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A Review of Ultrafine Particle-Related Pollution during Vehicular Motion, Health Effects and Control

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Abstract
Given the increasing vehicular pollution and emission of ultrafine particles (UFP) from it, there is growing concern regarding environmental and health effects worldwide. Although research has been done to examine such effects but a composite literature review of such studies is lacking. It is intended to review the historical developments, present position and forthcoming trends of such research. The scope of this review encompasses formation, release, health effects and control of traffic generated UFPs and re-suspended from the roads and emanating from road tyre abrasion. PRISMA approach for reviewing literature has been followed. A database literature search examining such effects was carried out at Google scholar, PubMed, circulation and web of science etc. The criterion selected was peer-reviewed, empirical, original articles, research and review papers up to July 2017. Overall 279 research and review papers, conference papers, reports, book chapters and lectures were studied and 206 ultimately incorporated in this review article. The developments in this field are discussed and recommendations suggested. This paper analyses the status of UFP related pollution during vehicular motion and reviews the current literature of the research done in this field. More scientific research pertaining to health and environmental effects of vehicular UFPs is needed, especially in developing countries, to support the policy framings.

Keywords: Ultrafine particles; Vehicles; Air pollution; Pedestrian; Health effects

1. Introduction

Dust, smoke and air pollution have been a matter of concern from very ancient times. The first scientific paper presented on particulates (dust) was "On dust and disease" by John Tyndall during a lecture on June 24, 1871 at Royal Institution of Great Britain [1]. Among the pioneer researchers to comprehend the importance and ill effects of travelers to air pollution was Professor Arie Haagen Smit [2] who studied carbon monoxide levels in Los Angeles.

Particles approximately less than (<) 0.1 μm in aerodynamic diameter (i.e. Dp<0.1 μm) are called ultrafine particles (UFP), [3]. Adverse human health impacts of UFPs are a matter of great concern for both the researchers and all other stake holders [4-6]. Vehicular motion can emit particles from the exhaust [7], or from abrasion sources like wearing of brakes, tyres or get re-suspended from road surface [8]. Majority of particle number concentrations (PNC) emanated from diesel engines comes under the nanoparticle range (Dp<50nm), while majority mass is in the accumulation mode range (50 nm<Dp<1000 nm). Whereas UFPs are usually hydrocarbons or sulfate materializing from nucleation through dilution and subsequent cooling from exhaust, on the other hand, accumulation mode particles consist of carbonaceous soot agglomerates created directly by combustion [9, 10]. Road vehicles are considered the key cause of UFP emissions [11, 12], making around 60% PNC and 90% along the roadsides in polluted city areas; and people residing, working or travelling near major roads have shown escalation in the incidence and severity of many health issues, especially at traffic intersections (TI) where free-flowing traffic emits about 29 times less PNC than TI's with traffic lights [13-15]. Near the automobile exhaust pipes, UFP concentrations can be around ~10^7 particles/cm^3 and after dispersion ~ particles/cm^3 which can be inhaled by commuters [16]. Measured UFP during road-chase studies can be as high as 10^7 particles/cm^3 [17]. In proximity to traffic sources, UFP sized-particles dictate PNC with a decline in their count observed as we move away from traffic source especially highways and main streets to the backstreets [18-24]. Studies for UFPs on the quantification of particle numbers, distribution of sizes and mass concentrations have revealed that diesel and gasoline vehicle exhausts are found ranging from 20-130 nm and 20-60 nm respectively with approximately spherical shapes [25-29]. Vehicular exhaust UFPs are very toxic due to high organic carbon (OC) content, including polycyclic aromatic hydrocarbons (PAHs) and quinines [30]. Carbon components in UFPs mainly come from exhaust of diesel vehicles [31]. Metals in UFPs have been collected beside a road with high traffic [32] which concludes that UFP contain mostly traffic-related metals like lead, cadmium, Zinc, Barium and Nickel and diesel soot high in Silicon [33-35].

