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AIR QUALITY (PM_{10}) SCENARIOS RESULTING FROM THE EXPANSION OF HYDROGEN FUEL CELL ELECTRIC VEHICLE IN EMILIA-ROMAGNA (NORTHERN ITALY)

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Abstract: PM_{10} is a critical pollutant for the air quality in Emilia Romagna, a Northern Italy region that includes a large part of the Po Valley. The atmospheric levels of PM_{10} is strongly affected by vehicular traffic emissions, due to fuel exhaust and also to tires, brake and road surface wear, and to road dust resuspension (non-exhaust emissions). This study presents atmospheric PM_{10} scenarios deriving from vehicular traffic emissions in Emilia Romagna as resulting in 2030 from the growth of the Fuel Cell Electric Vehicle (FCEV) and battery electric vehicles (BEV) fleet in the region. Both exhaust and non-exhaust vehicular emissions are considered, evaluated according to the most up-to-date regional bottom-up emission inventory, which attributes about 60% of total primary PM_{10} traffic emissions to wear processes. PM_{10} concentration maps for actual (2019) and 2030 scenarios are obtained by a Lagrangian dispersion model (PMSS). Preliminary results highlight the future impact on atmospheric PM_{10} from tires, brake and road surface wear produced by battery electric vehicles, due to their larger mass compared to FCEVs, which have smaller batteries and mass. These emissions will partially offset the lack of PM_{10} exhaust emissions for electric vehicles. Finally, the daily primary PM_{10} levels by traffic emissions simulated by PMSS and CHIMERE models were compared at specific sites relevant for the studied domain, i.e. the regulatory air quality monitoring stations, only for actual (2019) scenario.

Key words: PM_{10}, exhaust and non-exhaust traffic emissions, air quality, FCEV, electric vehicles

INTRODUCTION

According to the European Commission, cars are responsible for 12% of the EU greenhouse gas (GHG) emissions, making the switch to electric vehicles a key step in the EU strategy towards climate neutrality by 2050. The Commission, within the "Fit for 55" package, planned a reduction in GHG emissions from cars by 55% by 2030 and to reach zero emissions from new cars by 2035. If only the exhaust emissions by a vehicle are considered, there is a clear local benefit in battery electric in terms of NO_x and PM_{10} and GHG emissions. However, vehicles have also non exhaust emissions, e.g. particles due to the wear of tires, brakes and road surfaces, which are becoming the most relevant emission of primary PM_{10} for gasoline-fuelled vehicles (Padoan et al., 2018). With the expected number increase of electric vehicles, it is necessary to estimate the impact by their non-exhaust emissions on ambient PM_{10}.

Po valley is a large air pollution hotspot for Europe (EEA, 2020), where several impacts on public health and life expectancy by atmospheric pollutants were recorded (e.g. Vinceti, 2018; Khomenko et al., 2021). This study investigates primary PM_{10} scenarios due to the growth in hydrogen Fuel Cell Electric Vehicle (FCEV) and in battery electric vehicles (BEV), in the Emilia-Romagna region, representing large part of the Po Valley. The shares of FCEV and BEV vehicle fleet used in the study are based on reports drafted at both the European and the Italian level. A 2030 scenario was compared with the current situation (referred to 2019). The impact of traffic emissions was simulated by the Parallel Micro SWIFT SPRAY modelling suite (PMSS, Arianet, Milan and Aria Technologies, Paris), mainly comprising a 3D a diagnostic weather model and a stochastic Lagrangian particle model. PMSS results were compared to reference simulations by the Eulerian photochemical model CHIMERE for the current scenario.

MATERIAL AND METHODS

Methodology to evaluate emission factors for abrasion and the total annual emission at 2030

The latest regional emissions inventory, INEMAR referring to 2017 and providing the annual PM_{10} atmospheric emissions by traffic, was used in input of the dispersion models: these include both exhaust

