Issues in Modelling Traffic-Related Air Pollution: Discussion on the State-Of-The-Art

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Abstract. Traffic-related air pollution is nowadays considered as a major externality from the transport sector. This paper conducts a literature review on three main topics: mechanisms of traffic-related air pollution formation and disposal, models in use for their simulation, and methods and models for the economic quantification of emissions. Providing an up-to-date overlook on the modelling and quantification framework of traffic-related air pollution and highlighting pros and cons of each solution with regard to the goal of the research and to the context of application, this paper aims at describing the effective knowledge made on this theme and at identifying future research directions.

Keywords: Air pollution modelling · Air pollution quantification · Traffic related pollution

1 Introduction

This paper provides a synthetic state-of-art review of methods for the analysis of the formation, disposal and quantification of traffic-related air pollution, a major negative externality from the transport sector [1]. The goal is to provide an updated overview on the modelling and quantification framework of traffic-related air pollution and to highlight strong and weak points of each solution with regard to the goal of the research and to the context of application. The brief discussion carried out within this paper should be useful for scholars and authorities to appropriately choose the most suitable methodology according to their needs, also within research efforts under the umbrella of EU-funded mobility-related projects. This paper is intended as a swift tool to support researchers in the initial stages of their work, when compiling the literature review and assessing methodological options. The paper is structured as follows: Sect. 2 looks at the formation and disposal patterns of traffic-related air pollution, while Sect. 3 discusses models to estimate those patterns. Section 4 looks at techniques and methods for the quantification of traffic-related air pollution, and Sect. 5 discusses and compares contents and draws some conclusions.

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2 Formation and Disposal of Traffic-Related Air Pollution

Road traffic, one of the main modes for both freight and passenger transport, accounts for 81% of transport-related energy consumption in Europe [2]. Large amounts of polluting substances are emitted in the atmosphere, posing severe threats to the health of human beings and of planet Earth. Primary pollutants, such as PM_{10}, $PM_{2.5}$, SO_x, NO_x and CO, constitute a direct threat to human health and to the environment, being directly responsible of premature deaths and of natural degradation [3].

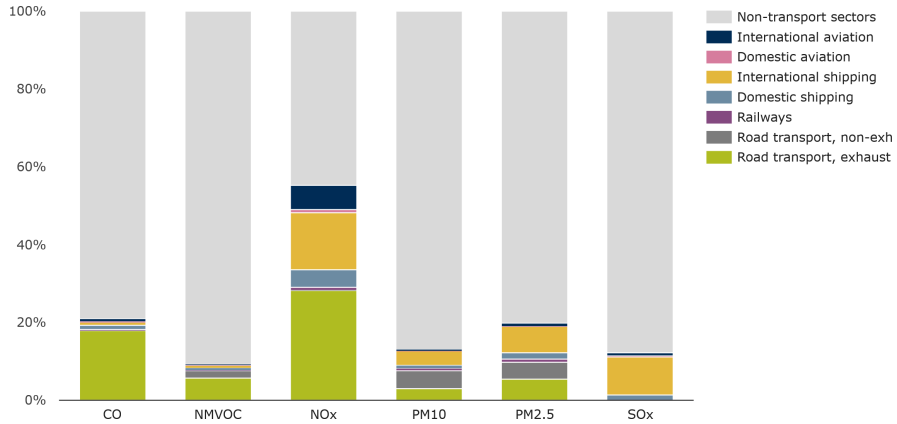

Fig. 1. Contribution of the transport sector to total emissions of the main air pollutants (Source: EEA, 2021 [5])

