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Title: Lung cancer risk assessment due to traffic-generated particles exposure in urban street canyons: a numerical modelling approach

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Pavlos Kassomenos
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SCIENCE OF THE TOTAL ENVIRONMENT

Cassino, 16th November 2017

Dear editor,

I am pleased to submit the paper "*Lung cancer risk assessment due to traffic-generated particles exposure in urban street canyons: a numerical modelling approach*" by Mauro Scungio, Luca Stabile, Valeria Rizza, Antonio Pacitto, Aldo Russi and Giorgio Buonanno.

Significance and Rationale for Publication:

Air quality in urban areas is worsened by airborne particles emitted from vehicles. These combustion-generated particles are responsible of negative health effects due to their ability to penetrate in the lungs, carrying toxic compounds with them. Exposure of people living in urban areas to these pollutants, can lead to lung cancer. Airborne particles, in fact, were classified as carcinogenic to humans (Group 1) by the World Health Organization (WHO). In urban areas, the coexistence of streets flanked by buildings (street canyons) and perpendicularly-blowing winds, can lead to the accumulation of pollutants (particles) inside the street canyons, exposing people to high concentration of particles. In the proposed paper, a novel approach was proposed in order to evaluate the lung cancer risk of people exposed to traffic-generated particles in a street canyon by means of the ELCR (Excess Lifetime Cancer Risk) model, considering the contribution of both sub-micron and super-micron particles. Once obtained the ELCR value at the tailpipe of the vehicles, it was imposed as input parameter in a CFD (Computational Fluid Dynamics) model, in order to evaluate the lung cancer risk in every point of interest within the street canyon and study the influence on the risk of parameters such as street canyon geometry and wind speed. The lung cancer risk was evaluated by hypothesizing two different exposure scenarios, and was compared to the risk associated to other particle sources.

Why the paper should be considered for publication in STOTEN:

In the authors' opinion, the proposed paper fits the aims and scope of the journal since it focuses on different subject areas, belonging to different spheres, such as air pollution quality and human health, risk assessment, environmental management and policy and human health risk assessment and management. Moreover, the paper can give a valuable contribution to the scientific community and to the readers of the journal, since the proposed ELCR model was applied for the first time to evaluate lung cancer in street canyons and the findings showed in the paper can have significant impact on the air quality management in urban areas.

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I hope the paper will be suitable for the publication on *Science Of the Total Environment.*

Kind Regards
Mauro Scungio

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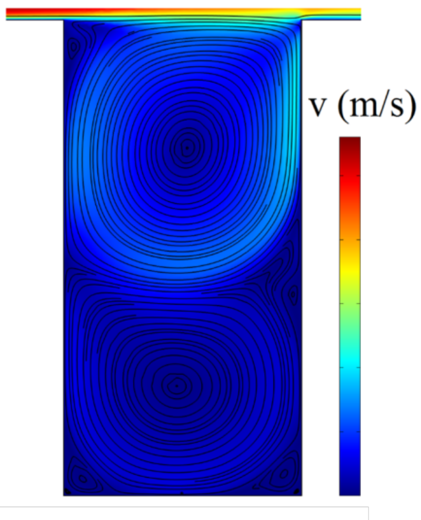
***Graphical Abstract**

