Knowledge Gap on Health Impact of Transportation-related Emissions in Cold Climate Cities

Knowledge Synthesis Grant: Living Within the Earth's Carrying Capacity

Short title: Cold Climate Transportation Related Air Pollution

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Abstract

This study aims to review and understand the magnitude of increased emission rates of vehicles in cold climate cities, explore the impact of increased local air pollution and population exposure to air contaminants, and understand the relevant health impacts. The study is conducted within the concept of urban carrying capacity (UCC) and considers its relevance for Canadian cities. It answers how much scientific evidence supports the reduced UCC related to transportation emission in a cold climate and identifies the critical interdisciplinary knowledge gaps.

The report is organized into three parts, (i) the concept of the UCC and its relevance to the study, (ii) transportation emissions in a cold climate, and (iii) the health impact of transportation emissions in cold weather.

Individual elements of the research have been addressed in the literature. Models, assessment tools, and assessment criteria have already been defined for UCC. However, none of the previous studies investigated UCC for cold climate air pollution. There is a general lack of UCC studies that relate transportation to air pollution.

Emission factors and the impact of extreme cold (<-7°C) on vehicular emissions are not well studied. There are limited data available. The effect of cold climate on the performance and efficiency of aftertreatment systems is not well documented.

Short-term health outcomes for testing associations between pollution and health outcomes after controlling for temperatures were studied before. The complex modifying effect of cold temperatures on pollution levels and health outcomes were studied in limited studies. It has been shown that cold temperatures aggravate the health impact of pollutants.

The primary research gap is on the relevancy of cold climate vehicle emission factors and health outcomes in UCC. Interdisciplinary research on quantifying emission rates, analyzing impacts on concentration on the ground at cold climate regions, and modelling health outcomes will guide Canadian cities' future policies and technologies.

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Nomenclature

ASC	*Ammonia slip catalyst*
ATS	*Aftertreatment system*
BC	*Black carbon*
CAC	*Criteria air contaminant*
CI	*Compression ignition (or diesel engine)*
CNG	*Compressed natural gas*
CO	*Carbon monoxide*
DOC	*Diesel oxidation catalyst*
DPF	*Diesel particulate filter*
EV	*Electric vehicle*
GDI	*Gasoline direct injection*
GHG	*Greenhouse gas emission*
HC	*Unburned hydrocarbons*
HDV	*Heavy-duty vehicle*
HEV	*Hybrid electric vehicle*
LDV	*Light duty vehicle*
LNT	*Lean NOx trap*
LPG	*Liquified petroleum gas*
MDV	*Medium duty vehicle*
NO	*Nitrogen monoxide*
NO_2	*Nitrogen dioxide*
NOx	*Nitrogen oxides*
O_3	*Ozone*
PAH	*Polynuclear aromatic hydrocarbon*
PEMS	*Portable emission measurement system*
PFI	*Port fuel injection*
PHEV	*Plug-in hybrid electric vehicle*
PM	*Particulate matter*
PM10	*Particulate matters with diameter ≤ 10µm*
PM2.5	*Particulate matters with diameter ≤ 2.5µm*
PMP	*Particle measurement program*
PN	*Particle number*
RDE	*Real-world driving emissions*
SCR	*Selective catalytic reduction (of NOx)*
SI	*Spark ignition*
SOA	*Secondary organic aerosol*
SULEV	*Super ultra-low emission vehicle*
TWC	*Three-way catalytic converter*
UCC	*Urban carrying capacity*
UFP	*Ultrafine particles*
ULCC	*Urban land carrying capacity*
VGT	*Variable geometry turbine*
VOC	*Volatile organic compounds*
VVT	*Variable valve timing*

Key findings

UCC includes a wide range of parameters such as air, water, recycling, and energy. Many studies looked at the air quality aspect of UCC, and models are available to analyze the impact of technologies and policies on the air quality element of UCC. However, no study has focused on the relationship between UCC and air quality in cold climate regions. Among limited studies on transportation cold climate emissions, a few of them indicated changes of emission factors at -7°C. No analysis was found for impacts of the ambient temperature of below -7°C on vehicle emissions. Overall, the combined relationships among cold temperatures, pollution, and related health outcomes are under investigated. Many reviewed studies described short-term health outcomes testing associations between pollution and health outcomes after controlling for temperatures. Only a few studies formally explored the complex modifying effect of cold temperatures on pollution levels and health outcomes. A small number of papers identified that cold temperatures aggravated the health impact of pollutants like O_3, $PM_{2.5}$, PM_{10}, and CO. For example, their association with increased cardiovascular disease and mortality in the cold seasons. Specific findings from this study include:

Vehicular Emissions: Several factors cause the effects of cold weather on vehicle emissions. The influential factors are categorized into three groups: (a) vehicle technology, (b) driving and use behaviour, and (c) vehicle calibration in connection with target emission regulations. In the vehicle technology, the compromised performance of the vehicle exhaust filtration system due to cold temperature, poor fuel vaporization and mixing, increased engine friction, lube oil degradation, and low conversion efficiency of not sufficiently warm exhaust after-treatment systems of vehicles are influential parameters. Hybrid electric vehicles also suffer from high tailpipe emissions if the powertrain does not often use the engine, causing an even colder exhaust system than that of conventional vehicles. As the regulation does not require vehicle emission testing below -7°C, and even that is not needed in many engines and vehicle classes, the engine and exhaust aftertreatment control units may not be strictly calibrated for emission reduction below the legislation threshold of -7°C. These factors can cause up to 10 times more harmful vehicular emissions (HC, CO, NOx, particles) in cold climate, depending on ambient temperature, vehicle technology, cold climate vehicle calibration, and trip duration.

Human Behaviour: Drivers in a cold climate often use more idling time for vehicle warm-up and cabin heating, leading to high tailpipe emissions. Vehicle tampering is another factor to consider. Lack of regular emission testing and enforcement has caused exhaust tampering and removal of filtration systems, particularly in cold climate environments when using filters are problematic. These significantly degrade the emissions control performance of conventional and hybrid electric vehicles in cold temperatures.

Health Effects: The studied health outcomes in this context included a variety of diseases and other outcomes. Some of the health outcomes reported were directly associated with the cold season, implying the seasonality of diseases and increased health vulnerability in the cold season, regardless of pollution. Season modifies the short-term effects of air pollution on morbidity. Mostly, seasonal relationships were found while removing effects of temperature, suggesting that seasonal exposures imply that other co-existing characteristics may impact health besides the temperature. For example, the variation in the air pollution chemical mixture composition and altered pollutants' concentrations resulting from altered emissions and meteorological conditions. However, the combined associations between warm/cold seasons, pollutants, and health outcomes were seldom identifiable in the literature. This represents a clear gap in our understanding of the impact of cold temperatures on pollution and related health outcomes.

Policy Effects: The study found many possible policy implications. Those include 1) expansion of vehicle emission testing protocols in the emission regulations to lower temperatures suitable for Canadian cities, 2) increased in-use vehicle emission testing in cold regions, 3) enforcement to reduce exhaust tampering, and 4) use of remote sensing technologies and portable emission testing under real-world driving conditions in a cold climate as part of market surveillance of performance of vehicle technologies in a cold environment.

Future Research Needs:

(a) Measurement and quantification of cold climate impact on vehicle technologies and vehicle emission profile;
(b) Public exposure to vehicle emissions in a cold climate;
(c) Policy recommendation for vehicle emission regulations in Canada under cold climate operation;
(d) Integrated UCC and air pollution modelling for cold climate;
(e) Chemical characterization of vehicle emissions and air pollutants in a cold climate to assess health impacts.

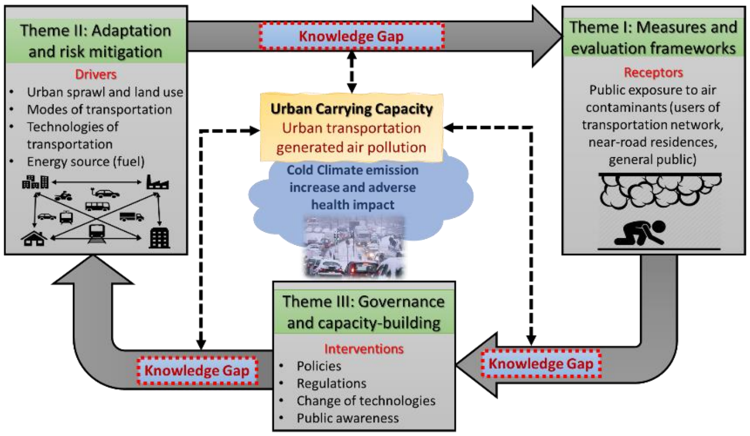


Figure 1- Schematic of critical findings, existing knowledge gaps, relationships between research themes

Part I – Urban Carrying Capacity

Carrying capacity is the maximum amount of a given species in a habitat so that the habitat is not significantly degraded or damaged [1]. Urban environmental powers are summed up in Urban Carrying Capacity (UCC) concept. There are many definitions and scopes available in the literature for UCC [2,3]. A widely accepted definition and evaluation method of UCC does not exist. The idea deals with environmental loads, carriers, resources, and human interactions with the environment. The term carrying capacity comes from ecology in the early 1890's definition of how much land can be used to graze livestock. In other words, how much is a sustainable size of a herd that can be fed in any particular ecosystem? UCC carries the exact definition, but in the interactions between humans, ecosystem and natural resources, infrastructure, and society in a city. Many types of approaches have been used to model UCC. Societal, environmental, and system approaches are the main three types of UCC models [4]. Any UCC model needs to be evaluated using an assessment method. Examples of assessment models include indicator-benchmark comparison (comparing parameters with a threshold) [5], pressure-state-response (human activity generates negative pressure on the environment and environmental degradation generates a response from the environment) [6], and energy analysis (using thermodynamics law) [7].

