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Vehicular Traffic in Urban Areas: Health Burden and Influence of Sustainable Urban Planning and Mobility

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Abstract: Vehicular traffic is one of the major sources of air pollution in European cities. This work aims to understand which characteristics of the urban environment could influence mobility-related air pollution, quantify the health impacts of exposure to traffic-derived $PM_{2.5}$ and NO_2 concentrations, and assess the potential health benefits expected from traffic interventions. The health benefits modeled are intended to provide a set of comparable data to support decision-makers and encourage informed decision-making to design healthier cities. Targeting a large geographical coverage, 12 European cities from 9 countries were comparatively assessed in terms of mean daily traffic volume/area, the number of public transport stops/area, and the percentage of green and outdoor leisure areas, among other urban indicators. This was implemented using an open-source data mining tool, which was seen as a useful engine to identify potential strategies to improve air quality. The comparison of urban indicators in the selected cities evidenced two trends: (a) cities with the most heterogeneous distribution of public transport stops, as an indicator of poor accessibility, are also those with the lowest proportion of km dedicated to cycleways and footways, highlighting the need in these cities for more sustainable mobility management; and (b) the percentage of green and outdoor leisure areas may influence the share of journeys by bicycle, pointing out that promoting the perception of green routes is relevant to enhance the potential of active transport modes. Socioeconomic factors can be key determinants of the urban indicators and would need further consideration. For the health impact assessment (HIA), two baseline scenarios were evaluated and compared. One is based on mean annual traffic contributions to $PM_{2.5}$ concentrations in each target city (ranging between 1.9 and 13 $\mu g/m^3$), obtained from the literature, and the second is grounded on mean annual NO_2 concentrations at all available traffic and urban background stations within each city (17.2–83.5 $\mu g/m^3$), obtained from the European Environment Agency database. The intervention scenarios modeled were designed based on traffic mitigation strategies in the literature, and set to ranges of 6–50% in traffic-derived $PM_{2.5}$ concentrations and of 4–12.5% in NO_2 concentrations. These scenarios could result in only a 1.7% (0.6–4%) reduction in premature mortality due to exposure to traffic-derived $PM_{2.5}$, and 1.0% (0.4–2%) due to exposure to NO_2, as the mean for all the cities. This suggests that more ambitious pollution abatement strategies should be targeted.

Keywords: health benefits; burden of disease; mitigation strategies; source apportionment; modal split; low emission zones; traffic bans; sustainability

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1. Introduction

Exposure to air pollutants is of special concern in urban areas because of the dense populations exposed and the diversity of emission sources, with complex chemical patterns. Air pollution is associated with a number of adverse health impacts, including chronic obstructive pulmonary disease (COPD), acute lower respiratory illness (ALRI), cerebrovascular disease (CEV), ischaemic heart disease (IDD), lung cancer (LC) respiratory Tuberculosis and diabetes mellitus, among others [1–3]. During recent decades, epidemio-

logical and toxicological studies have provided evidence for the implementation of health impact assessments (HIA) of air pollution [4].

Reducing health impacts from air pollution requires understanding the sources contributing to human exposure and quantifying their contributions. Vehicular traffic is one if not the major source of air pollution in urban areas [5–7]. It has become the dominant source of air pollutants, including carbon monoxide (CO), carbon dioxide (CO_2), volatile organic compounds (VOCs) or hydrocarbons (HCs), nitrogen oxides (NO_x), and particulate matter (PM), especially carbonaceous particles, contributing with around 11% to $PM_{2.5}$ concentrations across Europe and 28% to Black Carbon (as annual means for 2017) [8] Policies aiming to reduce traffic emissions comprise measures such as reducing the number of vehicles (congestion charges and parking restrictions), the progressive increase of active transport, such as cycling and walking, the transition to electric vehicles, low emission zones, and/or speed limit reduction. Studies evidencing the effectiveness of these local policies in reducing air pollution are somewhat scarce and conclusions show differences but their results are encouraging [9–12]. There is an agreement in the literature that traffic primary emissions are relatively well understood and that technological improvement in vehicle engines and fuels are efficiently decreasing their contribution to $PM_{2.5}$ concentrations [8,13,14]. However, a more detailed and quantitative understanding of the organic and inorganic fractions of secondary aerosol is necessary to help countries meet more ambitious targets. Further evaluation of these pollutants and their ultimate effect on public health is of interest to city air quality managers [15]. In this framework, more efforts are required to improve data availability and evaluation, as well as data openness for future smart city development [16,17], to further combine with other types of information in view of increasing their impact in terms of policymaking.

