимических реакций в присутствии двуокиси азота, образуя ядовитые кислородсодержащие соединения; возможно, альдегиды, кетоны и алкилнитраты. Являются одним из компонентов, участвующим в образовании смога	Narcotic, possible mutagenic effects. General toxic effects are not well understood / Наркотическое действие, возможно мутагенное действие. Общетоксические эффекты изучены недостаточно
PAHs (≥ 4 rings; e.g. pyrene, benzo(a)pyrene) / ПАУ (4 кольца и более; например, пирен, бенз(а)пирен)	Nitro-PAHs (≥ 4 rings), nitro-PAH lactones / Нитро-ПАУ (4 кольца и более), нитро-ПАУ-лактоны	Larger PAHs are major causes of carcinogenic effect of combustion products. Many nitro-PAHs are strong mutagens and carcinogens / Более крупные ПАУ являются основными источниками канцерогенного эффекта в выбросах при сжигании. Многие нитро-ПАУ являются сильнодействующими мутагенами и канцерогенами
Nitro-PAHs (≥ 3 rings; e.g. nitropyrenes) / Нитро-ПАУ (3 кольца и более; например нитропирены)	Hydroxylated nitro derivatives / Гидроксилированные нитропроизводные	Many nitro-PAHs are strong mutagens and carcinogens / Многие нитро-ПАУ являются сильнодействующими мутагенами и канцерогенами

Abbreviation: PAHs, polycyclic aromatic hydrocarbons.
Аббревиатура: ПАУ, полициклические ароматические углеводороды.

studies have proven a negative impact of fine particle on human health, including the incidence [17–20] and mortality [21, 22] from diseases of cardiovascular and respiratory systems. Contained fine particles include nickel, vanadium, sulfates, nitrates, and silicon compounds [23]. The proportion of nickel in particulate matter is a marker of air pollution with ICE vehicle emissions [24]. Fine PM consists of various airborne objects, such as dust, dirt, soot, smoke, and liquid droplets [25, 26].

It has been demonstrated that human health effects of fine particles are largely determined by their aerodynamic diameter: particles smaller than 10 micrometers (PM_{10}) are able to pass through the bronchial tree and accumulate in the lung tissue; particles smaller than 2.5 µm ($PM_{2.5}$) reach the alveoli, and those smaller than 0.1 µm ($PM_{0.1}$) penetrate the blood flow [27–30].

Suspended particles smaller than 10 µm (PM_{10}) have no safe exposure threshold and are considered priority pollutants in terms of public health impact [31]. The proportion of such particles in ambient air of industrial cities ranges from 30 % to 60 % of TSP [32–36] and is mainly attributed to motor vehicle exhausts, tire and road surface wear, contribution of which to emissions ranges from 30 % to 40 % [37]. Transport-related $PM_{2.5}$ was found to induce more pronounced systemic inflammation than industrial particles of similar composition [38]. Diesel exhaust is the major source of PM_{10} and $PM_{2.5}$ [39]. Up to 90 % of solid particles emitted by internal combustion engines powered by hydrocarbon fuels are fine particles ($PM_{2.5}$). They are usually used as the most informative marker of transport-related air pollution intensity produced by internal combustion engines, including for assessing the benefits of using various types of motor fuel, for example, liquefied natural gas compared to diesel or gasoline as regards their potential adverse effects on public health [40].

The analysis of big data arrays, cohort studies and meta-analysis has shown correlations between PM_{10} air pollution and stoke hospitalizations [41–43] as well as $PM_{2.5}$ air levels and the risk of stroke [44] and deaths from ischemic and hemorrhagic stroke

[45]. It has also revealed that nanoparticles are able to penetrate alveoli [46] and cause inflammation in cellular endothelium [47], which induces increased cell permeability [48] and DNA methylation [49]; arterial fibrillation [50] and autonomous disturbances [8] are observed, leading to higher mortality rates in the population. Thus, every 5 μg/m³ of increment of ambient $PM_{2.5}$ level accounts for a 7 % increase in the mortality rate [51]. At the same time, the risks of additional deaths from cardiovascular diseases related to $PM_{2.5}$ exposure are twice as high as those associated with PM_{10} [28].

It is assumed that ultrafine fractions of carbonaceous particulate matter pose the most serious health challenge compared to other ICE pollutants [52–55]. Human exposure to the latter usually occurs in the form of a three-phase system: "gas – liquid – particulate matter", where liquid and partially gaseous phases are absorbed by solid carbon particles, resulting in the phenomenon of deep penetration of liquid and gaseous pollutants to alveoli, the most vulnerable part of the respiratory system [56–58]. It should be noted that ICE pollutants, when not carried in the absorbed form by carbon ultrafine particles, are almost completely absorbed in the upper respiratory tract.

Fine and nano-sized fractions of carbon particles are capable of agglomeration and agglutination, which significantly increases their sorption potential (Figure).

Due to certain biological inertness, elemental carbon particles that have reached the alveoli are capable of accumulation in pulmonary tissue, thus increasing the risk of diseases in the etiology of which carbon black plays an important role as age and duration of employment increase.

Thus, both gaseous and especially particulate phases of emissions from internal combustion engine vehicles are significant public health risk factors.

Conclusions. Gaseous and aerosol air pollution attributed to motor vehicles with internal combustion engines is one of the most important risk factors for non-communicable diseases in the population. The gaseous phase of exhaust fumes mainly affects the respiratory system causing mucous membrane irritation and gas exchange disturbances. Certain gaseous emission components have potential or proven mutagenic and carcinogenic properties and suppress immunity. In addition, gas-phase components of vehicle emissions contribute to acid rains and global warming. Health effects of particulate matter emitted by internal combustion engines are determined by the aerodynamic diameter of particles that can accumulate in pulmonary tissue (PM_{10}), reach the alveoli ($PM_{2.5}$), and penetrate into the blood flow ($PM_{0.1}$). Airborne particles affect not only lungs, but also the cardiovascular system and increase risks of death from ischemic and hemorrhagic strokes.

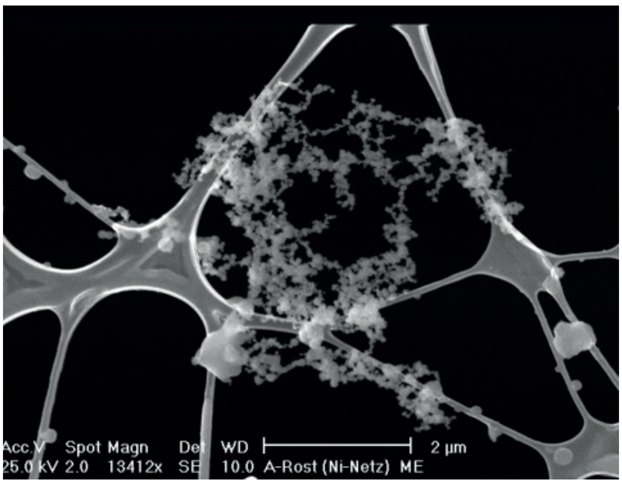

Figure. Agglomeration of airborne carbon and silicon nanoparticles in the vicinity of open-pit mines in Kola Peninsula [59]

Рисунок. Агломерационный комплекс витающих в воздухе наночастиц углерода и кремния в районе размещения открытых карьеров горнодобывающих предприятий Кольского региона [59]

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