UCC is used widely in urban planning. All aspects of urban planning and development are affected by the UCC, and the imbalance between UCC and urban development can seriously impair the quality of life in the city and, at the same time, degrade the environment. Cities are often overcrowded and densely populated. The ecological capacities are not sufficient to support a sustainable city. Urban carrying capacity can be defined as the high tolerance of a municipality from several inputs or specific activities; Inputs and activities directly related to the extent and level of development of the city. When planning the city, care should be taken that the inputs or actions (population, pollution, energy consumption, etc.) do not exceed a specific limit (indicator-benchmark comparison). The limit can be set in a variety of ways. Still, in any case, it must ensure that no damage is imposed to the urban health indicators (such as public health, the environment, life satisfaction). It is a prerequisite for sustainable development, and sustainable urban development is essential in the current era of rapidly increasing urbanization [3].

UCC concept is applied to many indicators. It may cover the environmental capacity of a city for water resources and reuse, garbage disposal and recycling, and ambient air quality and toxic emission sources. The focus of the current report is air quality in cold climate cities and UCC relationships to transportation emissions. Although it is difficult to isolate one impact from others as UCC covers a broad range of indicators, focusing on cold climate aspects of transportation is appropriate for knowledge synthesis and identifying the gaps. Six primary elements in the contexts of traffic-related air pollution were identified. Those elements include (1) vehicle transportation emissions in cold climate cities, (2) urban planning of a cold climate city (network design, infrastructure) that impacts travel behaviour, (3) urban ecology, (4) the social aspect, (5) health impacts, and (6) air and carbon pollution (greenhouse gas emissions, GHGs). Figure 1 represents the primary elements of UCC concerning transportation-generated air pollution and its health impacts in cold climate cities. This figure shows the connections between each component. For example, transportation emissions directly impact health, but it impacts air pollution and GHGs of the city. Urban planning impacts transportation emissions by changing the distanced travel and modes of transportation. It also has social impacts as transportation infrastructure is related to economic and social development in the city. A systematic approach [8,9] that considers all aspects of intercorrelation seems more appropriate in UCC studies; however, knowledge synthesis could be focused on a narrow and specific area. Among all identified impacts, only vehicle emissions, air pollution, and health impacts are considered in this study.

UCC indicators and categories

For an accurate development of the UCC concept and its use in solving problems related to urban development, it is necessary to know the indicators and factors affecting it. The indicators determine the UCC limit in each city, and also, using the indicators, the status of urban development at a particular time can be compared with the UCC limits. In general, UCC indicators are divided into two broad categories, natural and manufactured, which, in addition to meeting the human demands, must be within a specific range not to cause significant and irreversible damage [3].

There are many effective indicators in UCC, and they cover almost all the features of urban life and urban development. A review study [10] looked into 48 studies to evaluate the popular and effective indicators in UCC assessments, which reached 335 indicators discussed in the studies. They divided all indicators into categories, including energy, land-use, transportation, infrastructure, water, waste treatment, air quality, natural conditions, disaster, population, education, social service, living quality, economic development, technology, ecological environment, public perception, agriculture and poultry and cultural aspects.

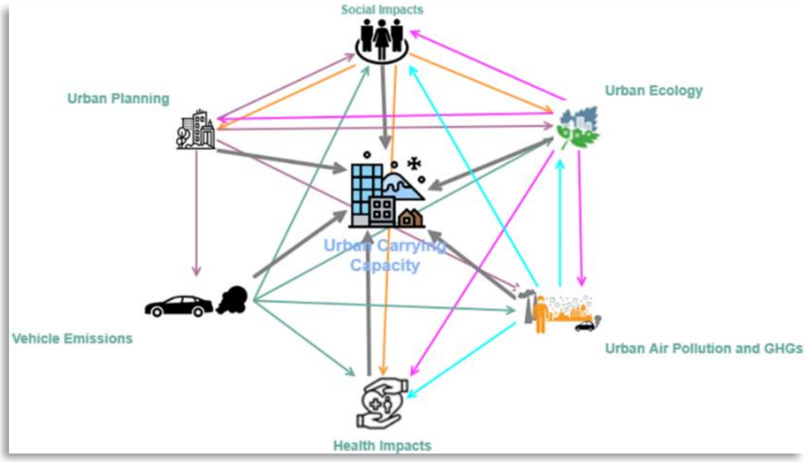


Figure 2-Main elements of UCC considered for the impact of transportation emissions in a cold climate city

Not all of the indicators are equally effective, and for each purpose, some of them are much more effective. Some of these indicators have been repeated many times in the literature and have a high research value. In contrast, others might be very appropriate in practice and have a significant impact. Therefore, they implemented a popularity-suitability bi-dimensional model to evaluate the effect of each indicator in terms of popularity and suitability. The data of a Chinese city were used in the model. It was concluded that the most effective indicators in UCC are per capita GDP, per capita water supply, per capita daily domestic water consumption, population density, the ratio of sewage treated, energy consumption per unit of GDP, green coverage rate of built-up area and per capita green space. In another study [11], the indicators were categorized more generally and listed the UCC components as environmental impacts and natural resources, infrastructure and urban services, public perception, institution setting and society supporting capacity. Each indicator's allowable or desirable value can be obtained from different sources and then must be compared in a suitable ratio with the values directly measured from the city or urban area. The approach helps decision-makers make better policies for the city, and the output can be used in urban planning.

Although a complete urban carrying capacity assessment is one in which all the available indicators can be seen, there are many studies to look at specific indicators or components and their particular effects on UCC. Transportation carrying capacity was assessed in Indonesian cities to balance supply and demand by using land-use control [12]. In terms of the urban population, UCC model was developed based on geographic information system data to estimate population capacity in each land-use subspace [13]. In another study, an ecological sensitivity analysis was used to assess the UCC, focusing on land-related indicators called urban land carrying capacity (ULCC) [14]. The UCC concept was used to provide a sustainability index of the urban population based on public green space [15].

A study in the Iranian capital city selected 30 indicators for evaluation. Based on the indicators and in each zone defined a variable called load number to compare it with the load number limit for each indicator under the concept of UCC. The indicators of this study have been selected and categorized based on the PSIR (Pressure-State-Impact-Response) framework and the concepts of sustainability and UCC. The results showed that no urban zone is in the range of desirable carrying capacity [16]. These studies are generally carried out to examine one aspect of the UCC (e.g., the environment). Still, due to the close relationship between the indicators, other indicators from other sectors are also included in the analysis. The carrying capacity of the environment in a Chinese city in a case study was measured and assessed [17]. The UCC model consists of 4 components, each component consisting of several indicators. The indicators are quantitative and measurable, and for each element, the current situation is compared to the available capacity. The Euclidean vector was used to sum the indices obtained in each component, and a general conclusion was reached for the two years 2005 and 2010. In 2010, as social support increases and pollution decreases, the city can tolerate more human development as the UCC increases by 3%. Table 1 and Table 2 summarize indicators and categories of UCC.

Table 1- Selected indicators and their categories [16]

Categories	Indicators
Landform	Elevation
	Slope
Disaster vulnerability	Earthquake vulnerability
Groundwater depth	Groundwater depth
Urban land use per capita	Residential
	Educational
	Sanitary
	Greenspace
Urban land-use area	Build up / total area
	Transportation / total area
	Green space / total area
	Transportation network
Population	Gross population density
	Population growth rate
Energy consumption	Gas consumption
	Gas consumption/gas resources
	Gas consumption rate
	Electricity consumption

	Electricity consumption / Electricity resources Electricity consumption rate
Material consumption	Water consumption Water consumption/water resources Water consumption rate Annual groundwater extraction
Waste production	Waste production Waste production rate Recycling rate
Air pollution	Average CO emission Polluted days of the year
Traffic congestion	Traffic volume

Table 2- Selected indicators and their categories [17]

Categories	**Indicators**
Natural resources	Water supply Construction land
Environment	SO2 emission NO2 emission PM10 emission Chemical oxygen demand discharge NH4-N discharge
Ecosystem	Forest area Leaf area index
Society support	GDP per capita The proportion of total GDP invested in environmental protection

UCC assessment models

Due to the close relationship between the urban carrying capacity concept and urban sustainability, UCC assessment methods are very similar to sustainability assessment [18,19].

The ecological footprint is a sustainability assessment method first introduced by William E. Rees (1992). In this method, available resources and environmental impacts determine how much land is needed for each activity compared to existing capacity. Appropriate carrying capacity (also called biocapacity) is expressed in global hectares (gha) or gha per capita units. By collecting data from the regional population, the ecological footprint can be defined for the indicators (with the same unit as the biocapacity) to compare with the region's capability and determine the status in terms of UCC. The difference between ecological footprint and biocapacity is the output of the analysis and determines the level of sustainability of the region [4,20,21].

IPAT equation is another method for UCC assessment that is used initially to model environmental impacts. In this equation (I = PAT), "I" represents the environmental impacts. The environment can withstand a certain amount of influence, which is called the carrying capacity. "P" in the equation stands for population, and "A" represents affluence and is a parameter that considers population consumption. In a way, it is always assumed that with the increase of affluence and production in society, consumption also increases and increases the environmental impact of the population. "T" is a representative for technology in the equation and is defined by the view that increasing the level of technology increases environmental impact. In each analysis, the technology parameter can be different. For example, in climate change analysis, the amount of greenhouse gas emissions per capita as technology can be considered in equation [22]. But it must be borne in mind that by increasing productivity due to technology development, environmental effects can be reduced, and the above view should be reconsidered [23].

Energy analysis is a thermodynamic-based method for UCC assessment using the finite nature of energy (Wei et al., 2015). Usually, by defining an alternative energy parameter (called emergy), all the energy required directly or indirectly for activities is calculated [24]. The assessment can then be completed by estimating the maximum possible energy consumption for sustainable activity (given the available resources). In defining the energy parameter, all different types of energy (including energy sources, materials, time, human labours and services), access levels to them and their properties (including renewability, concentration, resource exchange dynamics) are considered [25].