Spark Ignition (SI) engines emanate number-weighted UFPs [36-38]. Research has indicated that PNC distribution peaking around 10–20 nm is frequently recorded near a roadside [39, 40, 41]. Proximity to roads [42-44] and height from the ground [45] relates PNC distribution from automobiles. Escalated air pollution affects drivers, pedestrians, dwellers and cyclists. UFP exposure to commuters in line source like traffic can be upto 30% more than those at point source like residential, commercial or public buildings [46, 47]. Efforts have been made to associate temporal variations of PNCs with real-time traffic emissions [48, 49]. Prominent factors for such variations are traffic conditions, ventilation in vehicles and prevailing meteorological conditions [50]. There is a significant variation in exposure while commuting by different transport modes like bicycles, cars, trains, cars etc. [51, 52].

Hence it is evident that UFPs from vehicles and their undesirable health impacts are seen on not only commuters but all people around exposure vicinity. Therefore this review has been complied which encompasses study of formation, release, health effects and control of UFPs generated from vehicles and those re-suspended from the roads and emanating from road tyre abrasion and suitable recommendations have been offered to minimize health risks due to it.

2. Methodology

Available evidence from empirical studies regarding UFPs emanating from exhaust of vehicles and their effects on commuters, pedestrians, dwellers, etc. and their health were evaluated. Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) approach [53] for reviewing literature has been followed (Figure 1).