A number of studies have evidenced that information on the shape of a city and the land use distribution determine the location of emission sources and the pattern of urban traffic, affecting urban air quality. Urban configuration has long been known to be a major cause of poor air quality [18]. Previous research has demonstrated the relationship between sprawl indicators, such as density and street network, and air quality. However, the exact relationship between development patterns and air quality has been elusive due to difficulties in quantifying patterns or using indicators poorly suited for spatial analysis [19]. In McCarty and Kaza [20], authors found that after controlling for demographic factors and the level of urbanization, both the pattern of urbanization and the mixing of different land cover types are important determinants of pollutant levels and air quality, and, thus, conclude that public action for mitigating pollutant levels could refer to land-use strategies in addition to other emission control mechanisms. New techniques which integrate satellite remote sensing and Geographical Information Systems (GIS) are being recently used to continually monitor air quality at the microscale level to effectively evaluate the role of urban conditions [21,22].

With regards to the health benefits of reducing air pollution, previous works have frequently been based on air quality measurements, largely focusing on the urban pollution mix [23,24]. Health impact assessment applies a health impact function combining risk estimates (from the epidemiological literature), which relate hypothesized air quality changes to a population at risk [25]. This kind of study frequently assesses scenarios where air pollutant concentrations are reduced to meet national limit values or WHO guidelines, obtaining satisfactory results with evidence of postponed mortality and reduced hospital admissions [26–39]. Other studies address stricter limits to achieve significant health benefits [40,41]. Recently, Malmqvist et al. [42] concluded on a substantial possibility to reduce the health burden attributed to tail-pipe emissions. A number of these studies underscored the importance of using spatially and temporally resolved data in local air quality impact assessments to characterize the overall city burden and identify areas of high vulnerability. However, it is important to note that the amount of studies focusing on a specific pollution source, with a quantified contribution to a selected parameter, is relatively scarce [2,29,37,42–46], which could be related to the lack of source-specific

epidemiological studies, both short- and long-term. In Mak et al. [2], geo-processed traffic emission figures were distributed to respective districts of Hong Kong via mathematical means, finding correlations between NO_x and mortality within different case studies in the range 0.371 to 0.783, while varying from 0.509 to 0.754 for $PM_{2.5}$. On the other hand, Stockfelt et al. [47] reported that associations between source-specific PM air pollution and incident cardiovascular disease were mixed and generally weak.

In this framework, the aim of this work was to assess traffic-related air pollution in urban areas from a holistic perspective, addressing urban characteristics, health impact assessment and traffic mitigation strategies. To this end, urban indicators and air pollutants (traffic-derived $PM_{2.5}$ and NO_2) from 12 urban environments in Europe were evaluated, providing a broad geographic perspective. Traffic-related $PM_{2.5}$ scenarios (all of them pre-COVID19) were selected to capitalize on the availability of comparable $PM_{2.5}$ source apportionment assessments, already published in the literature. The specificity of these source apportionment assessments, based on well-established chemical compositions, was compared with the higher spatial availability of NO_2 concentrations, with a more typical distinct local pattern than $PM_{2.5}$, in order to describe differences and highlight the strengths and weaknesses of each parameter when feeding HIA models. Traffic reductions were proposed through an extensive literature review and contextualized according to the current state of urban planning factors in the cities. The avoided premature mortality resulting from the effect on air quality of the selected traffic reductions was modeled. A conceptual model of the methodological approach is shown in Figure S1 in Supplementary Materials.