Another method that establishes a good relationship between the components of analysis is pressure-state-response (PSR). This method uses a cause and effect framework for analysis and categorizes the indicators of analysis. According to this method, human activities put "pressure" on the system (population growth, energy consumption, etc.). This pressure changes the "state" of the system (such as land use in a city), and ultimately the human "response" is needed to prevent further destruction [26]. Newer versions of this method have also been developed, such as PSIR, including "impact" [16] .

A straightforward and versatile method for UCC assessment is indicator-benchmark comparison. In this method, for UCC indicators, values such as minimum, recommended, acceptable, threshold, etc., are defined. Based on these values, the indicators of the analysis site are scored to determine the status of UCC. Also, in this analysis, each indicator and variable in the overall analysis has weight compared to other indicators that the researcher determines according to the data and the target of the research [18,27,28].

Air quality in UCC context

Environmental impact assessment is essential to sustainable development [29]. Air pollution is one of the most critical environmental impacts of human activities. Due to the crucial role of UCC assessment in sustainable urban development, air quality indicators are vital in this assessment. In addition to being directly considered in many UCC assessments, air pollution also impacts other significant indicators of urban carrying capacity, such as public health [30].

The concentration of nitrogen dioxide in the city was used as an indicator for energy consumption [31]. With the help of a model, a specific limit of NO_2 emission is specified as the carrying capacity for energy.

In another study [17], SO_2, NO_2 and PM_{10} emissions were considered as environmental indicators whose values were compared with their assimilative capacity as a threshold. The assimilative capacity of an atmospheric pollutant depends on parameters such as meteorological conditions, terrain characteristics, and emission characteristics. Two indicators of "average annual carbon dioxide emissions" and "number of polluted days per year" in each area of the city were used as air pollution indicators [16].

In another study [18], air pollution was discussed as waste in the air and waste in water, CO_2 emissions, solid waste and sewage as environmental indicators. Pollutants studied include SO_2, CO, NO_2 and PM_{10}, and the number of days of polluted air per year.

In Canada, air quality is assessed by comparing it with a set of federally mandated indicators. The air quality management system (AQMS) provides a guide for better air quality management across Canada. It is based on Canadian Ambient Air Quality Standards (CAAQS). CAAQS includes limits on harmful substances of NO_2, SO_2, $PM_{2.5}$, and O_3. They were first introduced in the Canadian Environmental Act, 1999. CAAQS are continuously updated based on the latest scientific findings. The latest CAAQS limits will be effective in 2025. The concept of CAAQS and its relation to AQMD is similar to the indicator-benchmark-comparison method of UCC modelling. However, an integrated approach to using the UCC concept for air quality management purposes does not exist. For example, the annual average limits are not based on the capacity of any certain airshed to hold emissions, based on localized ecological conditions and weather state. Limit values and calculation procedures are merely based on extensive health impact studies.

Part II- Vehicular emissions in a cold climate

Criteria air contaminants and vehicular emissions

A vehicle generates emissions when it is at the beginning of the trip (cold start emissions), during the trip (hot exhaust and resuspended dust particles), idling, and at the end of the trip when the vehicle is parked (evaporative emissions). All modern on-road and off-road vehicles contain exhaust aftertreatment (*i.e*., filtration) systems that contribute to lowering criteria air contaminants. However, suppose the vehicle exhaust aftertreatment system is not operating in its design conditions (mainly temperature-related). In that case, it may emit different pollutants such as unburned hydrocarbons and CO, or NO_2 and NH_3, which can contribute to public health risks [32,33].

Moreover, the exhaust of a vehicle contains many toxic substances for which only four main components are regulated: CO, HC, NOx, and PM. Many other classes of harmful material are included in the four main categories but are not measured separately. For example, HC consists of a wide range of hydrocarbons that may consist of polycyclic aromatic hydrocarbons (PAHs); a few are known carcinogens. NOx has a different health impact, and the NOx fraction may change significantly depending on vehicle technology. PM contains sulphate and nitrate, organic matter, metals (engine lube oil and engine wear), and black carbon. PM is an indicator of the total mass of particles emitted from the exhaust. Still, particle size and particle number (PN) in the nano-size range are significantly more important when new engine technologies are used. PN has been only introduced as an emission limit just recently in a limited European class of vehicles.

The other issue with vehicular emissions is that many studies have found that in-use emissions of vehicles are significantly higher than certification limits due to lack of maintenance, quality of fuel and lube oil, exhaust tampering, and adverse weather conditions such as cold climate. In many cases, emissions are sacrificed for power and fuel economy. Moreover, a cold climate can impact vehicle emissions' characteristics and the resulting air quality. Reducing harmful exhaust gas emissions in conventional vehicles relies on exhaust after-treatment systems, which require operating temperatures of 300°C to 400°C, which is not available during the initial cold phase period of vehicle operation. For example, during a cold start, the temperature of the particulate filter is low, which is further intensified under cold climate since it will take longer for the particulate filter to reach the required operating temperature [34]. Thus, PM emissions from the engine directly go to the environment. Furthermore, the duration of the cold phase period in a vehicle increases substantially under cold temperatures. In cold climate cities, most urban short trips (*e.g*., 10-15 min) conclude before the vehicle has reached a fully warmed-up condition. For instance, on a cold winter day, most vehicles, after travelling a short distance to a school drop-off zone, are still in the vehicle cold phase with the low-efficiency operation of the exhaust aftertreatment systems.

Thus, harmful vehicular emissions drastically increase as vehicle startup temperature decreases [35], while existing emission regulations only consider vehicles' tailpipe emission and operating temperature down to -7°C, well above many countries' cold season temperatures. Hence, it is expected that engine control unit calibrations are not tuned to maximize emission reduction below that limit. The levels of air pollution in below-zero climates may also be intensified by house heating combustion processes and meteorological conditions, such as thermal inversions, which trap and increase pollutants' levels. Thus, extreme cold (or hot) temperatures can influence pollutants levels in the air and the chemical mixtures [36]. These conditions may affect public exposure to harmful vehicular emissions in cold temperatures increasing health risks and loss of productivity and life.

There are many ways to categorize vehicles, including based on vehicle sizes such as LDV, MDV, and HDV, vehicle fuel such as gasoline, diesel, ethanol, biodiesel, CNG, LPG or based on vehicle powertrain such as CI, SI, HEV, PHEV, EV. For the purpose of this study, vehicles are categorized based on powertrain as CACs and GHGs are dependent on vehicle powertrain and emission regulations levels imposed by various jurisdictions. As the subject of the study is urban transportation, it is expected that vehicle fleets that are mostly operating in cities are a matter of concern. Terms including diesel and CI vehicles, also gasoline and SI vehicles are used interchangeably, noting that not all SI vehicles use gasoline. SI vehicles also use LPG, CNG, among many other fuels.

Vehicle exhaust contains many species that only a few of them are regulated. Regulated exhaust emissions from both gasoline and diesel vehicles are HC, CO, NOx, and PM. Some new regulations also include PN emissions. NMVOCs, CH_4, CO_2, PAHs, PANs are examples of non-regulated emissions. Primary emission regulations in the European Union, US, and Canada are similar but not identical for different vehicles.

The stricter emission regulations have caused automotive manufacturers to adopt many technologies to reduce exhaust emissions and improve the vehicle's fuel economy. Improvements are made on the engine side, such as using an electronic control system, sensors to monitor emissions, better fuel injection and improved air-fuel mixing, among other technological advances such as VVT, VGT, electronic throttle, GDI, and hybridization. Aftertreatment technologies are used to reduce emissions further. The exhaust of a modern vehicle includes many components such as TWC, DOC, DPF, SCR, ASC, and LNT, depending on fuel, technology, and vehicle application.

Among many exhaust and non-exhaust vehicle-related emissions, two toxic compounds of particulates and NOx are discussed further as they impose relatively higher health impact and risk.

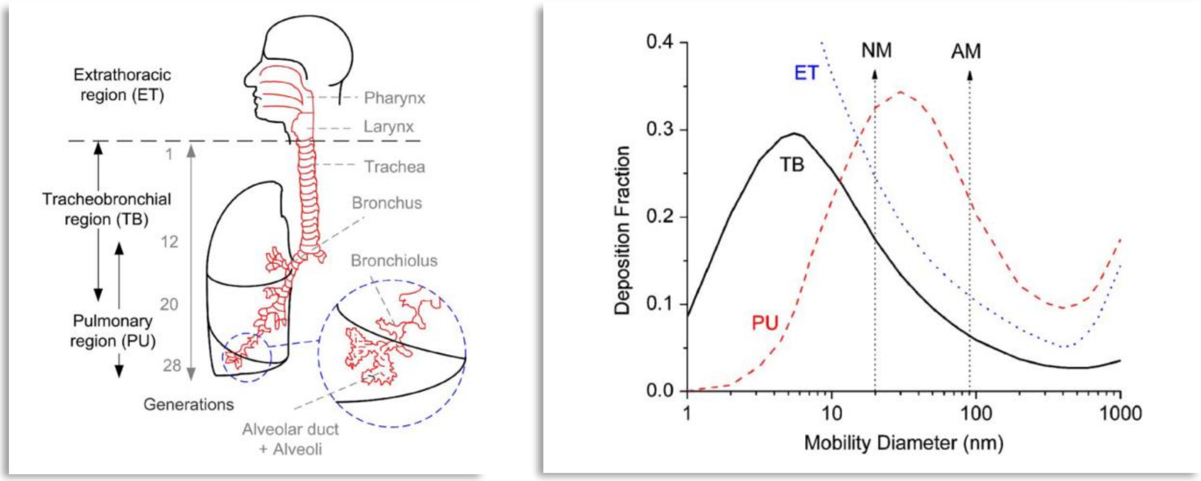
Particulate emissions

Any engine emits particulates. Gasoline SI engines with port fuel injection or light gaseous fuel emit fewer particles, hence, not regulated. The most advanced gasoline SI engines with direct fuel injection systems emit fine particles characterized by PN and are now regulated in the European Union. A use of GPF seems necessary to meet emission limit values for those types of engines. The issue of transportation-related exhaust particles is significantly related to diesel engines. As part of diesel diffusion flame combustion, particulates are generated and emitted into the atmosphere if not treated in the exhaust.