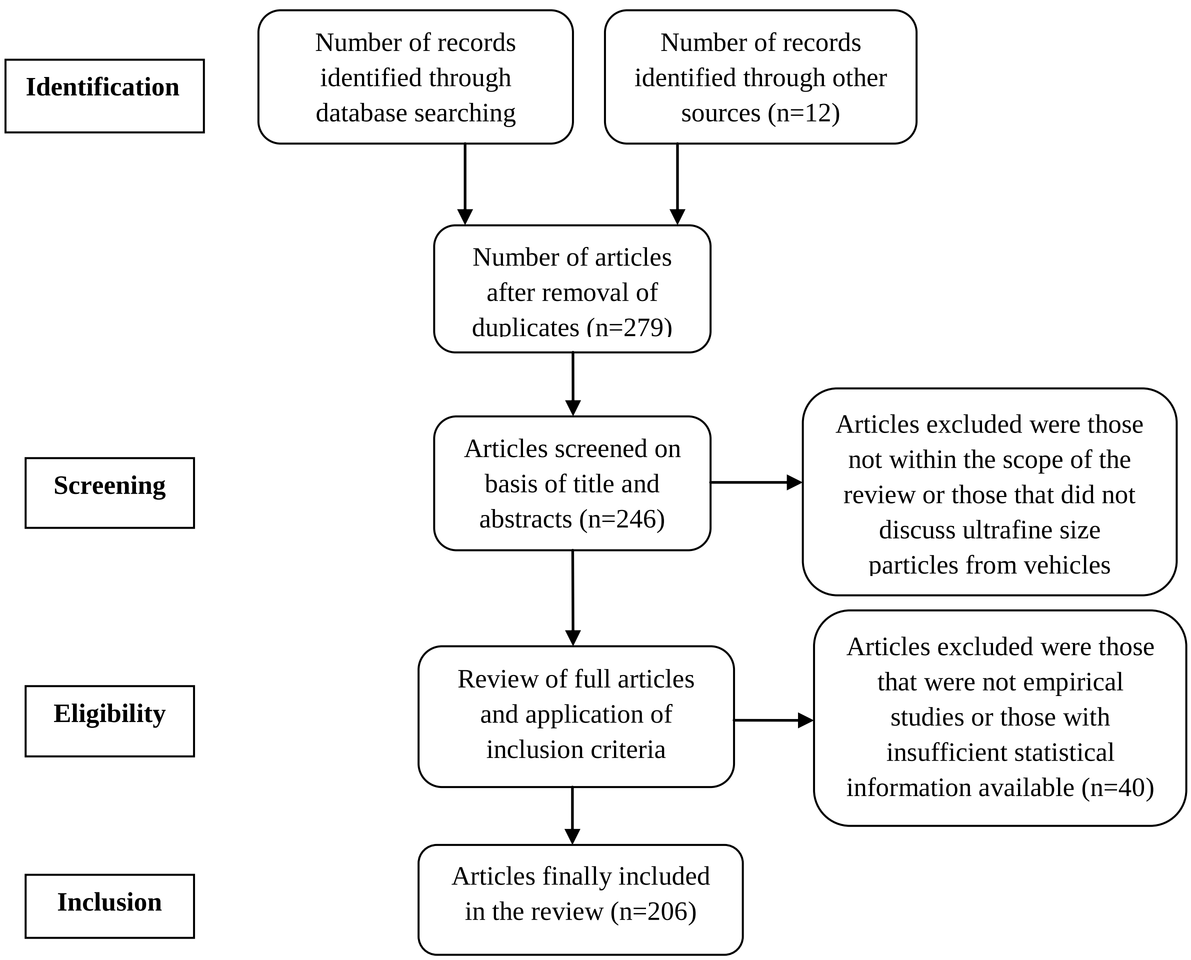

Figure 1: Methodology adopted for this review [PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analysis)].

A database literature search examining such effects was carried out at Google scholar, PubMed, circulation and web of science etc. The criterion selected was peer-reviewed, empirical, original articles, research and review papers upto July 2017. The key words and terms used were “air pollution, vehicle, UFPs, ultrafine particles, diesel”, “respiratory, neurological, cardiovascular diseases”, and “commuters, pedestrians, roadside dwellers, drivers”. The search algorithms consisted of permutations and combinations of all keywords. More articles were explored using references of these articles. This yielded 267 articles in total. 12 additional articles obtained from other sources (i.e. other literature reviews and databases) which led overall 279 papers. Elimination of 33 duplicates and articles not within the scope of the review resulted in 246 articles. 40 articles were excluded based on abstracts since they did not conform to the scope of this review or they did not present original, empirical data or for failed to provide sufficient statistical information for assessment of the presented findings. The remaining 206 articles were then assessed, studied and incorporated in this review.

3. Results

3.1 Diesel and engine exhaust UFPs

The prime source of atmospheric UFPs in urban regions is diesel and automobile exhaust [54-69]. The vibrant behavior of UFPs along roadside atmosphere is attributed to its volatile components which fluctuate with condensation and evaporation together with condensable organic compounds (COCs) that are pivotal in UFPs formation there [70-72]. Diesel combustion as a byproduct releases carbon nanotubes and fibers from engine exhaust [73] and gas-combustions [74]. The daily profile of UFPs relates to use of automobiles locally [75]. High concentrations of UFPs have been seen in school buses and cars [76-81]. Highest mean diurnal fluctuations in UFP range were reported during mornings when people are going to schools and offices [82, 83]. High pollution incidents or proximity to high-traffic roads can increase the mass concentration of UFPs many folds [84, 85]. 2-stroke spark engines can be fitted with catalytic converter having copper metal spray of nanaosize range and diesel particulate filter (DPF) like cordierite can reduce UFPs in exhaust [86-92]. A study about UFP Emissions of direct injection (DI) Gasoline Cars with/without gasoline particulate filters (GPF) revealed that with better filtration capability of GPF emissions can be lowered [93].

3.2 Resuspension, tyre-road interface and tunnel studies

Traffic-generated UFP emission from pavement–tyre interface has concluded UFP largely originate from the tyres, and not road pavement [94]. Poor ventilation and recirculation in tunnels cause high PNC there [95]. Researches focusing in tunnels [96-99] have concluded that organic carbon (OC) and elemental carbon (EC) are the major constituent species of particles emitted from gasoline and diesel vehicles. Hence commuters and pedestrians on or near roads must use masks to block such pollutants from entering the body.

3.3 Health effects of UFPs on humans

UFPs can travel from various entry routes such as inhalation, dermal, oral, olfactory, or through ingestion of food having UFP deposits and once into the respiratory tract they may transport to other parts of body enabling deep penetration to lungs, triggering acute and chronic illness like asthma, chronic obstructive pulmonary disease (COPD), childhood leukemia, prostate cancer, cardiovascular and olfactory diseases, mitochondrial damage etc. [100-119]. Developed countries employ land use regression models for studying spatial distribution of UFP and hence zonation of areas into safe and severe as regards to health implications is possible [120].