emissions (EE) and those from tire, break and road surface wear (hereafter non-exhaust emissions, NEE). For the 2019 scenario, a top-down spatial and temporal disaggregation procedure was applied to the emissions: the PM_{10} traffic emissions, originally assigned to each municipality, were attributed only to the grid cells on the main roads in that area. For the 2030 emission scenario, a bottom-up methodology was used, based on the vehicle fleet composition expected in 2030: the 2030 fleet was obtained by modifying the current fleet (i.e. 2019) according to the expected renewal rate and the entry of BEVs, hybrid electric vehicles (HEVs) and FCEV vehicles. The total number of vehicles was left unchanged between 2019 and 2030, but different shares were applied for each category. For passenger cars (PC), the predicted share of BEV, HEV and FCEV in 2030 resulted in a 10%, 2.3% and 0.7% respectively, out of the 2 918 129 PC in the region. The same procedure was applied to road tractors (RT) and BUSes, while for heavy vehicles (HDV) only a renewal of the vehicle fleet was applied because in this category the introduction of battery-powered vehicles is not foreseen. In the region the share of electric and hydrogen-fuelled RT increased from 0.01% and 0.00% in 2019 to 9.8% and 0.9% in 2030. Electric and hydrogen-fuelled buses in 2019 were 0.2% and 0.0% respectively, and are expected to be 4.2% and 3.4% in 2030. In the following, with HDV+BUS we will refer to sum of HDV, BUS and RT.
In drafting the annual PM_{10} emissions inventory updated to 2030, two different methodologies were followed, one for the EE and one for the NEE. For the EE, the class-dependent exhaust emission factor for PM_{10} (EF_{EE}) derived by COPERT 5 was applied to the expected fleet in 2030, based on its class composition, assuming an average annual distance of 14,000 km for the PC and about 40,000 for HDV+BUS. For NEE a non-linear relationship between the EF and the vehicle mass was assumed, based on Beddows et al. (2021), leading to the non-exhaust PM_{10} emission per unit mass. Mass for FCEV and BEV PC was assumed of 1.4 Mg and 1.8 Mg respectively (Timmers et al., 2016). While for hydrogen-powered RT a mass of 17 Mg was used, 21 Mg for electric RT, 16 Mg for hydrogen-powered BUS and 20 Mg electric BUS. For vehicles with internal combustion engine (ICE) the mass corresponding to the relevant subclasses (i.e. mini, small, medium and large) was used. For battery–equipped PCs the regenerative braking system (RBS) was also taken into account: this system allows to recharge the battery by recovering energy during deceleration and braking, reducing the wear of the brakes compared to traditional systems. Finally a specific EF_{NEE} was obtained for PC and HDV+BUS, allowing the calculation of the total annual NEE of PM_{10} for the Emilia Romagna region.

Modelling suites and model set-up

The impact of vehicular traffic emissions was assessed by the means of the Parallel Micro SWIFT SPRAY modelling suite (PMSS, Arianet, Milan and Aria Technologies, Paris, Trini Castelli et al., 2018). A modulation of both hourly and daily (weekdays, Saturdays and Sundays) emissions of the examined sources was applied. The simulation period covers the whole month of February 2019. For the calculation of the 3D wind and temperature fields, 20 vertical wind and temperature profiles obtained from the WRF-ARW meteorological model (Skamarock et al., 2008) were used, and also ground-based meteorological data collected from 12 stations of the local Environmental Agency (ARPAE) monitoring network. The simulation domain covers the entire Emilia Romagna region and part of the neighbouring regions and seas, for a total area of approximately 285 x 150 km^2, with a resolution of 500 x 500 m^2. The road network considered includes main roads (urban and extra-urban) and motorways in Emilia Romagna.

RESULTS AND DISCUSSION

Emissions factors for abrasion and total annual emissions at 2030

The first results concern the EF_{NEE} of PM_{10} (EF_{NEE}) for the analysed vehicle types (PC, HDV, RT and BUS). Considering the average mass values of the various PC types representative of the 2030 vehicle fleet, the following average EF_{NEE} were obtained: 25.5 mg km^{-1} $vehic^{-1}$ for ICE, 24.4 mg km^{-1} $vehic^{-1}$ for BEV, 22.8 mg km^{-1} $vehic^{-1}$ for HEV and 21.7 mg km^{-1} $vehic^{-1}$ for FCEV. Regarding HDV and RT the EF_{NEE} values resulted: 106.8 mg km^{-1} $vehic^{-1}$ and 120.0 mg km^{-1} $vehic^{-1}$ for HDV and RT ICE respectively, 135.2 mg km^{-1} $vehic^{-1}$ for RT BEV and 118.6 mg km^{-1} $vehic^{-1}$ for RT FCEV. In the BUS category, the EF_{NEE} are 112.3 mg km^{-1} $vehic^{-1}$ for ICE, 128.4 mg km^{-1} $vehic^{-1}$ for BEV and 112.6 mg km^{-1} $vehic^{-1}$ for FCEV.
The total annual emissions of PM_{10} for the years 2019 and 2030 due to vehicular traffic were then compared, examining the emission due to exhaust and those due to abrasion for the considered vehicle categories. Total annual PM_{10} emission due to exhaust decreased in 2030 respect to 2019 of 52.4% for