The contribution of the transport sector to total emissions of such elements is shrinking; however, transport still accounts for 20% of global CO, SOx and PM2.5 emissions, and for 54% of NOx emissions (Fig. 1) [1]. Emissions of GHGs (Greenhouse Gasses), with particular reference to CO_2 (carbon dioxide), CH_4 (methane) and N_2O (nitrous oxide) are growing due to human activity and in 2011 their concentrations reached 391 ppm, 1803 ppb, and 324 ppb respectively[1] [4]. Increasing GHGs emissions are directly correlated with global warming and climate change. Surface temperatures have been growing for the whole 20th century and the rate has increased in the early years of the new millennium, together with more frequent extreme weather events and other phenomena related to climate change [4, 5]. Albeit globally the transport sector accounts for approximately 14% of global yearly GHG emissions (Fig. 2), at the European level the sector is responsible for around 26% of GHG emissions, with the figure also showing an increasing trend (Fig. 3) [6, 7].

Given the differences in polluting sources and trends and the different cycles and sectors of impact of primary pollutants and GHGs, the two groups of pollutants are normally discussed, analyzed and modelled separately [3]. Some of the models adopted

[1] ppm stands for “parts per million”; ppb stands for “parts per billion”.

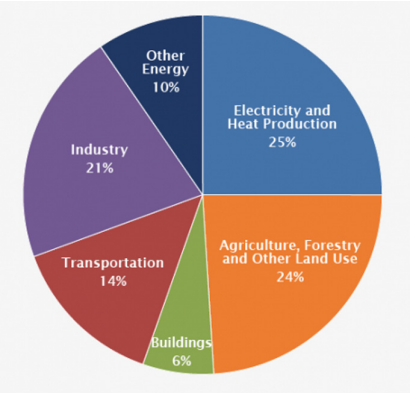

Fig. 2. Global GHG emissions by economic sector in 2014 (Source: EEA, 2021 [7])

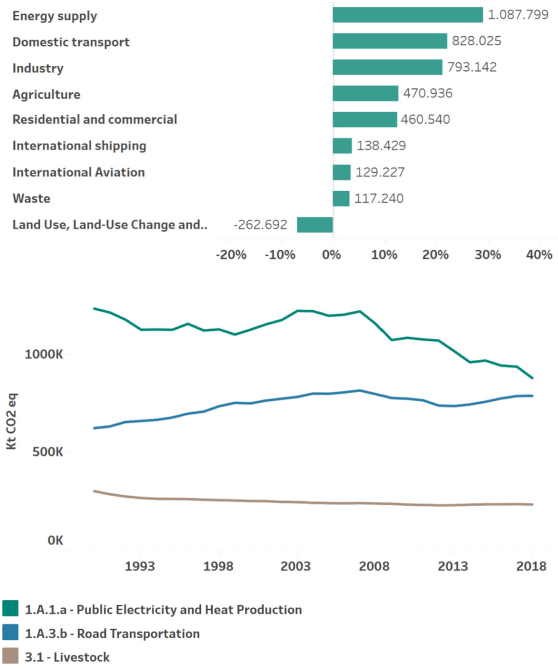

Fig. 3. GHG emissions by economic sector in the EU in 2018 and emission trend (Source: EEA, 2021 [7])

by researchers and institutions later discussed in this paper, however, are able to comprehensively evaluate emissions from the transport sectors, including both short and long-term impacts on the environment and health-related consequences.

Pollutant emissions from road traffic are generated by motorized vehicles during the various phases of the trip, and their quantity, type and emission patterns are affected by

a number of factors. These can be generally classified as travel-related, driver-related, facility-related, fuel-related and environmental (Fig. 1; [8]) (Fig. 4).