The respiratory tract deposition of particles in humans is dependent upon the particle diameter [121]. Particles greater than (>) 1 µm aerodynamic diameters generally linger on epithelial i.e. outer surface after accretion and cleared by cough, muco-ciliary movement, and/or macrophage phagocytosis [122-125]. The diminutive size of UFPs aids them to infiltrate the lung membranes rapidly [126, 127]. The toxicity of UFPs is dependent on its composition, quantity and position of the deposition dose [128, 129]. Diesel nanoexhaust is toxic as it contains PAHs like benzo-a-pyrene (BaP) which is a well known carcinogen [130, 131]. Vehicular UFP influences cardiopulmonary mortality and cancers in children by living in close proximity to main roads and highways [132-135]. Professional and diesel locomotive drivers with a lot of exposure to traffic driven UFPs have shown elevated rates of myocardial infarction and incidence of lung cancers [136, 137]. Research on healthy patrol officers concluded that vehicular UFPs may stimulate signaling pathways causing pro-inflammatory, pro-thrombotic and hemolytic responses [138].

The biological response of UFPs depends mostly on the enormously tiny size and high surface area available for adsorption of detrimental organic chemicals [139-142] which are then transported to the pulmonary system and is eventually mixed onto blood stream [143]. Systemic inflammation from the lungs can affect heart and central nervous system (CNS) [144, 145] causing disorders like Parkinson's and Alzheimer's disease [146]. The inhaled UFPs can escape natural clearance mechanisms of tissues resulting in long–term retention of UFPs with threat of oxidative damage culminating into risk of toxicity [147]. UFPs inhibit phagocytosis and stimulate inflammatory responses [148]. UFPs harm respiratory system mainly by the injury of epithelium and oxidative stress [149-151]. Inhaled insoluble UFPs may translocate into the circulation and cause direct effects on hemostasis or heart functioning [152]. Hence it is advisable not to reside in close proximity to traffic roads as well as take all preventive measures to minimize exposure to UFPs to avoid such diseases.

3.4 Bicyclists and pedestrians

Research studies examining personal exposure of bicyclists and walkers to UFPs in the transport microenvironment are limited [153-162]. The average exposures of UFP density for walkers have been seen 1.4 times in excess than people driving a car [163, 164] and ventilation exposure 4.3 times greater [165]. Personal exposure is highest to walkers and bicyclists near dense traffic and public buses [166]. Hence bicyclists and walkers can substantially decrease their exposure to UFP by choosing a route with less busy roads.

3.5 Traffic Intersections (TIs)

25% of a driver's total exposure to UFPs is from passing through TIs which constitutes only 2% entire journey time owing to high PNC at TIs as a result of frequent changes in driving conditions like stopping vehicle for a short time and accelerating quickly to move forward when the TI lights change and traffic alignment alters [167-170]. Developing countries tend to have more PNC than their developed counterparts and atmospheric dilution, increased distance from exhaust pipes, high-efficiency filters along with ensuring recirculation of air in cars help in decreasing UFPs exposure to drivers [171]. Re to UFP at TIs, engines must be switched off and smooth running traffic maintained.

3.6 Traffic speed, temporal variations and meteorological conditions

The higher the speed of vehicle, the greater is the UFP concentration, the smaller is the size and volume of particles owing to greater load on engine and fuel consumption. The nearby passing diesel traffic further increases PNC. Traffic jams with speeds <20 mph show inferior concentrations and larger particles. Hence there is converse relationship between the number and volume of particles when speed is the grouping variable. UFP number concentration calculated downwind from freeway was found higher than upwind at night, thus indicating effects of temporal variations [172, 173]. UFP formation in diluting engine exhaust and their number and concentration levels along with nitro-polycyclic aromatic hydrocarbons (NPAHs) in UFPs depends strongly on meteorological factors, colder ambient temperature, traffic density and mode, street geometry [174-180].

Hence smooth running of the traffic at optimum speed must be regulated to reduce UFPs and their health effects. Cold starts must be avoided and precautions taken like nobody should be standing near the tailpipe when the engine is started in such meteorological conditions.

3.7 Traffic generated UFPs in Indian context

There have been limited studies in developing countries like India in this field [181-183]. India’s present vehicle count stands around forty million increasing 5% annually, thus exposing its huge population to risks of UFPs especially in the absence of mitigation actions [184]. It is expected that the generation of UFPs would continue to rise till alternatives to conventional fuel vehicles like electric and solar powered cars are introduced on a mass scale and commitments to Paris Agreement are adhered to strictly.