2. Methodology

A summary of the methodology steps as a flow diagram is shown in the Supplementary Materials (Figure S1).

2.1. Selection of Study Cities and Baseline Scenarios

The analyses in this work focused on $PM_{2.5}$ and NO_2 as the main tracers of vehicular traffic in urban areas [8,48]. An extensive literature review was carried out to identify urban environments in Europe with published data on the contribution of road traffic emissions to $PM_{2.5}$ (Figure 1 and Table 1). The initial review was based on that reported by the World Health Organization [49]. Cities where a comparable methodology was applied were selected for this study. This methodology should meet specific requirements, namely: (1) $PM_{2.5}$ samples should have been collected using high volume samplers, and following the current standard protocols (EN 12341), (2) a representative number of samples should have been collected along at least one year, (3) a widely used and standardized source apportionment method, based on an extensive chemical database (major and trace inorganic compounds), should have been used to identify and quantify the contribution of traffic emissions, (4) all those studies reporting data prior to 2005 were discarded, due to a lower traffic contribution observed at a global level after that date, partly explained by more stringent environmental and exhaust regulations/policies (e.g., EURO-emission standards). The traffic contributions to $PM_{2.5}$ obtained (Table 1) were considered as the baseline scenario, and as average contributions for the entire city given that the site typology was urban background (Table 1). The study period considered ranged between 2007 and 2016. Even though the emission and environmental conditions of the earlier studies in this period may not be representative of current scenarios, they were still considered relevant from the point of view of (methodological) comparability with more current studies. The source apportionment method in the studies selected is Positive Matrix Factorization (PMF). It should be mentioned that the chemical species included in the analyses differed across studies, and even though this should be considered a limitation, it was considered the best approximation possible. The absence of uncertainty estimates (e.g., bootstrapping), which is frequent in receptor modelling studies, should also be considered a limitation of this work. Despite this, targeting receptor modelling studies was estimated to facilitate comparability between studies due to the comparable sampling methodologies and the fact

that most studies used the same receptor models for data processing [15]. The uncertainties of the alternative approach (i.e., dispersion models) are described in the literature [50–53].