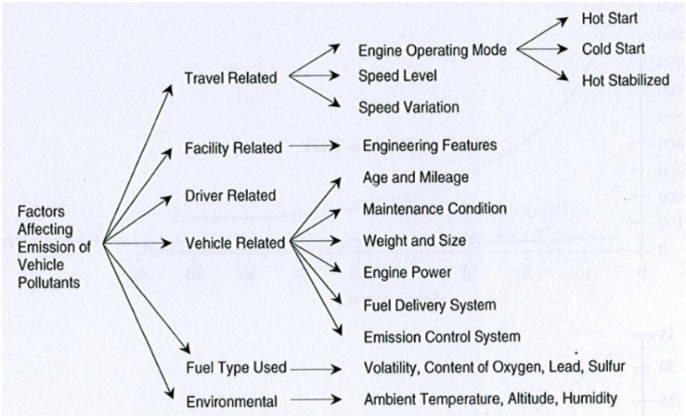

Fig. 4. Factors affecting vehicle emissions (from Sinha and Labi 2007 [8])

The sensitivity of emissions to these factors has been object of a number of report and studies. Comprehensive reviews have been conducted by [9] and by [10]. Travel-related factors include speeds and vehicle operating modes, typically cold start, hot start, and hot stabilized period [11]. Cold starts are generally acknowledged to produce higher emission rates. The consistency and smoothness of travel speed, as well as load, acceleration rates, and fuel types also impact emission rates. For most vehicle types, emissions are lower at higher speed, and rise at low speeds and when the engine is forced at high rates [12, 13]. Driver-related factors are hinged on the driver's behavior: aggressive drivers exert more severe accelerations and decelerations and require more effort to the engine, thus reducing time spent at low-emitting conditions. Facility (i.e., infrastructure) design can favor the operation of motorized vehicles at low-emitting speeds or modes, by encouraging smooth and non-aggressive driving. Infrastructural and technological interventions such as traffic flow management signal coordination, moreover, can result in emission reductions up to 25% [14, 15]. Vehicle-related factors include vehicle age, mileage, condition, weight, size, and engine power. In general terms, lighter-duty and newer vehicles emit significantly less [12]. Environmental conditions, and particularly temperatures, have an impact on emissions. Low ambient temperatures require more time for engines and emission-control systems to warm up and cause higher emissions, even in the case of hybrid-electric new generation vehicles [16].

Factors related to the environmental and meteorological conditions, as well as to the morphology of the territory in which the emitting source is located, affect the pollutants' dispersion of in the atmosphere. Atmospheric conditions, such as temperature, stability, precipitation, wind, humidity and intensity of solar radiation, impact on the temporal and spatial variation of pollutant dispersion and, therefore, on the concentration of air pollutants. Particularly relevant atmospheric phenomena ruling pollutant dispersion are the atmospheric stability (related to the change in temperature, wind speed and wind

direction with height): a stable atmosphere suppresses vertical motion within its domain and thus lowers dispersion rates; thermal inversion (which entraps cold air layers and pollutants under a warmer plateau); and ceiling height: night-time and winter conditions are normally associated with lower ceilings and lower dispersion rates [8].

Topography and urban form also affect pollutant dispersion: higher morphological complexity corresponds to lower dispersion rates and thus higher pollutant concentrations, as it affects the wind speed and direction and temperatures in the area. Regardless of the urban or natural environment, steep grades and obstacles to airflow, such as building or natural elevations, contribute to the "canyon effect" and to a slower pollutant dispersion [17, 18].

The assessment of determinants, magnitude, and characteristics of pollutant dispersion can be a complex task, especially in urban areas or unregular terrains, due to the range and diversity of polluting sources, topographical and morphological features, and to the contribution of anthropic activity. The next section discusses a number of pollutant dispersion models developed by scholars to achieve the task.

3 Models for the Simulation of Traffic-Related Air Pollution Formation and Disposal

Pollutants are emitted in the atmosphere according to a number of dispersion factors including meteorological conditions (in particular wind speeds, atmospheric stability, temperature gradients), the number of emitting sources and the emission rates of such sources [8]. A number of models for assessing the emissions' impact on pollutant concentrations have been developed, among which some of the most relevant are the box model, the Gaussian plume model, and the numerical model.