Diesel engine technologies have progressed considerably owing to strengthening emission regulations based on health impact studies. Those improvements contain both in-cylinder and combustion advances and after-treatment system (ATS) technologies that include many types of filters. Fuel atomization and air-fuel mixing improved considerably as the fuel injection technology progressed to high injection pressure from less than a few hundred bars to more than 2000 bars. Other measures include double-stage turbocharging, variable geometry turbocharger, enhanced cylinder and charge movement. Diesel engine particle emissions were traditionally quantified by mass (PM). Recent findings on the health impact of diesel emission and progress in instrumentation led to the additional particle number (PN) metrics. For example, the increase of ambient particle number concentration has been associated with ambulatory blood pressure, a known cause of cardiovascular diseases [37]. The general definition of particle size range to be categorized as ultrafine particle (UFP) particles below 100 nm in the vehicle's exhaust. UFP is often referred to as particles that do not significantly contribute to the total particle mass. European Particle Measurement Program (PMP) is designed for a consistent and repeatable exhaust UFP measurement method [38]. Definition of UFP counting measurement in ambient air varies over a size range up to 700 nm, but it is known that UFPs are largely anthropogenic and traffic-related. For example, a recent study showed the impact of COVID-19-related traffic reduction on the immediate reduction of roadside UFPs [39]. A review study has shown the impact of motor vehicles on UFPs in cities worldwide and the effects of using DPF in diesel engines on the effective reduction of ambient UFPs [40]. A five-year Canadian study on Toronto's roadside reported an average value of 19,440 #/cm^3 for particle sizes between 8nm-300nm [41]. Roadside nanoparticles are a complex mixture of particles from several sources affected by atmospheric processing, local co-pollutants and meteorology. Nanoparticles are primary nanoparticles formed in high-temperature combustion, delayed primary particles formed as gaseous compounds nucleate during the cooling and dilution process, and secondary nanoparticles formed from gaseous precursors via atmospheric photochemistry [42].

DPFs are the only known technologies that remove exhaust UFPs. Without DPF, other technologies may reduce PM to below emission regulation limits, but PN would be high. The physical properties of particles, such as size distribution and number concentration, depend on soot generation processes such as particle inception and agglomeration. In modern diesel engines, primary particles are fewer and smaller. The primary difference is particle size, which is much smaller for newer engines and is more dangerous for health. The average size of UFPs for a modern diesel engine is between 10-15 nm, while an older engine's average particle size is around 35 nm and the range of particle size is wider. Previous studies have shown that despite stringent diesel emission standards and considerable reduction of PM (e.g., from 0.6 g/bhp.hr to 0.01 g/bhp.hr by a factor of 60 based on US EPA Tier values), PN emissions have remained relatively constant, as UFPs constitutes only a small fraction of the total mass of particles [43]. Only after implementing DPFs in the ATS UFPs have dropped considerably. A study shows that PN emissions of a Euro III diesel vehicle equipped with DPF are an order of magnitude lower than that of a Euro IV diesel vehicle [44]. A comparison of heavy-duty diesel trucks of the model years 2007 and 2010 (the latest has DPF) shows a significant reduction in all regulated and unregulated emissions and a 72% reduction of PN[45]. DPF operates on the basis of UFPs filtration and then regeneration. Regeneration means burning the collected particles in the exhaust and requires exhaust heat. Cold climate impacts the process.

The high sensitivity of the human lung to the diesel exhaust UFPs makes the untreated exhaust of a modern diesel engine extremely hazardous despite the low particle mass due to the size and the high number of UFPs. Diesel particle deposition into the human lung depends on many parameters related to particles' physical and chemical properties such as mass, number, surface area, and volatile fraction ratio[46,47]. Figure 2 shows a schematic of the human respiratory tract and particle size deposition on various parts. The diesel particle size of 10-35 nm shows a significant deposition potential.



(a) (b)

Figure 3: (a) A schematic representation of the human respiratory tract, (b) Calculated deposition fraction of inhaled particles as a function of particle diameter for the three regions of the human respiratory system: extrathoracic (ET), tracheobronchial (TB), and pulmonary (PU). The arrows indicate characteristic nucleation (NM, mass median) and accumulation (AM, surface area median) mode particle diameter. [46]

Diesel particles may bear the potential for an increased deposition in those lung regions, which are highly susceptible to lung cancer [48]. The UFPs have a substantial surface-to-volume ratio that is favourable for depositing volatile toxic compounds such as PAHs on the particle surface when the particle is cooled down and diluted in the atmosphere. PAHs use ultrafine diesel particles as vehicles to effectively enter the human body and increase oxidative stress and inflammation within the body cells [49]. Some studies have shown traces of UFPs in the respiratory tract and extrapulmonary organs such as the liver and the brain[50]. It was found later on that UFPs are much more significant risk than known previously [51]. Another research has indicated independent impacts of PM2.5 and UFPs on human health, encouraging policies to regulate both ambient PM and PN [52].

NOx emissions

Raw combustion emission of transportation contains both NO and NO_2. The mixture is commonly referred to as NOx. The ratio of NO_2 to NOx varies depending on operating conditions, but a typical value of 30% has been reported with recent modern diesel engines producing less NO_2. After the DPF introduction to the market, roadside ambient particles were effectively reduced, but due to many catalysts in a current ATS, ambient NO_2 became a concern in European cities. Health impact studies are focused on NOx as a mixture rather than individual effects of NO or NO_2. Still, it seems the long-term effects of NO_2 on mortality and morbidity are as high as particles [53,54]. Many cities have reduced their particle-related air pollution, but NO_2 exceedances are a concern. In Europe, an estimated 10,000 premature deaths were attributed to vehicles' NOx emissions in 2013 [55]. NO_2 is also categorized as a strong GHG.

In modern diesel engines, the ATS includes a diesel oxidation catalyst (DOC) for NO to NO_2 conversion that will then be used in DPF for soot burning and regeneration at a lower temperature. NO_2 is a more active agent than O_2 for soot burning. The engine NOx emissions and scaped NO_2 are removed from the exhaust using an SCR catalyst and urea injection. Removing NOx as a stable gas from exhaust using SCR is often traded with engine power and efficiency. There have been incidents of diesel engine manufacturers defeating the emission regulations by increased NOx emissions in real-world driving of the diesel on average of 4-7 times and up to 38 times the allowable limits[56].

A recent study in the US shows that historical trends of NOx emissions from diesel vehicles are not as promising as gasoline vehicles. While gasoline vehicles' NOx emissions have been steadily decreased, NOx emissions of diesel trucks showed no change in the 1990s and a gradual decline afterward. Even with SCR implementation in modern diesel engines since 2010, actual NOx emissions are higher than expected [57].

The new engines use advanced timing, high injection pressures and high supercharging to improve fuel consumption and reduce CO2. Fuel consumption of new Euro 6 engines is up to 8% better than Euro 4/5 without SCR but using EGR and consequently engine out NOx peaks with the new engines are much higher with the older one. Over time the NOx limit of diesel emission regulations has decreased considerably. For example, for the heavy-duty truck in the US EPA Tier regulation, values decreased from 10.7 g/bhp.hr to 0.02 g/bhp.hr by a factor of 535. By introducing SCR in ATS of diesel engines, higher combustion temperature for an increased raw NOx to be removed by SCR. The presence of DOC in the exhaust for NO2 supply to DPF also increased NO2 to NOx ratio of diesel exhaust.

Impact of ATS on emission reduction

Diesel ATS is a proven technology for the effective reduction of emissions. Studies have shown a significant decrease in real-world driving PM and PN emissions of diesel vehicles using DPF and reducing NOx emissions using SCR and EGR.

A certified DPF is known to remove the diesel UFPs in a size range of 20 nm to 300 nm with a more than 99% filtration efficiency. PN's removal efficiency above 99% over a test cycle is a standard DPF certification process for retrofit purposes in some justifications. A study showed using DPF retrofitted heavy-duty diesel trucks in Switzerland would reduce air quality by 75% to 80% based on particle count [58] .

Besides regulated emissions, DPFs are reducing other emissions. An earlier study showed that DPF reduced total PM by 98%, and similar reductions were observed for all significant PM constituents. Considerable reduction of formaldehyde, acetaldehyde, fluoranthene and its derivatives were observed. The species of toxicological concern, such as certain PAHs, formaldehyde, and acetaldehyde, were reduced significantly [2008-01-0333]. DPFs reduce all diesel exhaust solid particles, including oil-ash engine wear metals, to ambient air level [59]. A Euro 3 diesel engine retrofitted with DPF emits lower PN than a Euro 4 or Euro 5 diesel engine. In contrast, Euro 5 SCR diesel engine has shown remarkable NOx reduction and minimum ammonia slip [44].

Comparison of Euro V, Euro V EEV, and Euro VI diesel bus emissions showed an effective reduction of PM1, BC, and LSDA due to DPF to the atmospheric background level [60]. SCR was shown to effectively reduce NOx emissions close to the standard limit of 3.5 g/kWh in an SCR truck under real-world driving conditions. Although the truck was not Euro VI, emissions were close to Euro VI limits [61].