PC, from 347 to 178 Mg yr^{-1}, in line with the introduction of a large number of BEV and FCEV. A smaller decrease (26.6%, from 357 to 262 Mg yr^{-1}) was estimated for HDV+BUS, where the electric penetration is expected to be smaller.
Total annual PM_{10} NEE for PC in 2030 results 1003 Mg yr^{-1}, assuming a 40% efficiency of the RBS. NEE in 2019, amounting to 1009 Mg yr^{-1}, are similar to 2030, as the introduction of electric and hydrogen PC will lead to a significant increase in the mass of the vehicle fleet. Similar results were obtained for HDV+BUS, for which a slight increase in total annual PM_{10} NEE was estimate, equal to 0.6%, from 349 in 2019 to 351 Mg yr^{-1} in 2030. Overall, the EE and NEE PM_{10} traffic emissions are expected to decrease of about 13%, from 2062 Mg vr^{-1} (2019) to 1794 Mg vr^{-1} (2030).

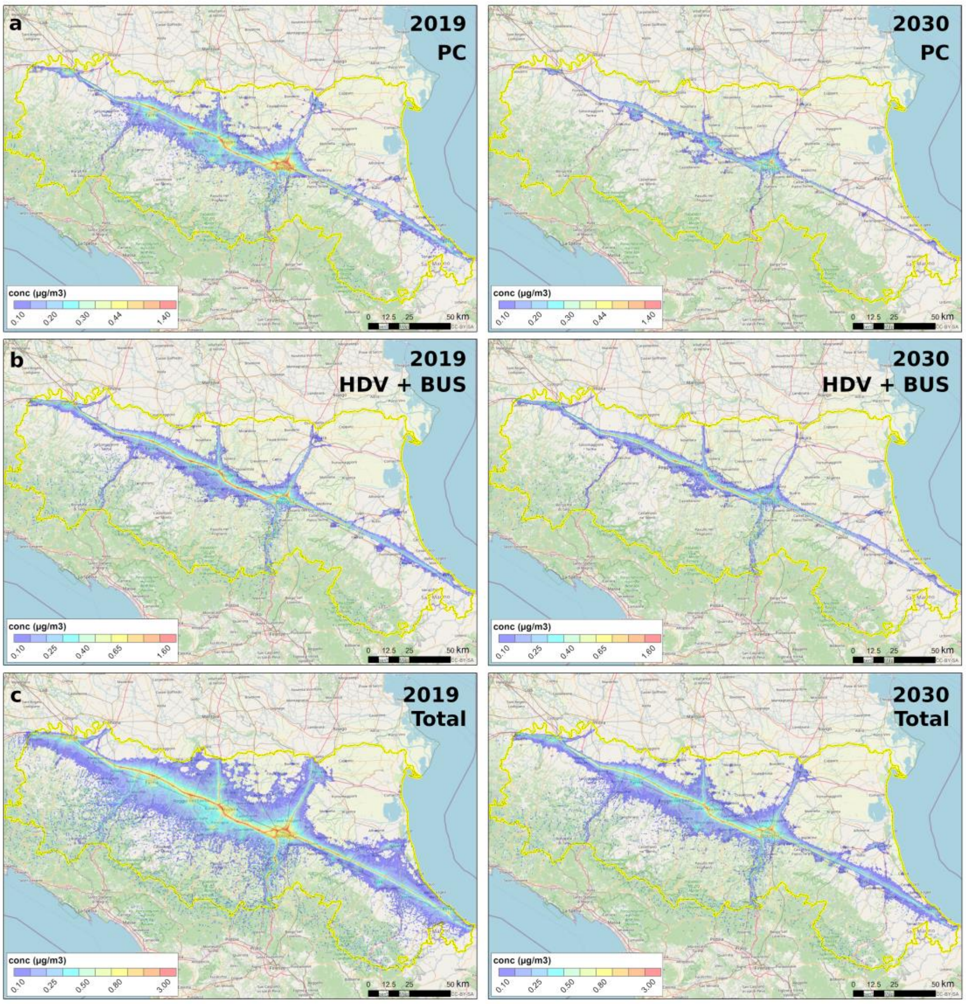

Figure 1. Concentration of primary PM_{10} at ground level (i.e. the first 4 m from the ground) due to traffic exhaust emissions of Passenger Cars (PC), Heavy Duty Vehicles, bus and road tractors (HDV+BUS), and their total, on February 15. The current scenario (2019) is on the left, the future scenario (2030) on the right.