The box model assumes uniform dispersion of pollutants to fill a box-shaped space, with two main factors (wind speed and mixing height) controlling dispersion patterns. Combination of multiple boxes are commonly used by scholars to improve the model's detail and solve flows as modified by the presence of buildings and other disturbing factors [19]. Box model approaches are the most basic air quality algorithm and have been often used to determine impacts from linear sources, such as highways or airport runaways; however, the analysis of morphologically complex environments through this technique is exposed to a certain degree of approximation [20].

The Gaussian Plume model uses normal distribution to describe the random wafting of plumes side to side and up and down, resulting in increased plume size with time and higher pollutant concentrations near the emitting source [8]. The Gaussian equation is used to estimate the dispersion of pollutants released from an emitting source at a steady rate, and the model is widely used as it produces similar results to those obtained with other more complex models, mathematical operations are easy to perform, it is consistent with the random nature of turbulence and dispersion, and it is often referred to in governmental guidelines [21].

Numerical models, such as for instance DANARD, RAGLAND, MROAD-2, ROADS (for further details see a review by [22]) use numerical analyses and algorithms by means of computer-based simulations to solve and analyze problems related to flows and dispersion [23, 24]. Numerical air quality models involve a three-dimensional grid

of conceptual boxes that occupy the space above a transportation corridor. Emitting sources impact the overlaying "boxes" and fill them at some given rate, then including the immediately outlying areas in a continuous process. Accounting for variables such as winds, emission diffusion and emission rates, and using well-behaved functions of time, numerical models can predict the movement of polluting particles across the "boxes" with successive time increments [8]. Whereas in the past Gaussian Plume models were the most commonly used thanks to their capacity to correctly represent complex terrains and to provide good estimates of ground-level pollutant concentrations [25], numerical models have been perfectioned and have become more practical with the recent development of powerful computers. Numerical models in general have proven accurate in simulating atmospheric dispersion, recently even including meteorological conditions [26]. Silva et al. [27] found numerical models to reliably and confidently predict CO_2 emissions and fuel consumption. The EEA (European Environmental Agency) confirms that numerical models can be used to conveniently simulate transport processes [28] while the American Environmental Protection Agency (EPA) has officially adopted the AERMOD numerical model [29], which has proven reliable under a wide range of meteorological and topographical conditions [30].

4 Models and Methods for the Quantification of Traffic-Related Air Pollution

Pollutant emission models are needed to determine the impacts from the transport sector and to forecast changes due to variations to the transport system. A great number of emission models has been proposed. The most relevant ones are adopted as standard by environmental agencies (e.g. EEA, USEPA) and are available in form of online tools or software for public use, such as for instance MOBILE 6.0 and COPERT. Faris et al. [31] conducted an in-depth, extensive review of emission models, providing a number of different classifications and great-value comparisons. For deepening the topic, we suggest that the reader refers to their contribution. Basing on input variables, state-of-art models can generally be divided into microscopic or macroscopic models. At times, mesoscopic models are also indicated [31]. Conventionally, microscopic models are used in simpler simulation, with less vehicle variety and few intersections and disturbing factors, while macroscopic models are suitable for replicating the city level [32]. Table 1 synthetizes the three kinds of models that we consider in this paper, including the main source of reference for each specific model, in case one is clearly identifiable.

Single-vehicle emissions simulated through microscopic models can be aggregated to estimate network-wide measures. The most relevant microscopic models can be divided into: comprehensive modal emission model (CMEM), first debated by An et al. [33]; VT-micro, developed by Rakha and Ahn [34], which offers realistic estimation and frequent updates [35]; VETESS, adopted by the CORSIM software used by the Federal Highway Administration in the United States of America, and found to have high probability of success in real world applications [36]; VERSIT $+^{\text{micro}}$, adopted by the University of Catalunya in their AIMSUN software [31]; the PHEM model, which uses an emission map, developed in terms of engine operating parameters rather than in terms of aggregate vehicle parameters, to estimate emissions microscopically, and has been