Exhaust emissions from thousands of heavy-duty diesel trucks were measured and analyzed over several years at the Port of Oakland and the Caldecott Tunnel in the San Francisco Bay Area to evaluate the effectiveness of ATS on trucks' real-world emissions. It was shown that DPF and SCR effectively reduced BC and NOx emissions. For 2010+ truck models, 94% less BC and 76% less NOx were measured compared to 1994–2006 models. If an older engine with SCR is retrofitted to DPF, exhaust NO2 emissions were increased by a factor of 6 [62]. A truck emission study in a traffic tunnel in 2014, 2015, and 2018 and a comparison with previous campaigns showed the effectiveness of DPF and SCR on emission reduction. As the US emission control levels changed in 2010, the truck fleet's PDF and SCR penetration rates were 91% and 59%, respectively. A similar study showed a DPF penetration rate at 5% and an SCR penetration rate at 2% before 2010. The study showed BC and NOx emission decrease of the fleet by 79% and 57%. NO2 emissions of the fleet remained constant despite intentional NO to NO2 conversion in DPF, which shows the effectiveness of SCR on NO2 removal. The study showed that SCR effectively removes NOx emissions by 30 g/kg or 90% compared to pre-2004 non-SCR engines. The impact of emission control devices on GHGs was also studied. The truck fleet's global warming potential in California was compared between no FPF engines of 1965-2006 MY and DPF+SCR engines of 2010+ MY. The approximate CO2-equivalent global warming potential estimated in 20 years was calculated at ~6500 g/kg for no DPF fleet and ~3500 g/kg for the DPF+SCR fleet, reducing ~45% [63,64]. The benefit of adopting DPF+SCR for California's truck fleet is estimated to be at a 65% net decrease in the social cost of statewide exposure to diesel truck emissions (-3.3 billion 2018 US dollars per year) and a 3% net decrease in global warming potential-weighted emission factor. Significant reductions in PM, BC, NOx emissions were reported due to the DPF and SCR implementation in the truck fleet compared to 2013, 2015, and 2017 [65]. DPF is also helpful in reducing secondary organic aerosol (SOA) formation potential in the atmosphere. A drastic reduction in the SOA precursor emissions for a hot-start DPF-equipped diesel vehicle was reported approximately two orders of magnitude less than the hot-start non-DPF-equipped diesel engines [66].

Aspects of cold climate impacts on UCC

In cold climate regions, the physical and chemical properties of the atmosphere are altered significantly. Figure 4 shows examples of such changes. Physical properties of the atmosphere, chemical kinetics, sun radiation, and intense atmospheric temperature inversion periods are the ones that influence the air quality the most. The alteration of air characteristics affects the air quality even if the emission rates are constant. In cold climate conditions, transportation emissions are considerably increased due to factors shown in Figure 5.

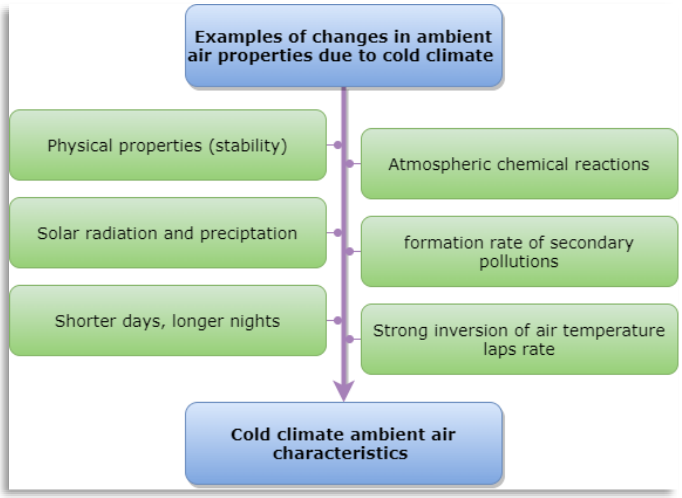


Figure 4: Impact of cold climate on air quality, drivers, and relationship to UCC

Cold temperature impact on vehicle emissions

Increased fuel consumption and decreased engine temperature are well-known issues since all engine types have challenges in the start-up period. At the beginning of the engine operation, due to thermodynamics equilibration with the ambient environment, engine parts, combustion chamber, oil, coolant, fuel system, and fuel are cold. As the engine design operating temperature is much higher than any ambient temperature, starting the engine even in warm weather is categorized as a cold start. The warm start happens after the engine has been working for a while and gets re-started.

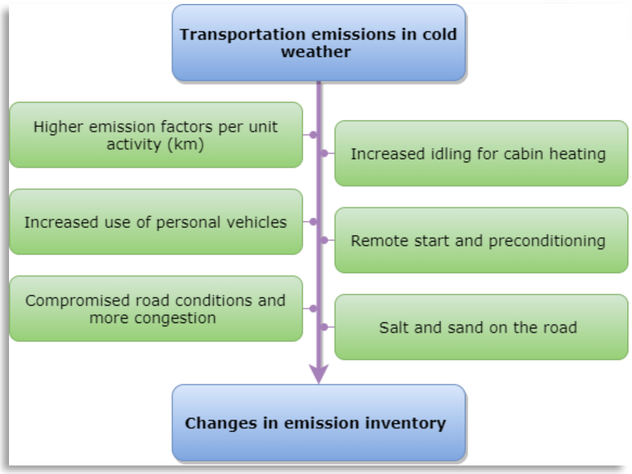


Figure 5: Impact of cold climate on vehicle emission rate, drivers, and relationship to UCC

A few seconds after the engine starts, the relatively cold temperature causes less fuel atomization, vaporization, air mixing, re-condensation of fuel droplets on cold surfaces, poor combustion, and high engine torque demand due to increased frictional losses of high viscosity lube oil, and more. At the same time, the exhaust temperature is low, and emission rates are high. Emissions are not eliminated in the exhaust due to disabled exhaust filtration systems. As the engine and exhaust warm up, the issues are resolved, and regular operation resumes. The modern engine employs a wide range of technologies to mitigate cold-start emissions and reduce the warm-up period's required time. Most engine emissions are generated during a cold start-up period in a standard emission measurement test cycle.

The issue of cold climate impact on vehicle and engine emissions has similarities with the cold-start period. After the start period, if the ambient is not too cold, many issues are resolved. Otherwise, several effects remain, and by each stop-start of the engine (occasional vehicle turnoff or mode switch in HEVs and PHEVs), the same issues will arise due to fast cooling off the engine and exhaust system. Figure 6 shows the possible impacts of cold climate on various engine emissions.

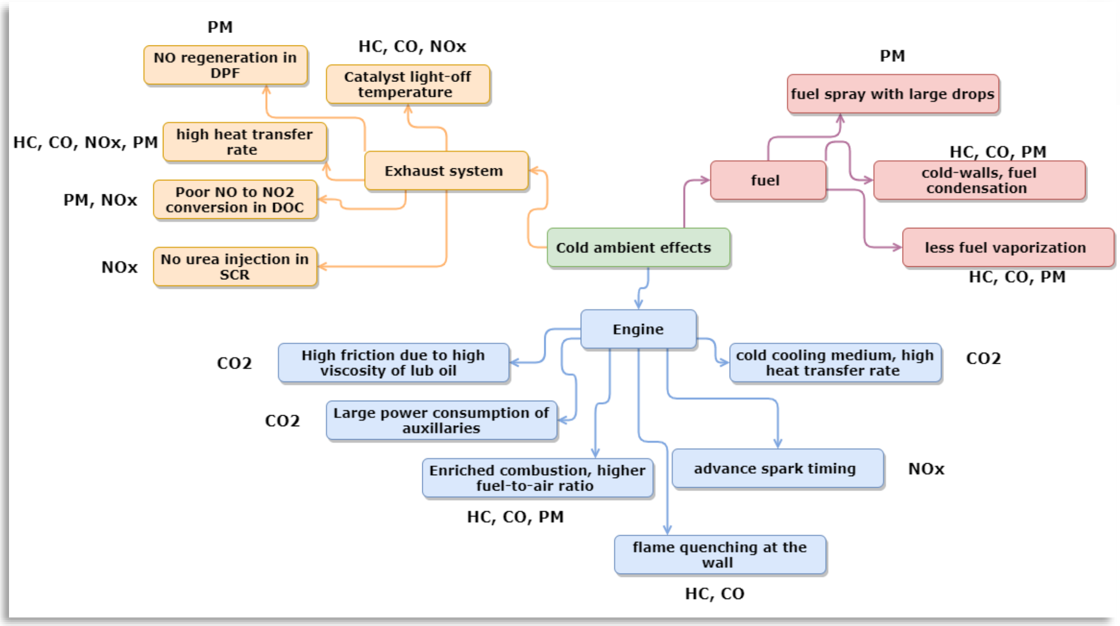


Figure 6: Various impacts of cold climate on vehicle emissions

Effects of cold ambient and cold start on diesel and gasoline engine emissions are summarized in Table 3.