CFD

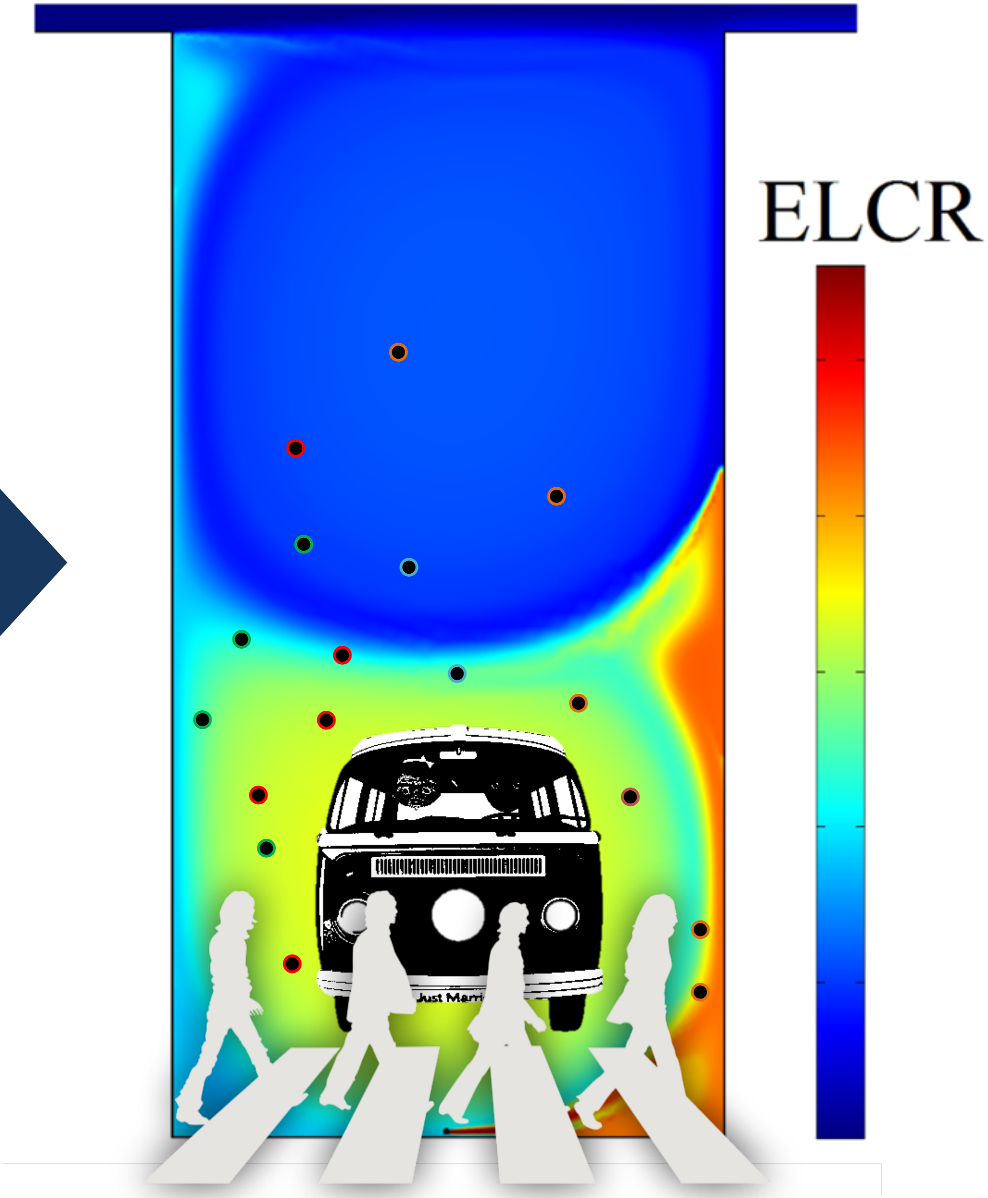


Emission factor data

Lung cancer risk model

$$ELCR_i = \frac{SF_i}{BW}\,\frac{m_i}{PM_{10}}\left(c_f \cdot \delta_S + \delta_{PM10}\right)$$

Lung cancer risk dispersion



***Highlights (for review)**

A modeling approach was proposed to evaluate the lung cancer risk in street canyons

Excess Lifetime Cancer Risk model was used to evaluate the “vehicles-emitted” risk

Both ultrafine and coarse particles were considered in the ELCR model implementation

ELCR was “dispersed” in the street canyon by means of a CFD simulation

ELCR at breathable height and effect of wind speed and canyon geometry were studied

Lung cancer risk assessment due to traffic-generated particles exposure in urban street canyons: a numerical modelling approach

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Abstract

Combustion-generated nanoparticles are responsible for negative health effects due to their ability to penetrate in the lungs, carrying toxic compounds with them. In urban areas, the coexistence of nanoparticle sources and particular street-building configurations can lead to very high particle exposure levels. In the present paper, an innovative approach for the evaluation of lung cancer incidence in street canyon due to exposure to traffic-generated particles was proposed. To this end, the literature-available values of particulate matter, PAHs and heavy metals emitted from different kind of vehicles were used to calculate the Excess Lifetime Cancer Risk (ELCR) at the tailpipe. The estimated ELCR was then used as input data in a numerical CFD (Computational Fluid Dynamics) model that solves the mass, momentum, turbulence and species transport equations, in order to evaluate the cancer risk in every point of interest inside the street canyon. Thus, the influence of wind speed and street canyon geometry (H/W, height of building, H and width of the street, W) on the ELCR at street level was evaluated for two exposure scenarios. The ELCR value calculated at the tailpipe with the proposed methodology was found to be equal to 2.1×10^{-2} (2 100 new lung cancer cases over a population of 100 000), for people hypothetically breathing directly at the tailpipe of the vehicles 24 hours per day for 70 years. By means of the CFD simulation, it was found that the ELCR value at 1.5 m from the ground is higher on the leeward side for aspect ratios equal to 1 and 3, while for aspect ratio equal to 2 the ELCR is higher on the windward side. In addition, the simulations showed that with the increasing of wind speed the ELCR becomes lower everywhere in the street canyon, due to the increased in dispersion.

Keywords: street canyon; ELCR; ultrafine particles; lung cancer, numerical modelling

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1 INTRODUCTION

Reduction of personal exposure to traffic-related pollutants and their resulting health effects is a key aspect in air quality management in urban areas. Amongst the pollutants, airborne particles are receiving particular attention by the scientific community since they are recognized to cause adverse health effects[1]. In urban areas, vehicular traffic is considered the main contributor to ultrafine particle emission[2] (UFPs, particles with diameter less than 100 nm), and even if a threshold limit value for light-duty passenger and commercial vehicles has been stated in terms of particle number[3], such local source is the most responsible of air quality deterioration in urban environment. Airborne particles, in fact, were classified as carcinogenic to humans (Group 1) by the World Health Organization (WHO) through the International Agency for Research on Cancer (IARC)[4], since a causal relationship was established between exposure to these pollutants and human lung cancer.

One of the most critical urban configuration in which the air quality get worse is the so called street canyon, which is a typical urban configuration of a street flanked by buildings on both sides. In a street canyon, air exchange provided by natural ventilation may become weak with consequent formation of high particle concentration zones. For these reasons, urban microenvironments may increase human exposure to high particle concentrations, and significantly contribute to the increase of the daily dose[5] likely leading to pulmonary and cardiovascular disease, as well as to lung cancer cases[1, 6].

There are a several papers in scientific literature addressing the evaluation of air quality in urban street canyons by means of numerical simulations and dedicated experimental campaigns. Numerical simulations of pollutant dispersion inside street canyons of different typologies were carried out by Kikumoto and Ooka [7] and Hertwig, et al. [8], finding that the canyon geometry strongly influence the ventilation efficiency and then the pollutant dispersion. Similar results were found in our previous papers, where the fluid flow patterns and the dispersion of UFPs inside street canyons of different aspect ratios (H/W, height of building, *H* and width of the street, *W*) with different turbulence modelling techniques were calculated[9]. The dispersion of UFPs inside street canyons was experimentally approached in real-scale and wind tunnel scale by Stabile, et al. [10] and Marini, et al. [11] finding different vertical particle number concentration (PNC) profiles between the two canyon sides depending on the wind direction and speed at roof level and proposing a benchmark for computational fluid-dynamic models of ultrafine particle dispersion. By means of an experimental campaign designed to compare atmospheric contaminants inhaled during bus, subway train, tram and walking journeys through the city of Barcelona, Moreno, et al. [12] found that average number concentrations of particles are highest in diesel bus or walking in the city centre, while Keogh, et al. [13] derived a comprehensive set of tailpipe particle emission factors for different vehicle and road type combinations, covering the full size range of particles emitted.