Table 1. Micro-, meso-, and macroscopic models for traffic related air pollution

Model category	Models	Source
Microscopic vehicle emission models	CNEM VT-micro VETESS VERSIT + micro PHEM EMIT MOVES INTEGRATION	An et al Rakha & Ahn Federal Highway Administration University of Catalunya Environmental Protection Agency
Mesoscopic vehicle emission models	Elemental model CONTRAM MEASURE	Herman
Macroscopic vehicle emission models	MOBILE EMFAC/MOVES CORFLO Watson COPERT CO_2MPAS	Environmental Protection Agency State of California Federal Highway Administration Watson et al European Environmental Agency European Environmental Agency

adopted in the VISSIM software [37, 38]; EMIT, that evaluates emissions depending on vehicle speed and acceleration as well as vehicle characteristics [39]; MOVES, developed by the American Environmental Protection Agency (EPA) and currently officially adopted in the United States, in its latest version MOVES3 [40]. Unlike the mentioned software, which use kinematic acceleration-speed relationship to model accelerations, INTEGRATION uses a vehicle dynamics model, computing fuel consumption for each vehicle on second-by-second basis for three operation modes (constant-speed cruise, velocity change and idling) as a function of travel speed [8].

Macroscopic models, instead, use average aggregate parameters to estimate network-wide emission rates. Some of the most relevant models using the macroscopic approach are: MOBILE (latest version 6.2 developed by EPA in 2004 [41]); EMFAC, developed in California and now replaced – together with MOBILE – by MOVES (adapted to network scale) and the TRANSIMS software [31]; CORFLO, developed by the Federal Highway Administration of the USA and characterized by fast simulation times, suitable for inexpensive computers [42]; the Watson model [43] which uses average speed to investigate fuel consumption; and COPERT (computer programme to compute emissions from road transport) developed by the EEA and widely adopted in transportation applications in Europe [44], for both emission inventories and dispersion modelling [45]. The EU has recently introduced a vehicle simulation model for CO_2 certification purposes, known as CO_2MPAS, which also contributes to the implementation of the COPERT software [46].

Finally, mesoscopic models, according to the review by Faris et al. [31], include the elemental model, CONTRAM, and MEASURE. The elemental model was proposed by Herman and adopted in the SIDRA INTERSECTION software in 1985, widely used in

Australia. CONTRAM (continuous traffic assignment model) intends to model traffic links with complex dynamics and is capable of accurate description of time-variable network conditions [47]. However, it lacks the ability to consider performance measures such as speed [48, 49]. The MEASURE (mobile emission assessment system for urban and regional evaluation) is a geographic information system GIS-based model compatible with microscopic models and tools as well [50]. It includes two major modules: start emissions and on-road emissions [51].

The monetary quantification of air pollution is a fundamental task in transport planning. According to an extensive review from Sharma and Khare [23] and to Sinha and Labi [8], three most common methods are used to determine the cost of environmental degradation due to emissions from the transport sector. A first technique consists in computing the costs for cleaning the air near the degradation source by means of physical infrastructures such as air scrubbers [52]. Air pollution costs, if quantified in this manner, can be excessive as the purchasing and operating costs of scrubbers are notable [53]. A second method describes costs as the social damage effects of air pollution, including the health care expenses due to respiratory issues, costs for repair of physical infrastructure, and compensation costs for damages to the natural environment. A review on quantification and internalization methods within this category is available in Aevermann and Schmude [54]. Finally, air pollution cost estimation can be conducted through the willingness-to-pay approach. This method has been object of a number of relevant contributions from authors exploring environmental and transportation issues, and investigates the extent to which persons and business are willing to pay to avoid a pollution-related problem. Recently, the willingness-to-pay approach has been extensively adopted to study the adoption of carbon taxes [55]. Contributions on the topic include Wang and Mullahy [56], Carlsson and Johansson-Stenman [57], Lera-López et al. [58, 59], and Istamto et al. [60].