PM_{10} concentration maps

Maps of simulated atmospheric levels of primary PM_{10} at the ground (i.e. within 4 metres from ground) due to EE for the current and the 2030 scenarios are presented in Figure 1, for PC and HDV+BUS. The results in Figure 1 refer to February 15, 2019, a day on which high PM_{10} levels were recorded (mean level across urban and rural background sites: 67 ± 8 µg m^{-3}). These maps highlight a large decrease in PM_{10} concentration in the future scenario, particularly along the main motorway, the major roads and main urban areas. The qualitative comparison between the concentration maps of Figure 1a (referring to PC) clearly shows the benefit on air quality of the renewal of the PC fleet. A decrease in concentration occurred, albeit minor, also for HDV+BUS (Fig. 1b), contributing to the overall improvement of air quality (Fig. 1c). Contrarily to EE, the variation in PM_{10} levels due to changes in NEE between the two scenarios is negligible, if compared to EE, for both PC and HDV+BUS.

Evaluation of the model simulations performance

At the location of the 51 air quality regulatory stations, we extracted the hourly time series of primary PM_{10} due to traffic (EE and NEE) simulated by PMSS for the lowest model layer (4 m from the ground). These hourly data were averaged to daily PM_{10}, since regulatory limits refer to this time interval and ARPAE at those 51 sites provides observations of daily PM_{10} levels (Directive EC 50/2008). These simulated PM_{10} levels by PMSS were compared with daily average values provided by a simulation run on the same domain by CHIMERE (Mailler et al., 2017), fed by COSMO meteorological fields. CHIMERE, contrarily to PMSS, provides estimates of atmospheric PM_{10} due to all the emission sources within and out of the regional domain (e.g. traffic, industrial and non-industrial combustion, Saharan dust, etc...) and also estimates the formation of secondary PM_{10}. In order to compare the performance of the two models, the primary PM_{10} due to traffic emissions was extracted from the primary anthropogenic PM_{10}, which is directly provided in output by CHIMERE. To this end, based on the latest regional emission inventory, we computed the mean share of PM_{10} emissions by traffic (EE and NEE) over all PM_{10} anthropogenic emissions for urban polluted sites and suburban polluted sites, resulting 23% and 15%, and for rural (including some clean suburban sites) and remote sites, resulting 10.5% and 6% respectively. It was assumed that these percentages represent the fraction of primary PM_{10} due to traffic emissions respect the total primary anthropogenic PM_{10} simulated by CHIMERE in urban, rural and remote areas, respectively: this allowed the estimate of the daily primary PM_{10} by traffic from the CHIMERE output.

Table 1. Pearson's correlation coefficient (*r*) between PMSS and CHIMERE primary PM_{10} due to traffic emissions (exhaust and non exhaust) at ARPAE station sites. Type "urb" and "sub" indicate urban and suburban; "rur" indicates rural and clean suburban sites, "rem" indicates remote sites.