In the present paper, an innovative approach for the evaluation of the lung cancer risk of people exposed to traffic-generated particles inside street canyons was proposed. In particular, a modified risk-assessment model was used to estimate the Excess Lifetime Cancer Risk (ELCR, extra risk of develop cancer in a population of individuals, for a specific lifetime exposure and dose-response data) contribution of both ultrafine and coarse particles from light duty and heavy duty vehicles in urban area through the risk model developed by Sze-To, et al. [14] which was recently applied in estimating the lung cancer risk for the Italian population[15], and smokers[16], and for people living nearby an incinerator plant[17]. The proposed approach consists in the evaluation of the ELCR in emission from the tailpipe of vehicles applying the above mentioned risk assessment model, using data of PAHs, heavy metals (As, Cd, Ni) and PCDD/Fs, available in literature. The calculated ELCR at the tailpipe is then used as input data in a numerical CFD (Computational Fluid Dynamics) scheme, based on the Spalart-Allmaras turbulence model and already used in our previous work[9a] in order to evaluate the lung cancer risk in every point of interest inside the street canyon, and analyse the influence of wind speed and canyon geometry on the ELCR at street level. Simulating the dispersion of the ELCR allows to consider the dispersion of both particles and relative toxicity, which represent a novel aspect of the proposed approach.

2 MATERIALS AND METHODS

2.1 ELCR model implementation

The risk model adopted in the present paper, originally developed by Sze-To, et al. [14], allows to estimate the lung cancer risk due to the exposure to the IARC Group 1 (carcinogenic to humans) agents deposited on inhalable airborne particles. The model accounts for the contribution of both ultrafine particles (UFPs) and super-micron particles. The contribution of UFPs is relative to the particle surface area, introducing a coefficient (c_f) to correlate the particle surface area-based cancer potency of the pollutant to the mass-based cancer potency of the pollutant itself (see Sze-To et al.[14] for major details). The equation for the risk characterization, for each pollutant, is:

$$ELCR_i = \frac{SF_i}{BW}\frac{m_i}{PM_{10}}\left(c_f \cdot \delta_S + \delta_{PM10}\right) \quad (1)$$

Where, for each *i-th* pollutant, $ELCR_i$ is the excess lifetime cancer risk, SF_i is the inhalation slope factor, representing the increase of the risk of getting cancer associated with exposure to the specific dose of a chemical every day for a lifetime, and then it is used as the relationship between dose and response, *BW* is the body weight of the receptor, m_i is the mass concentration of the pollutant present on the PM_{10} mass (mg m^{-3}), δ_S (nm^2) and δ_{PM10} (mg) are the particle surface area (S) and mass (PM_{10}) deposited doses. The conversion coefficient c_f, that correlates the particle surface area-based cancer potency of the pollutant to the mass-based cancer potency of the pollutant itself, has the value of 6.60×10^{-13} mg nm^{-2}, experimentally obtained by Sze-To, Wu, Chao, Wan and Chan [14]. It is assumed by these authors that the c_f coefficient depends on physical characteristics rather than the chemical composition of the particles, and then we adopted the original value of the coefficient since the particle size distributions considered in this study are similar to those used in the original paper of Sze-To et al. The *SF* for the IARC Group 1 carcinogenic chemicals used in the risk assessment model were obtained from the Office of Environmental Health Hazard Assessment[18], and are reported in Table 1. Further details about the ELCR model can be found in some recent papers of the authors[15-17].

Table 1. Inhalation cancer slope factor (SF) for the considered IARC Group 1 carcinogenic compounds, as provided by Office of Environmental Health Hazard Assessment.[18]

IARC Group 1 agent	**SF (kg d mg^{-1})**
Benzo[α]pyrene (B[α]p)	3.85×10^{0}
Arsenic (As)	1.51×10^{1}
Cadmium (Cd)	6.30×10^{0}
Nickel (Ni)	9.10×10^{-1}
PCDD/F	1.16×10^{5}

In order to calculate the ELCR at the tailpipe of the vehicles emitting particles in the street canyon, different combinations of vehicles were considered: gasoline and diesel-fueled light duty vehicles (LDV, including cars) and diesel-fueled heavy duty vehicles (HDV), in the following proportions: 5% HDV and 95% LDV[11] (60% gasoline and 40% diesel-fueled LDV)[19]. Data on pollutant mass concentrations (Group 1 carcinogenic chemicals) and PM_{10} concentrations at the tailpipe were obtained from the inventory guidebook of European Environmental Agency [20]. In particular, the emission factors of all the considered Group 1 carcinogenic chemicals are summarized in Table 2.

Table 2. Emission factors of the considered emitted pollutants (literature data).

