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Computational Fluid Dynamics Models to Estimate Pedestrian Exposure to Traffic-Related Air Pollution: A Review †

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Abstract: In recent years, computational fluid dynamics (CFD) has become a method widely used by the scientific community to study the dispersion of air pollutants in urban areas. This article analyzes the effectiveness of computational fluid dynamics models and their validation methods used to estimate pedestrian exposure to traffic-related air pollutants. This work proposes an exploratory methodology based on a literary review. A total of 28 articles were selected and analyzed from 455 articles published in the Scopus database in 2018–2023. The results show the effects of meteorological variables, such as wind speed and wind direction, on the dispersion of pollutants, especially the effects demonstrating that, at higher wind speeds, they tend to disperse more quickly, which reduces the concentration of these pollutants at the level of the pedestrian respiratory zone. Computational fluid dynamics is an advantageous tool; however, it is necessary to complement it with other models that consider the physical activity of people and thus more precisely evaluate the effect of inhaled pollutants on the entire respiratory system of pedestrians.

Keywords: CFD; air pollution; traffic; pedestrian exposure

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1. Introduction

A highly important aspect to consider in computational fluid dynamics applied to the dispersion of pollutants is turbulence modeling since, in urban areas, the presence of physical obstacles affects the flow, and therefore behavior, of pollutants, which makes the selection of a good turbulence model essential for the reliability of the results obtained. In addition, this selection can impact the time and computational requirements that are available.

Special attention should also be paid to the issue of the validation of data obtained from the computational model; validation is defined as the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

2. Methodology

This research was based on a literature review of models that use computational fluid dynamics to estimate pedestrian exposure to air pollutants from vehicular traffic. A search was conducted on research published in the last five years (2018–2023). Two search codes were developed in the Scopus database. The first search code consisted of the following formula, which we will call F1: (“AIR POLLUTION” AND “TRAFFIC” AND

"PEDESTRIAN" AND "CFD"). The second, called F2, consisted of the following formula: ("AIR POLLUTION" AND "TRAFFIC RELATED" AND "PEDESTRIAN LEVEL" AND "EXPOSURE" AND "CFD"). The criteria for inclusion in the database were then applied with respect to the type of document (article, book chapter, or book) and the language of the document (English). From these searches and inclusion criteria, we found a total of 555 documents that advanced to our next stage, the PRISMA analysis, which consisted of three steps: identification, screening, and inclusion, in order to search and select literature samples [1]. In Figure 1, we can see the process followed to select the 28 articles reviewed in this article.

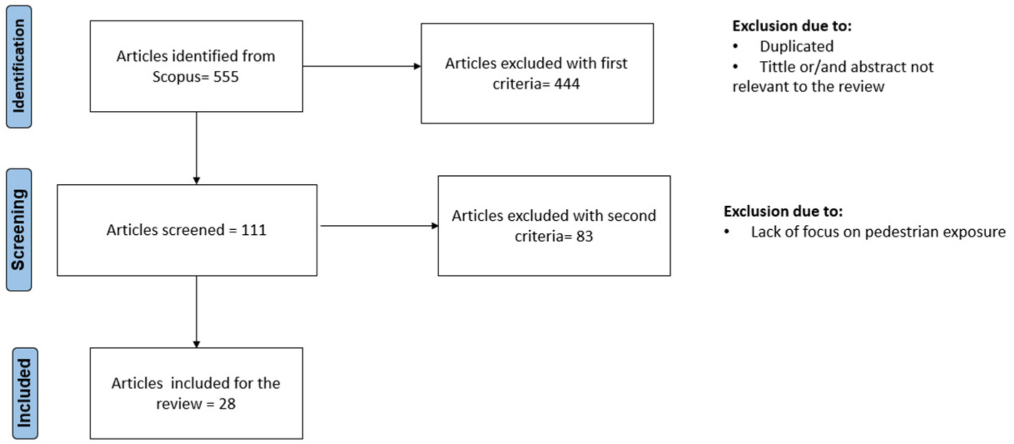

Figure 1. A flowchart outlining the protocol of review using PRISMA.

3. Results

For this review, we choose 5 different criteria to evaluate the 28 selected articles: software, boundary conditions, turbulence models, validation methods, and the assessment of pedestrian exposure.

3.1. Software

ANSYS Fluent was the most used option in the articles reviewed; a technical justification for this would be the fact that, in Fluent, meshing can be updated using a dynamic meshing method, which allows for a simulation of air pollution under real situations of vehicle movement. STAR CMM+ was the second most used software in this research, which generally allows for a good scalability of the physical model. OpenFOAM, which appeared in three articles in this review, is an open access program developed in 2004 that has been continuously validated in the CFD industry. Three of the articles did not specify with which program they worked; this made it difficult to verify the results obtained in these investigations.

3.2. Boundary Conditions

The boundary conditions of a model are highly important, since they must represent the environmental and physical conditions of the processes to be investigated with the use of CFD as close to reality as possible. In most of cases in this review, the division of the section that was analyzed was presented in a cube form with six planes: one at the top, one at the bottom, two lateral, and two others separately representing the input and output of the flow; each of these planes needed to be assigned some boundary condition. At the inflow, the velocity inlet boundary condition was specified in 20 articles; meanwhile, at the outflow, there were two trends: the specification of a constant static pressure outlet in 9 articles and an outflow boundary where all the flow derivatives were zero, in 8 articles. In the other walls of the domains, the predilected option was the symmetry condition.