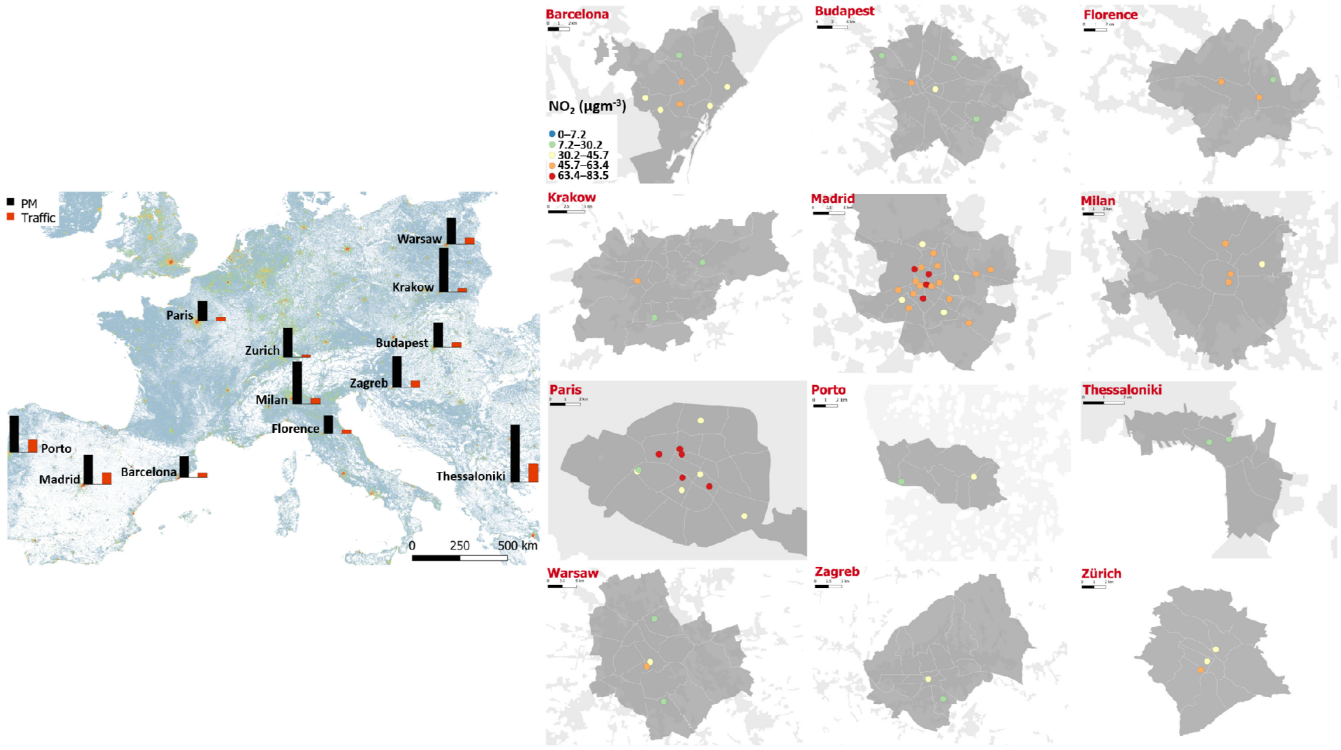

Figure 1. Location of the selected cities, with a visual comparison of $PM_{2.5}$ and $PM_{2.5}$ traffic contribution (**left**), and location of NO_2 monitoring stations, indicating concentration ranges (**right**).

Concentrations of NO_2 for the study period, and for all the traffic and urban background stations in each city, were obtained from the European Environment Agency database [54]. These concentrations were considered as a second baseline scenario for comparisons. Annual mean concentrations for each station used in this study were calculated from daily concentrations (Figure 1).

These two baseline scenarios (traffic-related $PM_{2.5}$ and NO_2) represent an opportunity to compare different approaches to provide traffic impact estimations through a HIA model. One is based on a receptor model fed with an extensive chemical database, resulting in accurate quantification of the contribution; another is based on a tracer, without exact quantification of the traffic impact but with a commonly higher spatial coverage in urban air quality monitoring networks, together with a more distinct local pattern.

2.2. Intervention Scenarios

A literature review was carried out to select studies reporting reductions in traffic emissions linked to specific abatement measures, as a basis for establishing the intervention scenarios to be tested in this study by means of a HIA model. Detailed information can be found in the Supplementary Materials (Supporting Information SI1 and Table S1). The review accounts for studies published between 2009 and 2020 in peer-reviewed journals, based on research databases Scopus and ScienceDirect. The search terms included "abatement measures", "traffic contribution" and "air quality". The measures considered in this review comprise: (a) the creation of low emissions zones (LEZ), (b) long-term strategies to foster active transport mode, (c) spatial planning-redistribution of public space, (d) promotion of public transport, (e) traffic policies, and (f) technological improvements/roads management.

Table 1. Summary of the traffic contributions to $PM_{2.5}$ and $PM_{2.5}$ concentrations in the cities selected.