Pollutant agent	**LDV (g km^{-1})**	**HDV (g km^{-1})**
Benzo[α]pyrene (B[α]p)	1.10×10^{-6}	9.00×10^{-7}
Arsenic (As)	5.89×10^{-7}	2.63×10^{-6}
Cadmium (Cd)	8.96×10^{-7}	3.13×10^{-6}
Nickel (Ni)	2.63×10^{-6}	1.02×10^{-5}
PCDD/F	1.16×10^{-11}	2.17×10^{-4}
PM_{10}	3.74×10^{-2}	2.83×10^{-1}

Surface area dose (δ_S), considered as the sum of the tracheobronchial and alveolar depositions, was evaluated on the basis of an indirect exposure assessment approach[21] using the following equation:

$$\delta_S = IR_{activity} \cdot \tau \cdot \int_0^{\infty} \left[\varphi_{Alv+Tb}\left(IR_{activity}, D_p\right) \frac{dS}{dD_p} dD_p \right] \qquad (2)$$

where S stands for particle surface area concentration, $IR_{activity}$ is the inhalation rate of the exposed population depending on their activity, φ_{Al} and φ_{Tb} are the alveolar and tracheobronchial fractional deposition depending on inhalation rate and particle diameter (D_p), $dS(D_p)/dD_p$ is the particle surface area distribution, and τ is the exposure time. In the present paper, an exposure time of 15 minutes per day was considered, as Buonanno, Giovinco, Morawska and Stabile [5a] found that this is a time typically spent outdoors in urban areas for Italian population. An additional exposure time of 24 hours per day, representative of an extreme scenario, was taken into account for comparison.

Particle deposition fractions and inhalation rates were adapted from the International Commission on Radiological Protection [22]: in particular, fractional depositions in alveolar and tracheobronchial regions of the respiratory tract for subjects in light activity (average values amongst male and female normally breathing from the nose) were considered. The surface area was calculated on the basis of the available number distribution assuming spherical shape of the particles. PM_{10} dose was not considered because its contribution to the ELCR total value is orders of magnitude lower than that of UFPs[16-17]. In the light of this, the δ_{PM10}, in equations (1) and (2) was ignored, as already done in recent papers of the authors[15-16, 23]. It should be pointed out, anyway, that PM_{10}, causes other health concerns such as inflammatory effects or asthma[24].

2.1.1 Literature survey for particle size distributions

In order to correctly account for the contribution of the particle surface area to the ELCR, the physical characteristics of the particles emitted from the different typologies of vehicles should be carefully assessed. One of the biggest issue, in this regard, is relative to the wide variation of the size distribution and concentration of the emitted particles with the different real-life riding conditions (urban, extra-urban, idling, acceleration, deceleration etc.). There are also a lot of discrepancies between particle characteristics measurement for on-road or dynamometer tests as well as for measurements at the tailpipe or in a constant volume sampler (CSV). In addition, the particle characteristics are different for the different engine technologies and after-treatment equipment installed on the vehicles. Summarizing, the available literature is characterized by inhomogeneous data since there are a lot of vehicles tested (with different engine technologies), measurements techniques (on road or at dynamometer, at the tailpipe or in CSV), and data presentation (emission factors or concentrations).

In the light of that, for the evaluation of the ELCR in street canyons (urban area) with the proposed methodology, the data for particle physical characteristics should be selected on the basis of two main aspects. The first one is relative to the need of consider only measurements made on the basis of vehicle urban cycles (limited velocity and frequent stops) and the second is relative to the choice of measurements made in CSV in order to account for the thermodynamic transformation of the freshly emitted particles, since the numerical model adopted for the present simulations does not account for these phenomena. In addition, in order to reproduce plausible emission scenarios, different kind of vehicles should be taken into account (light duty and heavy duty, diesel or gasoline fueled etc.).

In Table 3, the particle physical characteristics are reported for the different typologies of vehicles considered (light duty and heavy duty, diesel and gasoline vehicles), together with the main vehicle/engine characteristics. All the reported data are relative to measurements made on chassis dynamometer, reproducing urban riding cycles, and sampling in CSVs. The authors point out that the choice of particle size distribution can be different if the model adopted for the simulations account for thermodynamic transformation (i.e. measurements made directly at the tailpipe).

Table 3. Particle physical characteristics emitted from the different typologies of vehicles considered (LDV: light duty vehicles, HDV: heavy duty vehicles), together with the main vehicle/engine characteristics (DPF: diesel particulate filter, EGR: exhaust gas recirculation, DOC: diesel oxidation catalyst, CDPF: catalyzed diesel particulate filter).

Vehicle type	N (part. cm^{-3})	Modes (nm)	Standard	Aftertreatment equipment	Reference
LDV - gasoline	4.3×10^4	11/52	EU 6	3 way catalyst	Louis, et al. [25]
LDV - diesel	6.4×10^5	16/81	EU 4	DPF + EGR	Jung, et al. [26]
HDV – diesel (bus)	4.8×10^3	11/60	China-III	DOC + CDPF	Lou et al. [27]

2.2 CFD model details

The evaluation of the ELCR at street level in urban environment may be obtained by simulating the fluid flow evolution inside the street canyon. To this end, in the present work the commercial software Comsol Multiphysics® was used to solve the standard Spalart-Allmaras turbulence model and the conservation equation for species, as already done in previous papers of the authors[9, 17, 28]. In these papers, the model here adopted was validated against experimental data, showing good accuracy in reproducing particle dispersion.

The Group 1 substances are supposed to be deposited on the particle surface and their amount is directly related to the particle mass through the term (m_i/PM_{10}) of equation (1). The ELCR value is then directly related to the particle concentration; simulating the "dispersion" of ELCR (which is function of particle emission at the tailpipe) corresponds to the dispersion of particles in the street canyon for the evaluation of the ELCR in every point of interest of the domain, without calculating the dispersion of each pollutant and then the corresponding ELCR value in these points. In the present model, the dispersion of the particles was evaluated using an Eulerian approach, solving the following mass conservation equation with a *K*-closure method[29]:

$$\frac{\partial c}{\partial t} + U \cdot \nabla c = \ D + \nu_T \ \ \nabla^2 c \tag{3}$$

where c is the concentration and ν_T is the eddy viscosity, which is added to the molecular diffusion coefficient D in order to take into account the turbulent diffusion of the particles. UFPs were modelled as a gas phase, imposing their diameter by defining a corresponding diffusion coefficient as reported by Baron and Willeke [30]. The relation between diffusion coefficient and particle diameter is:

$$D = \frac{kTC_C}{3\pi\eta d_p} \tag{4}$$

where D is the diffusion coefficient, k is the Boltzmann constant (1.38×10^{-23} N m K^{-1}), C_C is the Cunningham slip correction factor[31], η is the air viscosity and d_p the particle diameter. Thermal effects on particle diffusion was not considered since for wind speed greater than 2 m s^{-1} turbulent transport and convection are predominant[32, 32b].