Table 3: Summary of vehicle emission studies and cold climate

Subject	Methodology and conditions	Major findings	Ref	Keyword
Vehicle emission testing	30°C and -7°C, Gasoline, E10 and E15 passenger car	A significant increase in PM, PN, BC	67	Vehicle Emission
Ambient air in the city center	Average temperature, the impact of cold start	Increased ambient CO PM remained constant	68	Ambient air, cold start
Chassis dynamometer, cold chamber	+23°C and +1°C, two passenger vehicles, gasoline and LPG	Increase THC and CO, mixed results for NOx, prolonged catalyst warm-up period	69	Vehicle emission
COPERT emission modelling	Impact of cold start and fleet renewal	50% of CH4 and CO, 40% of NMVOCs are generated in cold start.	70	Emission modelling
Chassis dynamometer, cold chamber	Two Euro6 light-duty diesel cars at -7°C and +23°C	CO, HC was higher but diluted over the test cycle, particulate	71	Emission testing

Subject	Methodology and conditions	Major findings	Ref	Keyword
		remained unchanged, NOx was increased		
Review study	Comparing cold start cold emissions for GDI and PFI engines	Increased emission in most studies, maximum by ten times	72	Lit review
PFI and GDI vehicle chassis test	+23°C, -7°C, and -18°C	driving cycle dependency of emissions at cold ambient	73	Vehicle emission testing
PFI and GDI in a test cell	+22°C, -7°C and NEDC cycle	150%-200% PN increase in a cold climate	38	Vehicle emission testing
SI and CI vehicles in a cold chamber	+24°C and -7°C	Substantial increase of cold climate emissions for CO, HC. Mixed results for NOx.	74	Vehicle emission testing
GDI and PFI vehicle on the chassis dynamometer	+30°C and -7°C, testing all emissions including PN	Increase of all emissions except NOx	75	Vehicle emission testing
GDI and diesel vehicles on a chassis dynamometer	+23°C and -7°C, all emissions	CO2 increase, PM and PN increase only for GDI, NOx increase in diesel engines	76	Vehicle emission testing
Cold start RDE	20°C	Large contribution of cold-start emissions	77	Vehicle emission testing
Coolant temperature and cold start	The diesel engine in the laboratory and change of coolant temperature	An increase of coolant temperature from 20°C to 60°C improved emissions	78	Engine emission testing
Impact of cold climate on pollution	Ambient air studies for NO2 and NOx over a long time	Significant increase of NO2/NOx ratio as temperature drops	79	Ambient air
SOA formation potential	The testing exhaust of gasoline vehicles for VOCs	IVOC increase in cold start	80	Exhaust speciation of gasoline vehicles

Subject	Methodology and conditions	Major findings	Ref	Keyword
Impact of engine oil and coolant temperature	Engine test cell, diesel engine raw emissions	Impact of coolant T on emissions	81	Engine emission
Cold start idling	Three light-duty diesel vehicles, Euro5, idle testing	Increased all emissions except NOx at cold start	82	Vehicle emission testing at idle
Cold start and hot start NEDC	Gasoline Euro4 vehicle on a chassis dynamometer and NEDC	Highly dependent on the test section of NEDC. The highest increase in the UDC section and for NMHC, HC, CO, and NOx, in order.	83	Vehicle emission testing
WLTC diesel and gasoline testing	Emission testing at +23°C and -7°C for 12 vehicles	Significant increase of all emissions	84	Vehicle emission testing
SOA formation potential of exhaust	Chassis dynamometer, cold-start emissions of a large fleet	Larger contribution of older gasoline vehicles to SOA formation at cold start	85	Vehicle emission testing
Cold start emissions at cold ambient	A gasoline engine, engine dyno, -10°C, +25°C, +45°C	Higher HC and CO at first 60s and lower NOx at -10°C	86	Engine emission testing
Cold phase emissions of RDE	Impact of the ambient temperature of +1°C and +17°C of gasoline and diesel vehicle on cold phase emission of RDE using PEMS	The most increase observed in NOX of diesel, no considerable change I gasoline emissions	87	PEMS-RDE
GDI vehicle emission	Chassis dyno, large feet (82 vehicles), GDI, PFI, cold start comparison	Higher PM for all GDIs, larger organic gas fractions in cold start	88	Vehicle emission testing

Subject	Methodology and conditions	Major findings	Ref	Keyword
PN in cold and warm climate close to rad	Near-road emission testing in a long experimental campaign between -19°C and +30°C	3.8 times overall PN emissions	89	Ambient, near-rad testing
Preheating intake to reduce emission	Euro5 diesel engine, engine lab, intake heating	Reduced emissions by intake heating	90	Engine testing, intake heating
Cold start energy consumption	Using emission testing data, cold start energy consumption was calculated for ambient of -6.7°C and 24°C	Considerable fuel consumption penalty at cold climate cold start	91	Emission database and calculations

A comparison of gaseous emissions and particulates of passenger vehicles was reported with gasoline and alcohol at 30°C and -7°C ambient temperature. The particulate emissions increased significantly [67].

In Brisbane, Australia, it was shown that cold start emissions of CO in the central city in the afternoon cause an increase in ambient CO concentration. No change in ambient particulate emissions was observed[68].

Two passenger vehicles with Euro 3 and Euro 6 emission regulation levels were tested in a controlled-ambient test chamber at +1°C and +23°C on a standard driving cycle chassis dynamometer with gasoline LPG. Emissions at cold temperatures were higher at all stages. The time to reach catalyst conversion was 100s for the warm test and 160s for the cold test. The most increased emissions were THC and CO [69].

A modelling study using COPERT showed the impact of cold-start emissions on cumulative fleet emissions in Poland. The study showed that nearly 50% of CO, CH_4, NMVOCs are emitted in the cold start phase of the fleet. NOx and PM2.5 results were not changed between cold start and warm operation periods [70].

Two light-duty passenger diesel vehicles with the most recent emission regulation limit of Euro6d were tested in a cold chamber test cell on a chassis dynamometer. Emission in cold testing at -7°C was generally higher, but CO and HC emissions were diluted considerably over the 30 min-23 km test cycle. Particulate emissions remained relatively constant. The only emission increased in cold climate testing was NOx. Further research on cold climate NOx emissions for diesel-SCR vehicles and RDE tests was recommended [71].

Cold start cold ambient emissions of GDI and PFI gasoline vehicles were compared at +30°C and -7°C. It was found emissions were increased in cold climate cold start mode by as high as ten times. GDI engines emitted much higher PM and PN [72].

Comparison of GDI and PFI vehicle emissions at +22°C, -7°C, and -18°C showed significant CO, THC, and particulate emission increase in FTP-75 cycle, while no significant changes were observed in the US06 driving cycle [73].

PN is a concern for the GDI engines. The European limits are set to 6×10^{11} #/km. Using GPF showed effective reduction of PN below limits even at cold ambient temperatures in a recent real-world driving emission study [92,38].

The increased emissions of cold-start for both SI and CI engines are summarized in Figure 7.

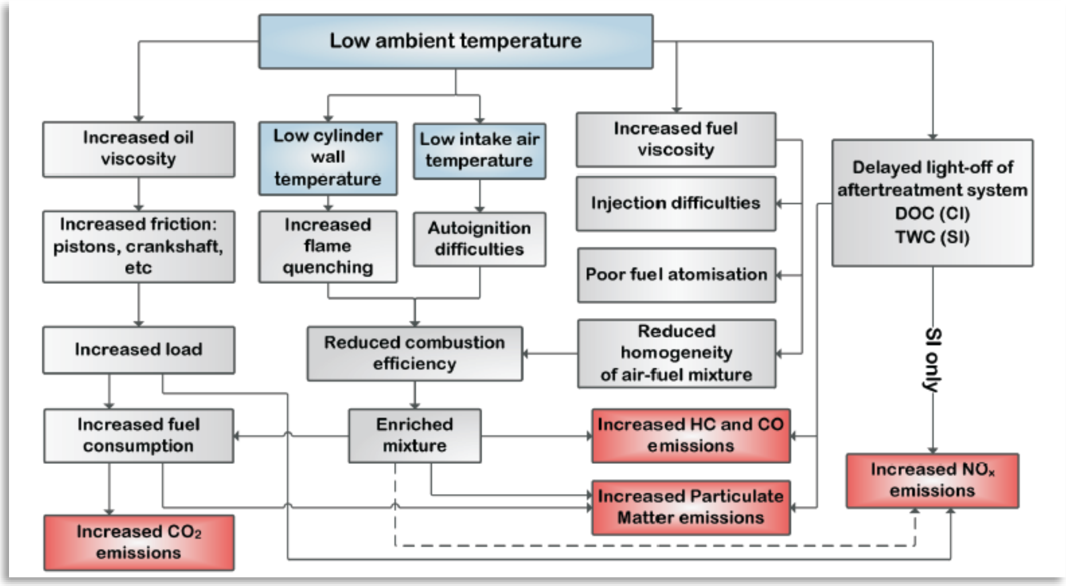


Figure 7- Cause and effect diagram of fundamental difficulties of cold start in low ambient temperature for SI and CI engines [93]

Ten light-duty SI vehicles (Euro 4 and Euro 5) and four CI vehicles (Euro 5) were tested at +24°C and -7°C. The study concluded that the current -7°C emission testing regulation is not enough to cover all possible emission increases. It shows significant improvements in Euro5 vehicle emissions in cold climates than Euro4 vehicles, but no progress was observed for fuel consumption [74].

A decrease in ambient temperature from 30°C to −7°C significantly increased fuel consumption and vehicle emissions except for NOx. The results emphasize the need for not neglecting PFI engine particulate emissions in cold climates [75].

Eight diesel and six gasoline in-use vehicles were tested for cold climate effects on emissions, comparing +23°C and -7°C with various exhaust emission control technologies. It was found that CO_2 emissions were higher for both diesel and GDI cars, with diesel vehicles exhibiting more increase. PM and PN remained unchanged in diesel vehicles but increased in GDI vehicles. However, diesel vehicle NOx emissions were raised up to 3 times for cold ambient testing of diesel vehicles [76].

It was suggested that the cold start emissions need to be included in the urban section of the RDE certification emission test as it contributes to 8% of CO and 5% of PN even at high >20°C ambient conditions [77].

Increasing engine coolant temperature improved cold-start emissions of a diesel engine [78].

A long-term study of ambient air NO2 and NOx concentration showed a significant NO2/NOx ratio at cold climate temperatures due to cold start emission impacts of vehicles [79] as shown in Figure 8. It was found that tightened emission regulations in the US significantly reduced the SOA formation potential of gasoline vehicles by reducing IVOC of exhaust. However, cold start IVOC were higher for all vehicles independent of emission control technology [80].