3.8 Biofuels and UFPs

Biofuels from various sources have been tried to combat pollution from conventional fuels [185-187]. But a lack of proper policy to encourage their research and production is still lacking [188]. Biofuel usage has lessened particle mass and gaseous emissions but has increased the PNC including UFPs [189-192]. Lower calorific values of bio-fuels results in augmented fuel flow rates and higher density of bio-diesel results in more fuel mass consumption [193-195]. Hence biofuels should be introspected from this viewpoint and suitable mitigation technology evolved diminishing UFP from them to minimize health risks to commuters.

3.9 Effect of vegetation and noise barriers

There is no consensus on the positive consequences of vegetation and noise barriers along roadsides in mitigating UFPs. A few researches have supported their potential in reducing UFPs exposure to pedestrians and footpath dwellers by increased mixing and reduced pollutant concentrations [196-199] and hence reducing the Respiratory Deposited Doses (RDD) by about 36% for the duration of road traversing winds [200]. On the contrary some researchers report that vegetation in streets may enhance the pollution by obstructing the flow and trapping the particles [201].

Meteorological factors and variations in wind speed and route during days can decrease the pollutants at the rear of the trees [202, 203]. Particle deposition on vegetation depends upon the roughness of the surface of leaves; the coarser the leaf, higher is the particle removal; and velocity of deposition of particles is higher on needle shaped leaves as compared to broader leaves [204-206]. Hence vegetation with rough and needle shaped leaves and conifers grown alongside roads to minimize effects of UFP on commuters.

4. Discussions

The excess deaths attributed to UFP exposure are mostly not well documented. Numerous problems such as unavailability of cost effective wide sampling range portable instruments and standardized methodologies have made study of UFPs at TIs difficult. Hence new innovative methods are needed in designing such systems. Exposure to UFPs can be reduced by incorporating some simple measures in our daily life like keeping vehicle windows closed while especially while commuting through traffic and keeping safe gap from vehicles in front where possible. Traffic signals should be managed to reduce waiting time and consider alternative traffic management systems such as flyovers.

5. Recommendations

Based upon the comprehensive literature analysis, the authors offer the following recommendations for minimizing health and environmental effects of vehicular UFPs:

- The highest PNC occur over the entire cold start period with average particle number distributions being > 99% of total particle number below 100 nm. Hence it is recommended that the vehicle may be suitably protected against cold starts and subsequently emissions control by ethanol-diethyl ether-water fuel mixture or catalytic converter thermal management.
- Control of UFP emissions can be done using DPF like cordierite or fibrous porous ceramic filters which can get rid of carbon particulates nearly fully, together with fine particulates (<100 nm aerodynamic diameter) with > 95% and 99% efficiency in mass and number respectively covering an array of engine working environments.

- Combination of noise and vegetation barriers must be used along with roadside structures to increase mixing and reduce pollutant concentrations. Vegetation with rough and needle shaped leaves and conifers must be encouraged to be grown alongside roads.
- 2-stroke spark engines may be fitted with catalytic converter having copper metal spray of nanaosize range and diesel particulate filter (DPF) used.
- Reduction in particle emissions can also be achieved using electronic and automated engine regulation, digital twin spark ignition (DTSI), direct fuel injection systems and after-treatment of exhaust emissions techniques.
- Nano aerosol mass spectrometer (NAMS) may be employed to study effects traffic on human exposures to UFPs on or near roadways as it can measure the real time major chemical components in UFPs.

6. Conclusions

The present review suggests that UFPs emitted by vehicles present elevated health risk to drivers, passengers, pedestrians, nearby dwellers and people living in propinquity to main roads and highways. Results seen in the reviewed papers insinuates that exposure to exhaust UFPs leads to elevated likelihood of respiratory, cardiovascular, skin infections and cancers along with huge loss in life expectancy and expenditure on health costs. There is a complex relationship between vehicle sources, environmental mediums, receptor, and response measures for UFPs related exposure risks. There is an ardent need for different stakeholders like governments, industries, public, researchers, educational institutes, etc. to collaborate in minimizing the threat put forward by such UFPs.

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8. Competing Financial Interest Declaration

All the authors affirm of no tangible or prospective competing financial interests.

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