2.3 Computational domain and boundary conditions

The calculated value of the ELCR at the tailpipe, was used as input parameter in the above described CFD model in order to evaluate lung cancer risk in every point of interest inside the street canyon. In Figure 2 the computational domain and the boundary conditions employed are reported. The source value of ELCR was imposed at the centre of the street canyon (a square with side length equal to 0.1 m, at 0.1 m from ground approximating the vehicle exhaust pipe size), in order to simulate the vehicles emission. A uniform velocity profile was imposed at the inlet section of the computational domain, while zero pressure condition, symmetry condition and zero velocity condition were imposed at the domain exit, domain top, and on the walls, respectively. The air physical properties were taken at 25 °C and atmospheric pressure.

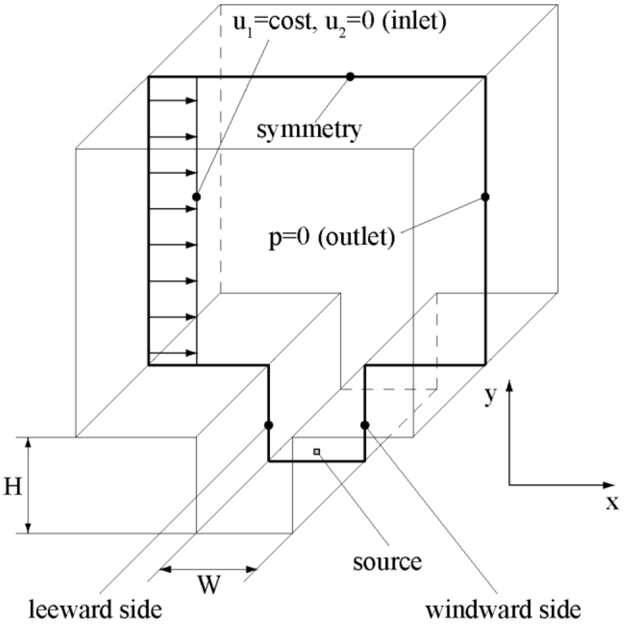

Figure 1. Computational domain and boundary conditions used for the numerical simulations.

ELCR was numerically obtained using different street canyon geometries and approaching wind speeds, in order to assess the influence of that parameters on the ELCR inside the canyon.

2.4 Parametric analysis

In order to evaluate the influential parameters on ELCR in urban environment, a parametric analysis was proposed, varying the street canyon geometry and the wind speed. The reference simulation condition is relative to an approaching wind velocity of 1 m s^{-1} and aspect ratio *H/W* equal to 1 (with height of building from street level *H*, and width of the street, *W* equal to 14 m). The background value of the ELCR was set to zero for all the cases in order to evaluate only the effect of the vehicle emissions. Starting from the reference simulation case, two additional aspect ratios (H/W=2 and H/W=3) and two additional wind speeds (3 m s^{-1} and 5 m s^{-1}) were evaluated.

3 RESULTS AND DISCUSSIONS

The value of the ELCR at the tailpipe, calculated with the above described model, was found equal to 2.1×10^{-2}, which means 2 100 new lung cancer cases over a population of 100 000, hypothetically breathing directly at the tailpipe 24 hours per day for 70 years.

In Table 4 the SF of the mixture (SF_m, calculated as $SF_m = \sum_{i=1}^{n} SF_i \cdot \frac{m_i}{PM_{10}}$), and the contributions of the five pollutants to such SF_m were reported. SF_m values resulted one order of magnitude larger than those typical of cooking-generated particulate matters, estimated by Sze-To, Wu, Chao, Wan and Chan [14] on the basis of the data reported in He, et al. [33], whereas they resulted 1 – 2 orders of magnitude smaller to the SF_m evaluated for particles emitted from incinerator plants[17]. The main contribution to the SF_m was due to the metals: As (39 – 53%), Ni (11 – 12%) and Cd (25 – 26%), whereas a smaller contribution can be addressed to B[α]P and PCDD/F.

Table 4. Mass fractions of emitted carcinogenic compounds on PM_{10} (expressed as mg/mg) and corresponding SF of the mixture (SF_m).

	SF_m	m_i/PM_{10} (mg mg^{-1})	Contribution to SF_m (%)
B[α]P	$6.01\times10^{-4} – 2.63\times10^{-4}$	$2.94\times10^{-5} – 3.18\times10^{-5}$	5 – 19
As		$1.57\times10^{-5} – 9.29\times10^{-6}$	39 – 53
Cd		$2.40\times10^{-5} – 1.11\times10^{-5}$	25 – 26
Ni		$7.03\times10^{-5} – 3.60\times10^{-5}$	11 – 12
PCDD/F		$3.10\times10^{-10} – 7.67\times10^{-11}$	3 – 6