Site Location	Population Estimate	Population Density (Inhabitants km^{-2})	GDP (PPP) *	Latitude	Longitude	Site Typology	$PM_{2.5}$ (μgm^{-3})	Source Apportionment Method	Reference Author	Reference Year	Study Year	Season	Traffic (%)	Traffic (μgm^{-3})
Barcelona (Spain)	1,593,083	15,726	45,752	41.39	2.17	urban	15	PMF	Amato et al. [55]	2016	2013–2014	year	20.0	3.1
Budapest (Hungary)	1,757,618	3347	37,399	47.50	19.04	urban	17.4	PMF	Perrone et al. [56]	2018	2015	year	19.0	3.3
Florence (Italy)	370,292	3616	44,543	43.77	11.26	urban	13	PMF	Amato et al. [55]	2016	2013–2014	year	20.0	2.8
Krakow (Poland)	761,873	2330	29,695	50.06	19.94	urban	31	PMF	Samek et a. [57]	2017	2014–2015	year	8.3	2.6
Madrid (Spain)	3,172,867	5250	43,074	40.42	−3.68	urban	21	PMF	Salvador et al. [58]	2011	2007–2008	year	39.0	8.1
Milan (Italy)	1,316,000	7239	51,768	45.46	9.19	urban	30	PMF	Amato et al. [55]	2016	2013–2014	year	14.0	4.3
Paris (France)	2,221,000	21,072	61,883	48.86	2.35	urban	14	PMF	AIRPARIF/LSCE [59]	2012	2009–2011	year	18.0	2.5
Porto (Portugal)	222,252	5366	24,819	41.15	−8.61	urban	25.8	PMF	Pio et al. [60]	2020	2013–2014	year	36.0	9.2
Thessaloniki (Greece)	315,196	16,323	19,745	40.64	22.93	urban	40.5	PMF	Saraga et al. [61]	2019	2011–2012	year	32.0	13.0
Warsaw (Poland)	1,735,442	3355	49,722	52.23	21.01	urban	18.8	PMF	Juda-Rezler et al. [62]	2020	2016	year	24.2	4.6
Zagreb (Croatia)	791,946	1235	21,600	45.84	15.98	urban	21.9	PMF	Perrone et al. [56]	2018	2013	year	21.0	4.6
Zurich (Switzerland)	366,765	4173	64,302	47.38	8.53	urban	21	PMF	Richard et al. [63]	2011	2008–2009	year	9.0	1.9

* Gross Domestic Product (GDP) at purchasing power parity prices (PPP) per capita ($). Available at: https://statisticstimes.com/economy/european-countries-by-gdp-per-capita.php (accessed on 23 February 2022).

2.3. Population and Mortality Statistics

Statistics on population data were obtained from the JRC-GEOSTAT 2018 regular grid map of 1 × 1 km cells [64], which reports the number of residents for the year 2018 in Europe. Each sampling point was assigned geographic coordinates corresponding to its centroid, and the population grid was then overlapped using GIS software to calculate the number of residents for a circular buffer of 1 km around each monitoring site.

All-cause mortality was obtained from the official agencies in each country, as published by Eurostat [64], with data corresponding to 2018. Mortality incidence corresponds to all-cause mortality and all ages per city, so the same incidence was assigned to the different sampling points within a city. Default death rates were expressed at an annual time step and were scaled down to daily levels when needed, as described in Section 2.5.

2.4. Urban Indicators

For further information, a search for key indicators of the state of each city was carried out. The objective of this methodological step was to establish a potential tool to select the most promising traffic intervention approach for a specific urban environment. Data was exported in shapefile format, using Overpass turbo (overpass-turbo.eu; accessed on November 2021), a web-based data mining tool for OpenStreetMap, and analyzed using GIS software. Results are discussed in Section 3. The included indicators are: (1) mean daily traffic volume/total area of the city: as available in opentransportmap.info (accessed on November 2021), (2) kilometers of primary and secondary roads/kilometers of cycleways and footways: tagged in OpenStreetMap as highway: primary/secondary/cycleway/footway, (3) mean distance between primary roads and residential buildings: with residential buildings tagged as land use: residential, (4) percentage of green and outdoor leisure areas: tagged as land use: grass and leisure: park, (5) number of public transport stops/total area of the city: using the tags highway: bus_stop, railway: subway_entrance/tram_stop, (6) index of distribution of public transport stops: it was calculated applying the nearest neighbor index tool in GIS software to the location of public transport stops and interpreted as an indicator of good homogeneity of accessibility to public transport throughout the city, the larger it is, the better accessibility, and (7) implementation of low emission zones: using the tag boundary: low emission zone.