The detailed impact of the cold operation on volumetric efficiency, fuel consumption, and emissions was investigated in a diesel engine by variation of coolant and engine lubricating oil temperature. The coolant temperature variation between 90°C and -30°C doubled pollutant emissions [81].

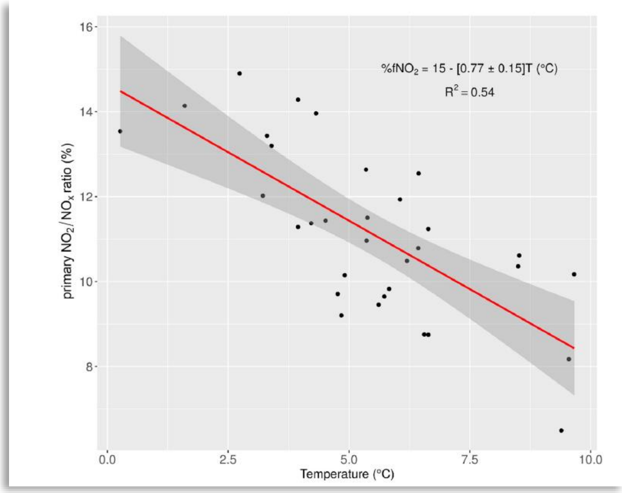


Figure 8: Increased NO2/NOx ratio as the result of reduced temperature [79]

Regulated and unregulated diesel exhaust emissions at idling conditions for cold start and warm re-start were studied at the ambient temperature of 0°C. NOx idling emissions were less impacted than HC and CO emissions. Unregulated emissions such as CH_4, C_2H_4, C_3H_6, and N_2O were increased in cold start idling [82].

Cold start and hot start emissions of a gasoline Euro4 vehicle were tested on a chassis dynamometer environmental chamber. The ratio of cold-start emissions to hot start emissions in the UDC section of the NEDC driving cycle showed the most significant ratio of 12.8 times for NMHC, followed by 7.76 for HC, 4.05 for CO 3.73 for NOx [83].

A comprehensive and comparative study of Euro6 vehicles (diesel, gasoline Flex, HEV) was done at +23°C and -7°C on a chassis dynamometer with the WLTC cycle. Figure 10, as an example, shows the significant difference for a SI PFI vehicle compared to a GDI engine for PN emissions. THC, CO, NOx, SPN, and NH3 were negatively impacted for all vehicles at low ambient temperatures.

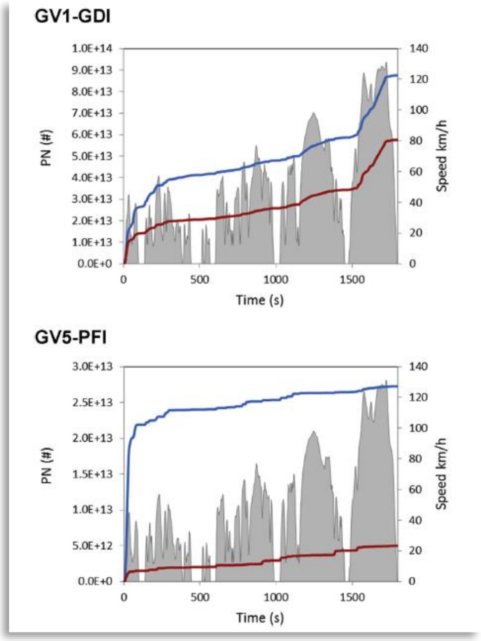


Figure 9- PN emissions for PFI and GDI engines at high and low temperatures tested over the WLTC [192]

SOA potential of both PFI and GDI vehicles with various emission control levels from pre-LEV to SULEV were measured on a chassis dynamometer. Stricter emission regulations have reduced the SOA formation potential of gasoline vehicle exhaust, but the contribution remains the same between older and newer models. Older models substantially produce higher organic gas emissions at the cold start [85].

A comparison of cold-start emissions (first 60s) of engine emissions showed three times higher CO, 3.5 times higher HC, and 50% lower NOx at 10°C compared to 25°C [86].

Comparison of gasoline and diesel emissions in the RDE test using PEMS at 1°C and 17°C showed increased NOx emissions by 30% on diesel vehicles and no considerable change in a gasoline vehicle [87].

82 light-duty vehicles with PFI and GDI engines were tested. Cold start contributes a more significant fraction of the total unified cycle emissions of more clean cars. Organic gas emissions were the most sensitive to cold-start compared to the other pollutants. There were no statistically significant differences in the effects of cold-start on GDIs and PFIs, but overall PM emissions of GDI were higher than PFI [88].

Near-road plume measurement of 130,000 vehicles showed that PN emissions were 3.8 times higher in cold weather than in warm climate [89].

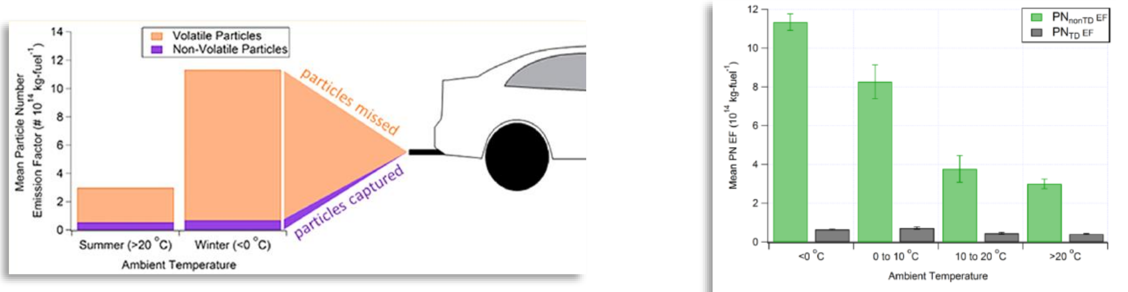


Figure 1. Bar plot of mean PN nonthermal denuded emission factors (PN_{nonTD} EFs, green) and PN_{TD} EFs (black) binned by temperature. Error bars represent 95% confidence interval.

Figure 10- increased PN emissions in the cold ambient in a large sample [89]

Intake air heating of a Euro5 diesel engine reduced HC by 50%, NOx by 17%, and PM by 50% in the cold start period [90].

Canadian and US emission testing data was used to analyze cold start contribution to energy consumption. At 24°C, fuel penalty was averaged at 20% increase while at -6.7°C, the fuel consumption penalty increased to 40-80% [91].

Part III – Health Impact of transportation emissions in cold climate cities

Sub-zero temperatures impact traffic emissions as described earlier. Our findings show that it possibly affect health. The evidence on cold temperature modifying effects on pollutants and health is limited in the literature. Traffic is a significant contributor to urban air pollution. Pollutants' concentrations in cold climates are subject to changes due to meteorological conditions, atmospheric chemistry, human behaviour, and traffic patterns. There are over 400 million people that live in cities with winter days below freezing temperature. Air pollution results in several health impacts, which may be intensified in a cold climate due to the conditions previously described. In the health impact study domain, we identified 1019 papers, of which 76 were selected for a scoping review, according to inclusion criteria. The papers describe short-term impacts on health – from air pollution, which could not be attributed solely to traffic. Predominantly, the studies focused on respiratory and cardiovascular morbidity and mortality and their association with criteria pollutants. Most papers tested associations between pollution and health outcomes after controlling for temperature. Only eight pieces formally explored the modifying effect of cold temperatures on pollution levels and health outcomes. Among those, five studies identified that extreme cold and/or warm temperatures aggravated mortality and cardiovascular diseases in cold, warm and both seasons and associated with O_3, $PM_{2.5}$, PM_{10}, and CO. The other three studies found health associations with the temperature but not the pollutants tested.

Health impact background

Outdoor air pollution has long been recognized as a threat to human health, contributing to mortality and morbidity. Several body systems are impacted, from acute short-term outcomes to chronic long-term health effects, such as the respiratory and cardiovascular systems or fetal development during pregnancy[94]. The World Health Organization declared that ambient air pollution is a significant environmental risk to health and mortality [95]. In addition, the International Agency for Research on Cancer considers outdoor air pollution a leading environmental cause of cancer deaths [96]. In most cities, transportation is a significant source of air pollution leading, for example, to early deaths in the US [97].

Traffic contributes to a wide range of short- and long-lived air pollutants, including primary pollutants ($PM_{2.5}$, PM_{10}, NOx, SO_2, CO, VOC, HC), and secondary pollutants (O_3, SOA). Transportation contribution to air pollution is from the combustion engine and vehicle tailpipe emissions, exhaust, tire and brake wear, road resuspended dust particles and evaporative emissions. Zero-emission clean vehicle technologies such as fuel cell electric vehicles and electric vehicles still generate wear and resuspended dust particles [98,99].

A recent study on the effects of temperatures on mortality shows that cold temperatures have more consequences than hot temperatures, without considering the role of air pollution [100]. While many research studies identified the impact of warm temperatures on air pollution-related health outcomes, there is scarce evidence addressing those links in a cold climate, *i.e.*, below-zero and below -7°C [101,102]. It is also unclear how much further prospective emission regulations should go for the sake of air pollution and public health, for example, considering coexisting variables such as ambient temperature [103].

On the impact of cold climate transportation emissions on health, main research questions are (1) what are the reported associations between health impacts and air pollution in cold weather (i.e., below zero °C temperatures)?, (2) does cold weather modify the health impacts of air pollution?, (3) are the health impacts of air pollution reported in the cold temperature different from those identified in the warm temperature?, and (4) can the health effects in cold climates be directly attributed to a specific source, e.g., traffic?