In Figure 2 the airflow fields and the corresponding ELCR distribution, calculated imposing the obtained value of ELCR at the tailpipe as input boundary condition, are reported for each aspect ratio of the street canyon, for a wind speed of 1 m s^{-1}, considering people exposed to traffic emissions 24 hours per day for 70 years. As can be seen, the air flow fields are different for the different aspect ratios analysed. For H/W=1, one main clockwise-rotating vortex was observed, while for H/W=2, two counter-rotating vortices are visible: the one below rotating counter clockwise and the one at the top rotating clockwise, in accordance with the free-stream wind direction. For the H/W=3 configuration, three vortices are generated in the street canyon, as depicted in Figure 2 (c). The same flow configurations were observed also in other similar street canyon simulations of Scungio, Arpino, Cortellessa and Buonanno [9b], and Scungio, Arpino, Stabile and Buonanno [9a]. The corresponding ELCR distribution fields (reported at the right of each flow field in Figure 2) are strictly related to the flow patterns. In particular, higher ELCR values can be observed at the bottom of each H/W configuration, since the interaction between the fluid flow inside the canyon with the free-stream wind is weaker at the base of the street canyon, as found in Scungio, Arpino, Cortellessa and Buonanno [9b]. With the increasing of the H/W ratio, this interaction becomes even more weaker at the bottom of the street canyon and then, as a consequence, the dispersion of pollutants emitted is limited in this point, leading to the increase of the ELCR value, that becomes maximum at the bottom of the H/W=3 street canyon configuration. In addition, looking at Figure 2, since the variable direction of rotation of the vortex at the base of each H/W configuration (once clockwise and once counter-clockwise), the distribution of the ELCR varies. In particular, referring at the bottom of the street canyon, where people spend most of the time, higher ELCR values are observed on the leeward side for W/H=1 and W/H=3 (bottom vortex rotating clockwise), and on the windward side for H/W=2 (bottom vortex rotating counter-clockwise).

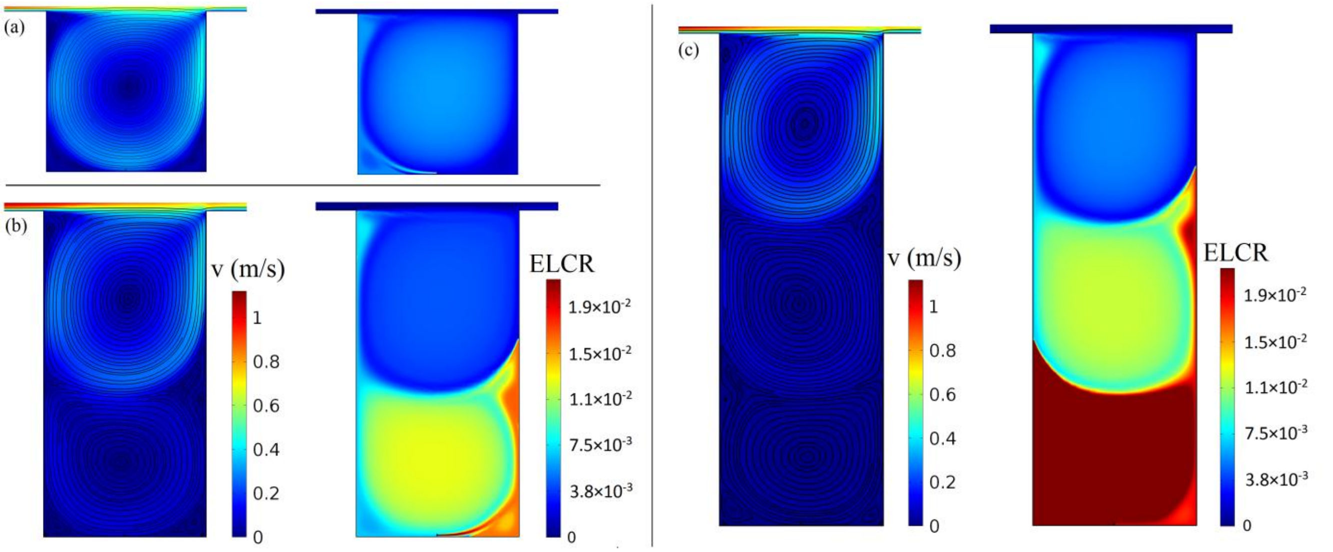

Figure 2. Airflow fields and corresponding ELCR distribution for H/W=1 (a), H/W=2 (b) and H/W=3 (c), for a wind speed of 1 m s^{-1}, considering people exposed to traffic emissions 24 hours per day for 70 years.

In Figure 3 the ELCR calculated at a breathable height of 1.5 m on the leeward and windward sides of the street canyon is reported as a function of wind speed and aspect ratio H/W. In particular, on the top panel of Figure 3, the ELCR is showed as function of the wind speed (1, 3 and 5 m s^{-1}) for the three analysed aspect ratios (1, 2 and 3), while on the bottom panel of Figure 3 the ELCR is showed as function of the H/W ratio for the different wind speeds. The top panel of Figure 3 confirms what stated above: the ELCR value at 1.5 m from the ground is higher on the leeward side for aspect ratios equal to 1 and 3, while for aspect ratio equal to 2 the ELCR is higher on the windward side, for all the three wind speeds analysed. As a general behaviour, with the increasing of wind speed the ELCR becomes lower everywhere in the street canyon, due to the strengthened interaction between the free-stream flow and the flow inside the canyon. In addition, the effect of wind speed is more pronounced for wind speeds between 1 and 3 m s^{-1} than between 3 and 5 m s^{-1}, and this behaviour is more visible on the leeward side, for H/W=1 and 3, and on the windward side for H/W=2. As can be observed from the bottom panel of Figure 3, the ELCR value at 1.5 m tends to increase with the increasing of the aspect ratio, with a different trend on the leeward and windward side of the street canyon: on the leeward side the ELCR tends to increase more than on the windward side, with the increasing of the aspect ratio, for all the three wind speeds analysed.