2.5. Health Impact Functions

Several studies link acute exposure to PM air pollution with premature mortality and morbidity, but questions remain about which species and sources in the vast PM mix are responsible for the health effects observed. Although a few studies exist on the effects of species and sources in U.S. cities [65], European cities—with a higher proportion of diesel engines and denser urban populations—have not been well characterized, with only a few examples available for short-term studies including sources or PM chemical components [45,66,67]. Similarly, the risks of long-term exposures are often based on ambient air pollution levels and on results from cohort studies, not including information on specific sources or chemical components [68].

The risk functions used in this work were all collected from the literature:

- For short-term exposures: Ostro et al. [45] for specific chemical components in $PM_{2.5}$ related to traffic.
- For long-term exposures: Hoek et al. [68] for bulk $PM_{2.5}$ mass, while Atkinson et al. [69] was used for NO_2 concentrations. It is worth mentioning that the coefficients reported in Hoek et al. [68] are based on a meta-analysis of 13 cohort studies, and are recommended by the HRAPIE project [4]. Atkinson et al. [69] is a recent study that calculates meta-analytic summary estimates using fixed/random-effects models, based on 48 articles analyzing 28 cohorts, with a high proportion of them performed in Europe.

The health impact functions were calculated following a log-linear model (1). Risk ratios reported in this study were in the range of those reported in the literature [70–78].

$$\Delta Y = Y_O \left(1 - e^{-ß\Delta PM}\right) POP\ A^* \quad (1)$$

where:

ß: mortality risk estimate
Yo: baseline mortality rate
POP: exposed population
ΔY: mortality change (change in the number of deaths expected per year)
ΔPM: change in concentration
A: 1/365
*Applied when mortality risk ratios were obtained from short-term assessments

A summary of the epidemiological studies considered is reported in Table 2. It should be noted that when considering short-term effects, the incidence was multiplied by a correction factor (A) in order to scale an annual mortality rate to a daily rate, as specified in function (1).

Table 2. Short-term and long-term epidemiological studies selected for the calculation of the health impact functions used in this work.

Study	Scale	Parameter	Health Outcome	Age Group	RR (95%)	IQR (μgm^{-3})
Ostro et al. [45]	Short-term	Traffic contribution to $PM_{2.5}$	Mortality, all-cause	0–99	1.037 (1.007–1.067)	5.2
Hoek et al. [68]	Long-term	$PM_{2.5}$	Mortality, all-cause	0–99	1.062 (1.040–1.083)	10
Atkinson et al. [69]	Long-term	NO_2	Mortality, all-cause	0–99	1.020 (1.010–1.030)	10

2.6. Health Impact Assessment Model

BenMAP-CE is a US-EPA health benefits modelling tool, used to analyze air pollution intervention scenarios [79]. A number of studies have implemented this tool for a variety of air pollutants and based on different epidemiological studies, associating reductions in specific pollutants, mainly PM_X and O_3, with health impact reductions, including premature mortality, chronic bronchitis, and hospital admissions [26,80]. The standards that epidemiological and air pollution studies should meet to be applied in BenMAP are: (1) to use the concentrations of the considered parameter as primary exposure pollutant, (2) to cover the potentially exposed population, (3) to present appropriate model specifications (e.g., controlling for confounding pollutants), and (4) to be published in peer-reviewed journals.

The BenMap HIA was run for 12 European cities in this work, according to the information indicated in Sections 2.1, 2.3 and 2.5. Thus, the model was run for two baseline scenarios: (a) mean traffic contribution to $PM_{2.5}$ in each city for the whole corresponding study periods, and (b) mean NO_2 concentrations for all the available measurement points within a city for the same periods. The benefit of selected traffic intervention scenarios was tested based on the literature review described in Section 2.2.