3.3. Turbulence Models

Among the most widely used turbulence models in the literature reviewed, we discovered only one article that used a LES turbulence model, whereas the rest used RANS models in some way. With regard to the RANS models, only one did not work with any derivative of the κ-ε equations, where κ represents turbulent kinetic energy, and ε represents the rate of the dissipation of turbulent kinetic energy. These equations are widely used for their robustness and low computational cost. The other type of equation based on RANS is κ-ω; in this equation, ω represents the specific rate of the dissipation of turbulent kinetic energy. This equation has a higher nonlinearity, and, therefore, its convergence is more challenging than in the equations of the different k-ε models. In addition, it is more sensitive to the initial value assumed for the solution, which makes it less robust.

3.4. Validation Methods

Validation is defined as the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model [2]. Table 1 shows the three validation techniques used in the articles reviewed, with their advantages and disadvantages.

Table 1. Advantages and disadvantages of different validation methods.

Validation Method	Advantages	Disadvantages	Articles Using the Validation Methods
Wind tunnel	Data are readily available in the literature.	As the data are not obtained from the same physical domain that is being modeled, these results do not reflect the actual behavior of pollutants in that domain.	[3–16]
Wearable sensors	They are easy to transport and place at measurement sites and are more accessible.	The calibration of these sensors should be performed for each measurement and ideally compared with data from monitoring stations.	[17–26]
Monitoring stations	The data they provide are the most reliable and allow for long-term measurements.	They are not available in all places, and it is difficult to cover pollution levels at pedestrian height.	[27]

4. Assessment of Pedestrian Exposure

An exceptionally common type of analysis found in the articles was to use CFD to assess pedestrian exposure to pollutants from vehicular traffic under different tree configurations. In one article, CFD simulations were performed with six different green infrastructure configurations. The results obtained show that the presence of high vegetative barriers could result in negative impacts on pedestrians and cyclists; this could be because this type of vegetation offers temporary retention to particles from traffic, therefore increasing the time in which these particles are in the environment [18]. Similar results concluded that the effect of planting trees along the road to prevent emissions of reactive traffic pollutants from entering the sidewalk was low because trees also increase pollutant concentrations by weakening the wind [27]. The position where vegetation is planted has also been found to be more critical than the area and volume of vegetation for reduction in particulate matter concentration [4].

Turbulence induced by traffic is another factor that affects the exposure of pedestrians; this phenomenon has been studied under different conditions of movement, in both vehicles and pedestrians. It is recommended that cars maintain a distance of 3.5 m from each other and that pedestrians walk on sidewalks, since the farther they are from the road, the lower the concentration of PM10 [5]. Another article notes that, if they neglected the effects of induced turbulence, CO concentration would be overestimated by 78% [14]. It was also noted that there was an extreme level of exposure during heavy traffic hours due to high emissions produced by the exhaust of the vehicles. Vehicle arrangement plays an important role in the dispersion of exhaust pollutants as well as vehicle speed; as speed increases, higher vehicle-induced turbulence occurs, accelerating the diffusion of exhaust pollutants and further distributing this pollution [3].

In some articles, models were used to simulate the mobility of both pedestrians and vehicles with CFD simulations. For example, by using the VISSIM model, a greater exposure of pedestrians at bus stops and pedestrian crossings were simulated, in addition to obtaining results with monitoring stations; it was concluded that, in these, the spatial variation in the concentration of pollutants [17] could not be observed. Another similar model, but this time with SUMO, was used to simulate the flow of pedestrians and their exposure to two different types of traffic, one continuous and one interrupted by an obstacle on the road, and the results reflected that the presence of obstacles significantly increased the exposure of pedestrians to pollutants produced by vehicular traffic [12]. Another strategy used in this field was performing simulations to study the effect of reversing lanes and evaluating how this influenced the concentration of PM2.5 at the road level. In a reviewed article, the results indicated that, under certain urban configurations and appropriate speed ranges, lane reversing could have significantly positive effects on reducing PM2.5 concentrations at a pedestrian height [16].

On the topic of quantifying exposure indices, two stand out: the first is the personal intake factor (P_IF), which is defined as an index to analyze the impact of factors such as vehicle speed and wind speed on exposure at the pedestrian level [28]; and the second is the respiratory dose of inhaled particles (RDD), which depends on the concentration of the particles during measurement campaigns, the exposure time of the people evaluated, and their ventilation rate [29]. This ventilation rate is a variable that depends on indicators of physical activity in people, such as palpitations per minute, respiratory rate, and vital capacity [30].

It is important to note that the use of both indices mentioned in the articles of this review only quantifies exposure at the entrance of the respiratory system—that is, at an average height of 1.5 m; in other words, it does not consider how the particles or gases emitted by vehicular traffic affect the entire respiratory system. Models have been found in the literature that can more accurately predict the rate of inhalation from pollutants, such as the cascade impact model to simulate regions of the respiratory system, and how different particle sizes affect each region [31]. As for studies using CFD to assess disease risk in particular, an innovative approach was found that could estimate the incidence of lung cancer in street canyons due to exposure to traffic-generated particles, with results showing that, as wind speed increased in the canyon, the risk of lung cancer decreased due to dispersion [32].

Quantifying exposure due to vehicular traffic remains extremely complex, as there are many factors involved, leading to uncertainty in the health effects caused by vehicle fleets, as mentioned in an article exploring pedestrian exposure to PM2.5 in two vehicle fleet configurations in Hong Kong [25].

5. Conclusions

- Tree planting near avenues does not necessarily improve the issue of pollutant dispersion since meteorological factors such as wind speed and direction must be considered.
- Ignoring the effect of vehicle-induced turbulence can lead to significant errors in computational models.
- There is no standardized methodology for validating computational results.
- Most CFD simulations only quantify pedestrian exposure at the entrance to the respiratory system.
- For future work on this topic, we recommend the following: complement the results of CFD simulations with other models that consider the physical activity of people, as well as variables related to respiratory capacity, and thus more completely evaluate how pollutants that are products of vehicular traffic affect pedestrians.

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