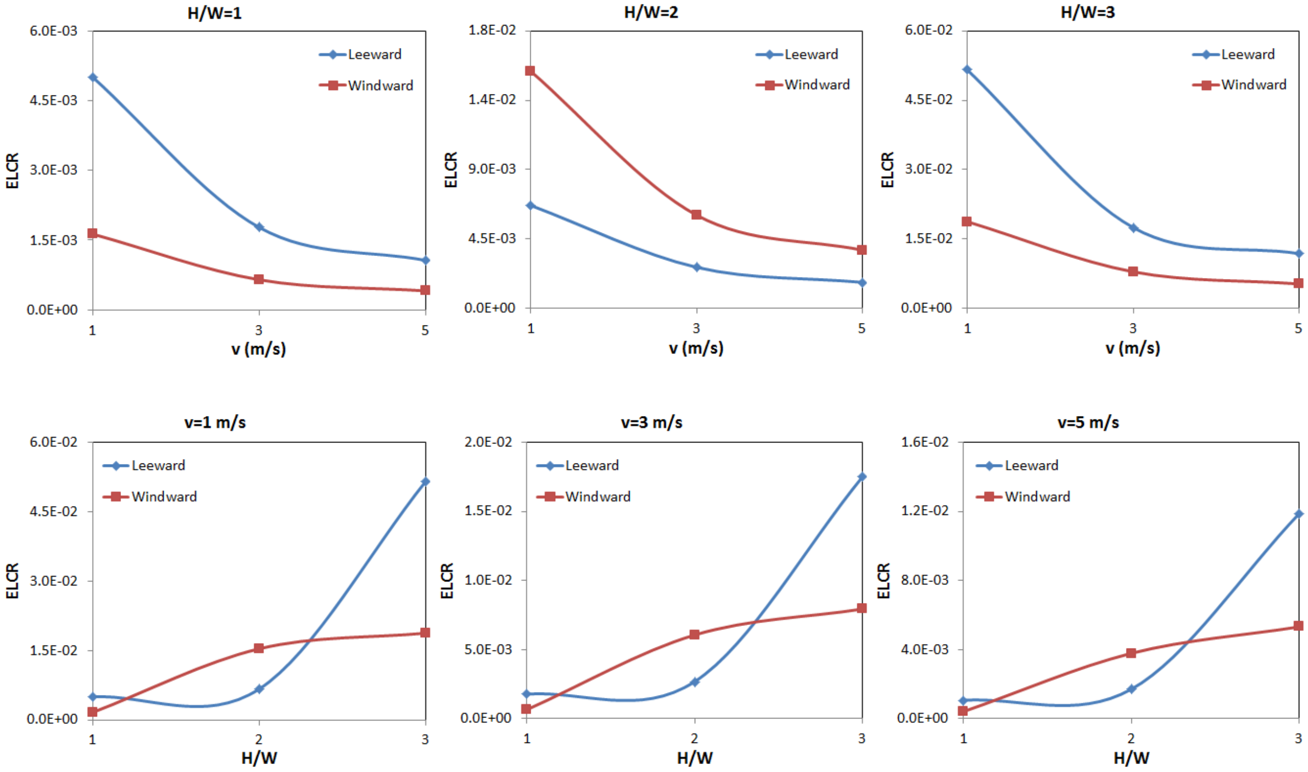

Figure 3. ELCR calculated at a breathable height of 1.5 m from the street level on the leeward and windward sides of the street canyon as a function of wind speed (top panel) and aspect ratio H/W (bottom panel). People exposed 24 hours per day for 70 years.

In Table 5 and Table 6 the calculated ELCR values are reported in details for all the aspect ratios and wind speeds considered, at a breathable height of 1.5 m, on the leeward and windward sides of the street canyon. The ELCR for the reference configuration are reported in bold. In particular, Table 5 reports ELCR values for people ideally living 24 hours per day in the street canyon for 70 years, while Table 6 reports ELCR values for a more realistic scenario of people spending 15 minutes per day in the street canyon for 20 years. It should be stressed that the ELCR values reported in the tables are representative of the extra risk to develop cancer (new lung cancer cases) due to the exposure of pollution from urban traffic only, without considering the background pollution eventually present in the street canyon.

Table 5. ELCR values calculated on the leeward and windward sides of the street canyon at a breathable height of 1.5 m, for people exposed 24 hours per day for 70 years. Reference simulation case in bold.

	H/W=1		H/W=2		H/W=3	
v (m/s)	Leeward	Windward	Leeward	Windward	Leeward	Windward
1	**5.0×10^{-3}**	**1.6×10^{-3}**	6.7×10^{-3}	1.5×10^{-2}	5.2×10^{-2}	1.9×10^{-2}
3	1.8×10^{-3}	6.5×10^{-4}	2.7×10^{-3}	6.1×10^{-3}	1.7×10^{-2}	7.9×10^{-3}
5	1.1×10^{-3}	4.1×10^{-4}	1.7×10^{-3}	3.8×10^{-3}	1.2×10^{-2}	5.3×10^{-3}

Table 6. ELCR values calculated on the leeward and windward sides of the street canyon at a breathable height of 1.5 m, for people exposed 15 minutes per day for 20 years. Reference simulation case in bold.

	H/W=1		H/W=2		H/W=3	
v (m/s)	Leeward	Windward	Leeward	Windward	Leeward	Windward
1	**1.5×10^{-5}**	**4.8×10^{-6}**	2.0×10^{-5}	4.6×10^{-5}	1.5×10^{-4}	5.6×10^{-5}
3	5.3×10^{-6}	1.9×10^{-6}	8.0×10^{-6}	1.8×10^{-5}	5.2×10^{-5}	2.4×10^{-5}
5	3.2×10^{-6}	1.2×10^{-6}	5.1×10^{-6}	1.1×10^{-5}	3.5×10^{-5}	1.6×10^{-5}