2.7. Methodological Limitations

The following aspects should be considered as limitations of this work: (a) the predominance of health-hazardous particle components is source and size-dependent, and hence when PM is treated as a bulk in HIA, the specific constituents potentially responsible for acute health outcomes may not be identified; (b) the NO_2 monitoring locations

within the cities ranged between traffic and urban background sites, and were considered representative of city-wide contributions for the purpose of comparison with population and health incidence statistics; (c) the source apportionment data spanned between years 2007 and 2016, and therefore different years were assessed for the different cities; (d) due to the different study years selected, different traffic mitigation strategies may have been in place in the different study locations and lower traffic contributions are expected to be found in several of the study locations, if the studies were repeated at the present time [8]; (e) spatial heterogeneity within a city was not considered in terms of mortality incidence due to data availability. All the datasets selected for this work were acquired from free Open Data Sources.

3. Results

3.1. Review of Mitigation Strategies

Table S1 shows the results of the literature review of studies on mitigation strategies targeting traffic emissions. 40 studies were finally selected. The abatement measures considered showed reductions in $PM_{2.5}$ ranging between 0.05% [32] (associated with PM removal by trees) and 38% [13] (implementation of diesel particle filters). In the case of NO_2 concentrations, reductions ranged between 0.3% [81] (replacement of non-electric vehicles with electric ones) and 22% [82] (LEZ). Figure 2 shows a graphical summary of all the results considered in this review as box plots, indicating high variability of values, even for measures in the same category. In view of this, percentages corresponding to median, 25th and 75th percentile values were selected as intervention scenarios, assuming that they could be reasonably achieved by several of the approaches discussed in this section. This means reductions of 1.5 (25th percentile), 5 (median) and 11.5% (75th percentile) for $PM_{2.5}$, which would correspond to estimated reductions of the $PM_{2.5}$ traffic contribution of 6, 22 and 50%, respectively, according to mean contributions reported in Table 1. In the case of NO_2, the selected intervention scenarios correspond to percentages of 4 (25th percentile), 9 (median) and 12.5% (75th percentile). In spite of the associated uncertainty of this selected reduction, it was considered that this is a reasonable threshold that could offer key information and encourage stakeholders to act on vehicular traffic management.

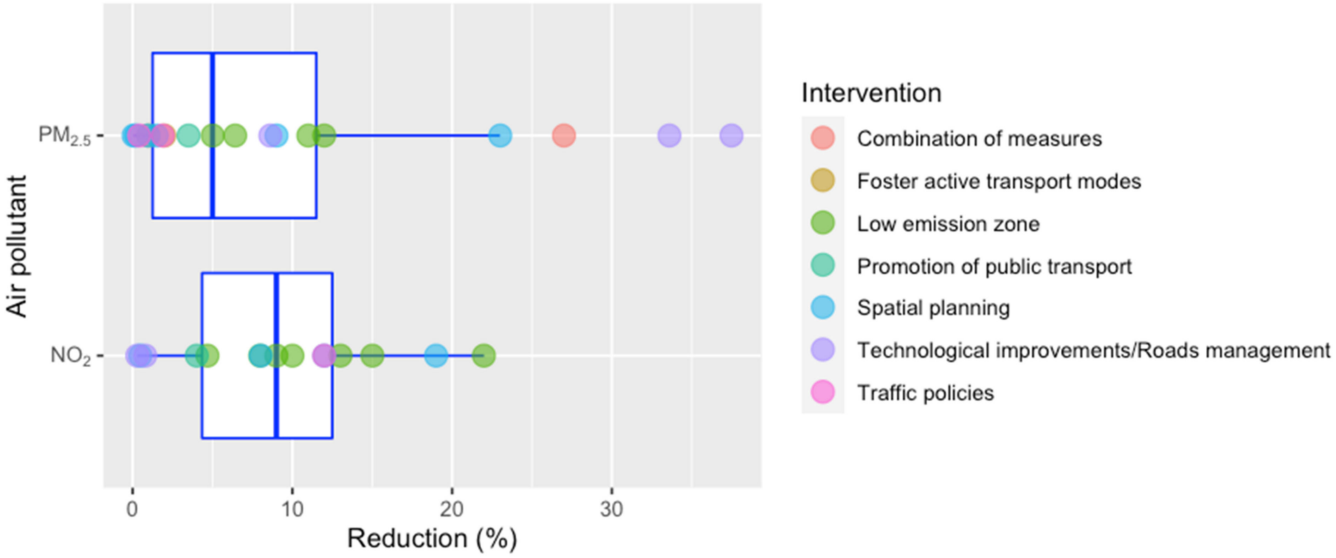

Figure 2. Summary of the results of the review on studies assessing the effectiveness of different abatement measures against traffic emissions (as reported in Table S1).