Station name	Type	*r*	*R*	Station name	Type	*r*	*r*
		1 – 28 Feb	9 – 24 Feb			1 – 28 Feb	9 – 24 Feb
Bogolese	urb	0.39	0.74	Timavo	urb	0.44	0.75
Cabina Mainsite	urb	0.15	0.39	Via Chiarini	urb	0.38	0.75
Caorle	urb	0.67	0.75	Villa Fulvia	urb	0.62	0.75
Ceno	urb	0.22	0.51	Zalamella	urb	0.74	0.80
Cittadella	urb	0.42	0.78	Castellarano	sub	0.62	0.76
De Amicis	urb	0.62	0.79	Cento	sub	0.74	0.82
Flaminia	urb	0.81	0.78	Remesina	sub	0.76	0.85
Franchini-Angeloni	urb	0.80	0.80	Badia	rur	0.61	0.79
Gerbido	urb	0.39	0.58	Besenzone	rur	0.44	0.34
Giardini	urb	0.73	0.87	Cabina Molinella	rur	0.70	0.73
Giardini Margherita	urb	0.11	0.37	Delta Cervia	rur	0.70	0.61
Giordani-Farnese	urb	0.48	0.73	Gavello	rur	0.50	0.51
Isonzo	urb	0.75	0.84	Gherardi	rur	0.59	0.56
Marecchia	urb	0.75	0.68	Lugagnano	rur	0.45	0.60
Montebello	urb	0.32	0.75	Malcantone	rur	0.58	0.61
Paradigna	urb	0.20	0.71	S. Rocco	rur	0.68	0.75
Parco Bertozzi	urb	0.68	0.82	San Pietro Capof.	rur	0.69	0.74
Parco Edilcarani	urb	0.56	0.82	Saragat	rur	0.41	0.55
Parco Ferrari	urb	0.78	0.87	Savignano	rur	0.82	0.77
Parco Montecucco	urb	0.51	0.65	Verucchio	rur	0.71	0.72
Parco Resistenza	urb	0.29	0.74	Castelluccio	rem	0.48	0.73
Porta San Felice	urb	0.36	0.61	Corte Brugnatella	rem	0.40	0.55
Roma	urb	0.40	0.71	Febbio	rem	0.41	0.68
S. Lazzaro	urb	0.46	0.82	San Leo	rem	0.71	0.71
San Francesco	urb	0.43	0.81	Savignano di Rigo	rem	0.51	0.67
San Lazzaro	urb	0.14	0.66				

Table 1 shows the linear correlations (estimated by the *r* Pearson's index) between the PMSS and CHIMERE simulated PM_{10} series derived as described above, for the entire month of February 2019 and for the central part of the month, 9 – 24 February 2019. In fact during the first week of February precipitations occurred in the region at several ARPAE air quality sites: since wet deposition processes were not considered in PMSS runs, during that period an overestimation of the concentrations by PMSS was observed. Linear correlation between PMSS and CHIMERE at the air quality sites is quite large, particularly over the period Feb 9 – 24: at 28 sites out of 51, *r* is larger or equal than 0.50, and the number of sites increases to 48 if the central period of the simulation is considered. The correlation is largest at rural sites, likely due to the inability of CHIMERE in reproducing traffic peaks in urban areas.

Simulation performance was estimated according to the Root Mean Square Error (RMSE), the Mean Absolute Error (MAE) and the Normalised Mean Bias (NMB) computed on daily PMSS and CHIMERE simulations, using the latter model as a reference. Results show that the difference in RMSE and MAE increases from rural (median RMSE = 0.17 $\mu g\ m^{-3}$, median MAE = 0.13 $\mu g\ m^{-3}$) to urban sites (median RMSE = 0.63 $\mu g\ m^{-3}$, median MAE = 0.49 $\mu g\ m^{-3}$), highlighting the potential ability of PMSS in simulating the dispersion of primary pollutants over urban areas. NMB indicates larger PM_{10} estimates by PMSS at most urban sites (median NMB = 0.56 $\mu g\ m^{-3}$), while PMSS exhibited larger estimates than CHIMERE only at half of the rural sites, providing contrasting results for this site type, resulting in a median NMB and a mean NMB of -0.24 $\mu g\ m^{-3}$ and 0.14 $\mu g\ m^{-3}$, respectively, partly due to the higher spatial PMSS resolution.

CONCLUSIONS

In this work, a future emissive scenario (2030), in which the introduction of a large number of BEVs and FCEVs in the vehicle fleet is expected, is compared with the current one, referring to 2019. The renewal of the fleet brings a clear benefit to air quality, due to the reduction of exhaust emissions. Regarding non-exhaust emissions, no substantial differences are observed between the two scenarios, however the lower mass (by ~20%) of FCEVs compared to BEVs results in lower non-exhaust PM_{10} emission factors. The average daily concentrations of primary PM_{10} from traffic emissions (exhaust and non-exhaust) calculated by PMSS were compared with those calculated by CHIMERE over a focus period (February 2019) at regulatory air quality monitoring sites. The models show good agreement in the temporal behaviour of the concentrations, showing the effectiveness of the simulation obtained from PMSS.

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