As can be seen from Table 5, which reports an extreme scenario representative of worst possible condition, the maximum ELCR value found under the assumptions made in the methodology section, is equal to 5.2×10^{-2} on the leeward side of the H/W=3 street canyon configuration, with a wind speed of 1 m s^{-1}. This ELCR value means that on a population of 100 000 individuals, there will be 5 200 new lung cancer cases, according to the proposed model. In the same extreme scenario, the lower ELCR value of 4.1×10^{-4} is relative to the windward side of the H/W=1 configuration, with wind speed of 5 m s^{-1}, meaning that 41 people will develop cancer over a population of 100 000. The reference configuration (H/W=1, wind speed of 1 m s^{-1}) presents ELCR values between 1.6×10^{-3} and 5.0×10^{-3} on the windward and leeward sides, respectively (160 and 500 new lung cancer cases over 100 000 peoples, respectively). For the scenario of people spending 15 minutes per day in the street canyon for 20 years, Table 6 reports lower ELCR values, as expected. Again, the worst condition is observable on the leeward side of the H/W=3 configuration, with wind speed of 1 m s^{-1} (ELCR equal to 1.5×10^{-4} – 15 new lung cancer cases over 100 000 peoples), while the lower ELCR is relative to the windward side of the H/W=1 street canyon, with 5 m s^{-1} of wind speed (1.2×10^{-6} – 0.12 new lung cancer cases over 100 000 peoples). The reference configuration (H/W=1, wind speed of 1 m s^{-1}) presents ELCR values between 4.8×10^{-6} and 1.5×10^{-5} on the windward and leeward sides, respectively (0.48 and 1.5 new lung cancer cases over 100 000 peoples, respectively).

As a comparison with the data reported in the present paper in Table 6, by applying the same risk model, Scungio, Buonanno, Stabile and Ficco [17] found ELCR values between 0.017 – 0.07×10^{-5} considering different scenarios of people living nearby a waste incineration plant in central-southern Italy exposed only to the particles emitted from the stack of the incinerator itself (without considering the background pollution), for the entire lifetime of the plant, supposed to be 20 years. Moreover, for typical Italian smokers the ELCR was found to be between 2 – 6×10^{-1} [16], considering typical smoking patterns, which is a value 3 – 4 orders of magnitude higher than that found in the present paper. In addition, the risk calculated in this work for the scenario depicted in Table 5 results comparable to the ELCR target limit of 1×10^{-5} reported by WHO [34], and can be considered "safe" if compared to the EPA target risk range of 10^{-6} – 10^{-4} since, as EPA reports, ‘‘even risks slightly greater than 1×10^{-4} may be considered adequately protective" under specific conditions[35].

4 CONCLUSIONS

In this paper, a novel modelling approach was proposed in order to evaluate the Excess Lifetime Cancer Risk (ELCR) for people exposed to fine and ultrafine particles emitted by light duty and heavy duty vehicles (both gasoline and diesel fuelled) in urban street canyons. To this end, the literature data of PAHs, heavy metals PCDD/Fs and PM_{10} deposited on particle surface, detected in emission from the vehicles, were used for the evaluation of the ELCR at the tailpipe. This value was then imposed in a numerical CFD model as input data, in order to evaluate the lung cancer risk of people living in the street canyon, at street level (at a height of 1.5 m), as a function of the wind speed and canyon geometry (aspect ratio, H/W), and considering two exposure scenario. The ELCR calculated at the tailpipe was found to be equal to 2.1×10^{-2}, meaning that for every 100 000 people hypothetically breathing directly at the tailpipe of the vehicles 24 hours per day for 70 years, 2 100 will develop lung cancer. On the basis of this value, imposed as input data in the numerical CFD model, the ELCR for people living inside the canyon was obtained. In particular, for an extreme scenario of people living 24 hours per day for 70 years in the street canyon, the maximum ELCR value found equal to 5.2×10^{-2} (5

200 new lung cancer cases over a population of 100 000) on the leeward side of the H/W=3 street canyon configuration, with a wind speed of 1 m s^{-1}, according to the proposed model, showing the presence of an accumulation zone inside the canyon that significantly worsen the air quality. In the same extreme scenario, the lower ELCR value of 4.1×10^{-4} is relative to the windward side of the H/W=1 configuration, with wind speed of 5 m s^{-1}, meaning that 41 people will develop cancer over a population of 100 000. For a more realistic scenario of people spending 15 minutes per day in the street canyon for 20 years, the worst condition was observed on the leeward side of the H/W=3 configuration, with wind speed of 1 m s^{-1} (ELCR equal to 1.5×10^{-4} – 15 new lung cancer cases over 100 000 peoples), while the lower ELCR is relative to the windward side of the H/W=1 street canyon, with 5 m s^{-1} of wind speed (1.2×10^{-6} – 0.12 new lung cancer cases over 100 000 peoples). From the parametric analysis, it was found that the ELCR value at 1.5 m from the ground is higher on the leeward side for aspect ratios equal to 1 and 3, while for aspect ratio equal to 2 the ELCR is higher on the windward side, for all the three wind speeds analysed. In addition, the simulations showed that with the increasing of wind speed the ELCR becomes lower everywhere in the street canyon, due to the strengthened interaction between the free-stream flow and the flow inside the canyon. Finally, the risk calculated in this work (considering the scenario of people exposed 15 minutes per day for 20 years) results lower if compared to the ELCR target limit of 1×10^{-5} reported by WHO, and can be considered “safe” if compared to the EPA target risk range of 10^{-6} – 10^{-4}, under the assumption described in the proposed methodology.

With the proposed approach, that allows to consider the dispersion of particles and relative toxicity, it will be possible to evaluate the effect of different sources that contribute to the total ELCR in urban area. The authors, anyway, point out that a not negligible amount of uncertainty can be associated to the proposed methodology, and that a proper uncertainty budget of the ELCR model is quite complex as it depends on measurement uncertainties, on model uncertainty itself, and on the uncertainty of the assumptions made (choice of fleet and fuel spread, fractional deposition, spherical shape of the particles etc.). Therefore, an ad-hoc study focused on an more accurate risk and correlated uncertainty evaluation, together with the evaluation of different particle sources in urban area that contribute to the total ELCR, could likely represent a future development of the paper.

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