Air pollution cost values are generally periodically defined by environmental authorities and institutions within the global effort for the fight against climate alternation. Within the European panorama, the European Commission regularly updates its Handbook on External Costs of Transport (latest version [61]) as well as a number of other documents on the internalization of transport-related externalities (like [62]). EC's documents provide air pollution cost estimates for various pollutant types, transportation modes, and operating patterns and speeds. Despite the use of internalization rates provided by public authorities has become a common practice within transport planning [63], emission estimation is not yet a well mastered task and gaps are still open for research on further approaches.

5 Discussion and Conclusions

In this paper, a short state-of-art review of methods and models for the formation, disposal and quantification of traffic-related air pollution has been presented.

In a first section, we have discussed the main factors producing traffic-related air pollution, highlighting the necessity to study different trip and engine phases (e.g. cold starts, constant-speed running, etc.) and the characteristics of trips, facilities, and the environment. It must be noted that, as discussed, the first leg of motorized journeys

is that with the highest impacts, especially when conducted in the urban traffic, causing additional negative externalities to an already suffering environment [64, 65]. This inevitably calls for models and monetization criteria suitable for the analysis of urban environments and of typical urban transport operations.

In Sect. 3, we discussed models for the simulation of traffic-related air pollution formation and disposal, stressing how increasingly powerful computers have allowed for a wider use of numerical models, whereas Gaussian plume models used to be extensively used in the last decades and show good accuracy while keeping computations simple, and box models are effective in simulating simple environments and operations. Finally, we have approached the topic of the quantification and monetization of traffic-related air pollution, discussing a number of models and tools (according to the micro-, macro-, and mesoscopic classification based on input variables) and different approaches to the determination of pollution costs. Table 2 synthetizes the capacity of micro-, meso- and macroscopic emission models to effectively and precisely describe road traffic emissions.

Table 2. Accuracy and relevance to road traffic simulation in the scale of the input variable-based modelling classification (own elaboration from Faris et al. 2011)

Modelling type	Accuracy	Relevance w/r to road traffic simulation
Microscopic vehicle emission models	Relatively accurate	High
Mesoscopic vehicle emission models	More accurate than macroscopic models	Moderate
Macroscopic vehicle emission models	Less accurate than microscopic models	Low

The topic of the quantification of transport-related emissions and of proposed mitigation strategies is particularly important for transport planners, which should be able to adopt and implement the right tools to understand (first) and mitigate, then, mobility-related externalities while pursuing emission reduction strategies in harmony with global and local sustainability objectives. Sadly, governments and planning authorities are often not aware of the origin and distribution of the most impacting emitting sources [6] and are unable to estimate benefits and outcomes of potential improvements [66].

In this review, we provided an overview on different possibilities for the simulation and evaluation of pollutant emissions due to the transport sector. Future efforts within reviews on this topic should more specifically address models for each type of pollutant, on the one side; and models for the simulation of specific territorial and traffic conditions on the other side. The role of technological advancements, both from a vehicle-related perspective (e.g., alternative fuels or traction, automation), from an overall mobility-system perspective and from an ICT perspective (e.g. driving assistant, traffic management systems), should also be studied as varying conditions could alter the models' accuracy.

Despite the extensiveness of the covered topics, the aim was to provide a comprehensive yet easy to read overview of the various possible approaches, also in order to support authorities and decision makers in their approach to the topic within transport planning efforts. The understanding of the matter and the capacity to perform suitable emission evaluation and quantification in transport planning is in fact fundamental to ensure the ability of planning documents to meet global and local emission reduction and air quality targets, ensuring that policy and investments are directed towards effective measures and interventions. Whereas standard air pollution costs as published by authorities (such as the European Commission) are now widely used and have been successfully integrated in planning processes, the estimation of the emissions to be quantified is not always a straightforward, well mastered task. With this contribution, we intended to shed some light on the most common available tools for planners to adopt.

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