Our selected studies were published between 1996-2020, studying various time frames. The earliest from 1985 and the latest from 2016. Our search included all cold climate regions or countries. However, we identified studies only from the following countries: thirty-seven papers from North America (Canada n=24, USA n=13). Twenty-one papers from Europe (UK n=5, Germany n=4, Sweden n=4, Iceland n=2, the Netherlands n=2 and one from each of the following countries, Croatia, Denmark, Lithuania, Norway, and Spain) and Sixteen papers from Asia [32,33,36,94-189]. Sixty-six papers focused on the associations between air pollution and health (In this context, *associations* refer to a statistical relationship between an independent variable, *i.e.,* air pollution in a cold climate and dependent one, *i.e.*, health outcomes). Another ten articles focused on the effect of temperature on health outcomes.

The papers included several study designs, including time series, case-cross-over, comparative research, and ecological. Also, the studies used various methodologies and statistical approaches such as generalized linear mixed models, additive Poisson regression models, or general additive models.

Twenty-eight articles described as the source of air pollution a combination of traffic indicators (*i.e*., specific pollutants) and other combustion sources, geologic elements, studded tires, or dust. Another 28 articles did not discuss any specific source for air pollution. Twenty articles indicated that the source of air pollution in the location studied was mainly traffic-related (*e.g*., BC, NO_2). Summery of eight papers that tested the temperature are summarized in Figure 11.

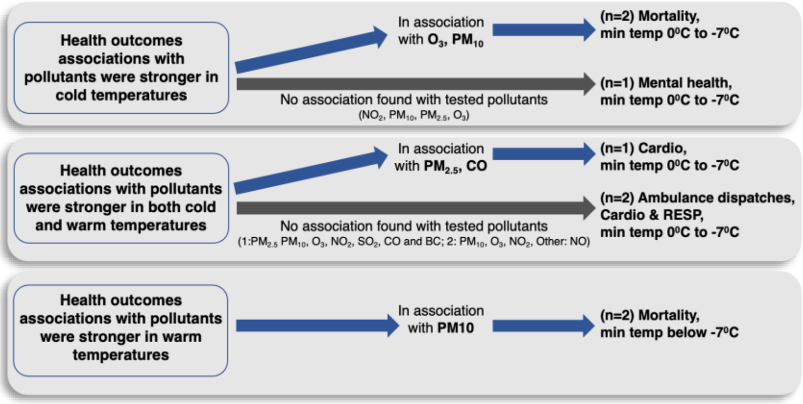


Figure 11- Eight studies tested the temperature and air pollution with health outcomes

We identified and reviewed 76 papers exploring the relationship between health outcomes and air pollution in cold temperatures (below 0 °C). The examined health outcomes were mostly of short-term nature and predominantly centred on respiratory and cardiovascular morbi-mortality. The reviewed papers primarily relied on criteria pollutants data. The majority of papers did not test for interactions of temperature, air pollution, and health outcomes. Most articles aimed to understand the relationship between pollution and health or temperature and health, where temperature or pollutants were considered confounders. Some of these papers described seasonal differences but did not formally explore the interactions of the three. We found only eight articles that explored the interaction of health outcomes, pollution, and temperatures. Five of them identified that both cold and warm temperatures impacted the magnitude of O_3, $PM_{2.5}$, PM_{10}, and CO effects on increased mortality and cardiovascular diseases when combined. Three of the eight papers reported associations of health outcomes and pollutants with cold temperatures in locations that did not reach temperatures lower than -7^{o}C. Another three studies found no association with the pollutants tested since only health outcomes and low temperatures showed associations. Hence, the findings provide a limited understanding of cold temperatures' impact on traffic pollution and health outcomes.

The impact of cold temperatures on pollution and health

Low and high temperatures can impact the pollution mixture, pollutants' levels and related health outcomes [51,126]; however, in most studies exploring health outcomes, the temperature or pollution are adjusted as a confounder to avoid potential bias to the research analysis and findings. Some of the studies reviewed suggest a possible association of seasonality with pollution-related health outcomes, which aligns with other reports [160]. However, in the reviewed papers, most studies considered temperature a confounder, and therefore, temperatures were adjusted for in the analysis models; thus, they removed the possible relationship with temperature. We only found a few studies that explored the modification of air pollution-related health effects by temperature. The evidence is even more scarce when considering cold temperatures below -7^{o}C, like many cities in the world. Harsh winters attributed to climate change and their possible impacts on pollution and health bring further attention to this topic. While the effects of warm weather are likely better documented, there is limited evidence on the impact of cold temperatures, which invites targeted exploration in cold locations to understand health impacts and pollution [102]. This is a gap in our understanding of the association between cold temperatures, air pollution and related population health. Studying the impact of cold temperatures on pollution and identifying health outcomes is a complex question that challenges existing methodologies. Available epidemiological methods can provide information on the seasonality of disease and pollution. However, bringing those together is more challenging and requires novel research methods, *e.g.,* artificial intelligence.

Air pollutants in a cold climate

Although we focused on traffic-related air pollution, it was impossible to identify papers that exclusively used traffic-related pollution data. Most studies used monitored data, which is readily available for research purposes. However, monitoring stations capture pollutants from all sources, making the direct connection between traffic pollution and health uncertain.

More specific connections could be made with better exposure characterization. NO_2 and PMs were significantly associated most frequently with health outcomes in the cold season among the criteria pollutants studied. Both contaminants (NO_2 and PMs) are commonly referred to as indicators of traffic pollution. However, they can also originate from other sources. The small number of papers that explored temperature's impact suggests future exploration of PMs, O_3, and CO with health impacts [102,107,177]. Existing literature has identified that pollutants play different roles in different seasons and regions.

Therefore, this invites future research to determine the interactive effects between temperatures and pollution while considering geographical variations [101,160].

Apart from criteria pollutants, other papers reviewed tested other pollutants. Indeed, criteria pollutants are monitored because of their known potential health impact. However, while there is substantial evidence on criteria pollutants, there are other pollutants, about which we know little about, and may significantly affect health outcomes. For example, GDI technology introduced for improved fuel economy emits nanoparticles due to the mixing of direct injection jet of fuel into the air [190]. SCRs (selective catalytic reduction) use a toxic agent, NH_3 (ammonia), as a reducing agent for NOx conversion. However, NH_3 may only be partially converted and released into the exhaust under conditions like cold exhaust in a cold climate [191,192]. Usually, testing non-criteria pollutants implies limited monitoring that is done through complicated and expensive processes. This limits our understanding of various emissions sources over time. The literature that explores other pollutants is growing. However, there is still a need to find ways to increase our knowledge of these pollutants (*e.g.*, developing standardized methods, a shift in the conceptualization of air pollution beyond criteria pollutants, considering mixtures, increasing funding).

Thus, it is unclear whether or how cold climate may impact traffic emissions, composition and behaviour of pollutants, and the potential health impacts. The knowledge gap is also increased because fuel composition is different in the winter and summer, affecting the type and mixture of emissions.

Health outcomes associations

The health outcomes studied included a variety of diseases and other outcomes. These health outcomes reflect previously reported pollution-related effects. Some of the health outcomes were directly associated with the cold season, implying the seasonality of diseases and increased health vulnerability in the cold season. A systematic review [160] identified that the season modifies the short-term effects of air pollution on morbidity. Although our study also found evidence of seasonal effects, we could not identify specific patterns of the associations between warm or cold seasons, pollutants, and health outcomes. Primarily, seasonal relationships were identified after removing the effect of temperature, suggesting that seasonal exposures imply that other co-existing characteristics may impact health besides the temperature (e.g., variations in the chemical mixture composition of the pollution and the pollutants' concentrations resulting from altered emissions and meteorological conditions). This represents a clear gap in our understanding of the impact of cold temperatures on pollution and related health outcomes.

Concluding remarks and knowledge gap

A strength of this study is the multidisciplinary perspective brought by the team to include various perspectives into the knowledge synthesis process and identification of research gaps that have implications for emission regulations, warning systems to vulnerable populations in specific weather conditions and locations, and public health.

Vehicular emissions in cold climates are less studied. Available emission factors are limited. Most studies focused on cold-start emissions rather than the prolonged operation of the vehicle in a cold environment. Impacts of extremely low temperature on engine management systems are not known as the minimum temperature that any technology may be tested for regulatory purposes is -7°C. New technologies such as GDI and advanced ATS in diesel exhaust systems may cause even further problems in extremely cold conditions.

The context of air pollution in cold climate cities and its relationship to transportation emissions have not been studied using the UCC concept. UCC approach provides comprehensive modelling tools and assessment criteria that could link increased emission rates and health impact in cold regions.

The health outcomes primarily represent short-term impacts, and there is no evidence reflecting the long-term effects of relative exposure to low pollution levels. Therefore, our study could not capture effects on chronic diseases, such as cancer and neurodevelopmental disorders.

The evidence on the relationship between cold temperatures, pollution, and related health outcomes is limited. The reviewed studies described various short-term health outcomes, some of which found seasonal associations of air pollution with morbidity and mortality. However, most papers tested these associations after controlling for temperatures, thus removing the possible impact of temperatures from the findings.

Considering the lack of evidence on the impact of extremely cold temperatures on traffic-related air pollution and health outcomes, the following gaps in current literature are noted:

- Limited information on emission factors of various transportation technologies in cold climate operation;
- Limited evidence on pollutants behaviour in a cold climate below -7°C;
- Cold temperatures were often included as a confounder in the analysis of health impacts, limiting our understanding of the combined impact of pollution and health;
- Limited knowledge on non-criteria pollutants and their impact on health outcomes in a cold climate;
- Very limited evidence explicitly addressing the impact of the interaction of traffic-related emissions, cold temperatures, and health;
- Limited literature evaluating long-term health effects of pollutants in a cold climate.

These identified gaps invite future interdisciplinary research that will employ advanced research methods to address the complexity of understanding mixtures of multiple pollutants and their health impact in a cold climate. This interdisciplinary research will have implications for policy, regulations, and practice implications. It will guide which measures can be taken to mitigate the effects of traffic-related air pollution on health outcomes in a cold climate.

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