In Supplementary Materials Table S2 summarizes the traffic-related air pollution abatement measures reviewed and already implemented in some European cities, with good performance. The effectiveness of ongoing measures such as the installation of electric

vehicle charging stations, or ecological distinctive to classify vehicles according to their emissions, still has to be assessed in the long term. Special efforts to reduce traffic emissions have been made the last decade, including intensive street cleaning, the age-based limit for taxis and public transport, low emission zones, planting of trees, reducing unnecessary engine idling of vehicles and school buses, charging flat rates to enter central areas, or bike-sharing programs, among others. The extension of these efficient measures should be encouraged.

3.2. City Characteristics

The interpretation of the HIA requires contextualizing relevant parameters that characterize each city, such as population density or land uses, among others. These parameters are also relevant for identifying those aspects that pollution abatement measures should target. In spite of the complexity of urban areas, interventions at the community level, such as urban and transport planning, have been demonstrated to be promising to improve environmental factors in a cost-effective way, and in many cities, there is still scope for further improvement in environmental quality through assessment of targeted indicators [83]. Thus, this section aims to understand the potential link between sustainable urban practices and reductions in traffic emissions, by assessing existing case studies where the characteristics described in Section 2.4 are relevant.

Population densities in the selected cities show great variability (Table 1), ranging from 1235 to 21,072 inh km^{-2}, with the lowest values corresponding to Zagreb, Krakow and Budapest, and the highest to Paris, Barcelona and Thessaloniki. Figure S2 shows the boxplots of the distribution of different indicators in the selected cities, considered relevant from an air quality perspective, and thus directly related to the previous described air pollution mitigation strategies. The indicators with higher differences between cities, with a wide distribution of values, are the mean daily traffic volume/area, the number of public transport stops/area, and the percentage of green and outdoor leisure areas, in the range of 1.3–42.7, 1.3–25.8 and 5–27%, respectively. The ratio of kilometers of primary and secondary roads/kilometers of cycleways and footways is the one showing the narrowest distribution, ranging between 0.1–1.4, while the mean distance between primary roads and residential buildings throughout each city comprises values between 1.9 and 11.3 km. A classification of the selected cities based on these indicators has been attempted, using hierarchical clustering as a statistical approach. Results have been represented as a heatmap for easy interpretation, where data values have been transformed into a color scale (Figure 3). This method allows the distinguishing of cities with common strengths/weaknesses, which could in turn be useful to provide recommendations on urban planning and traffic policies, with demonstrated effects on air quality and pollutants exposure. When focusing on the relative weak aspects of the different cities, Paris, Barcelona, Porto and Thessaloniki stand out with the comparatively highest daily traffic volume/area and/or ratio of kilometers of primary and secondary roads/kilometers of cycleways and footways. Barcelona, Porto and Thessaloniki also show the shortest distances between primary roads and residential buildings. On the other hand, Krakow, Zagreb and Budapest combine a relatively low number of public transport stops/area with a heterogeneous distribution throughout the city. Porto and Thessaloniki account for the lowest percentage of green and outdoor leisure areas, and Porto, Thessaloniki, Warsaw, Zagreb, Zurich and Budapest lack LEZ. A remarkable pattern is that cities with the most heterogeneous distribution of public transport stops are also those with the highest ratio of kilometers of primary and secondary roads/kilometers of cycleways and footways, highlighting the need in these cities for more sustainable mobility management. According to the studies previously discussed in Section 3.1, measures to improve these indicators would mean reducing NO_2 concentrations by up to 22% and $PM_{2.5}$ concentrations by up to 38%.

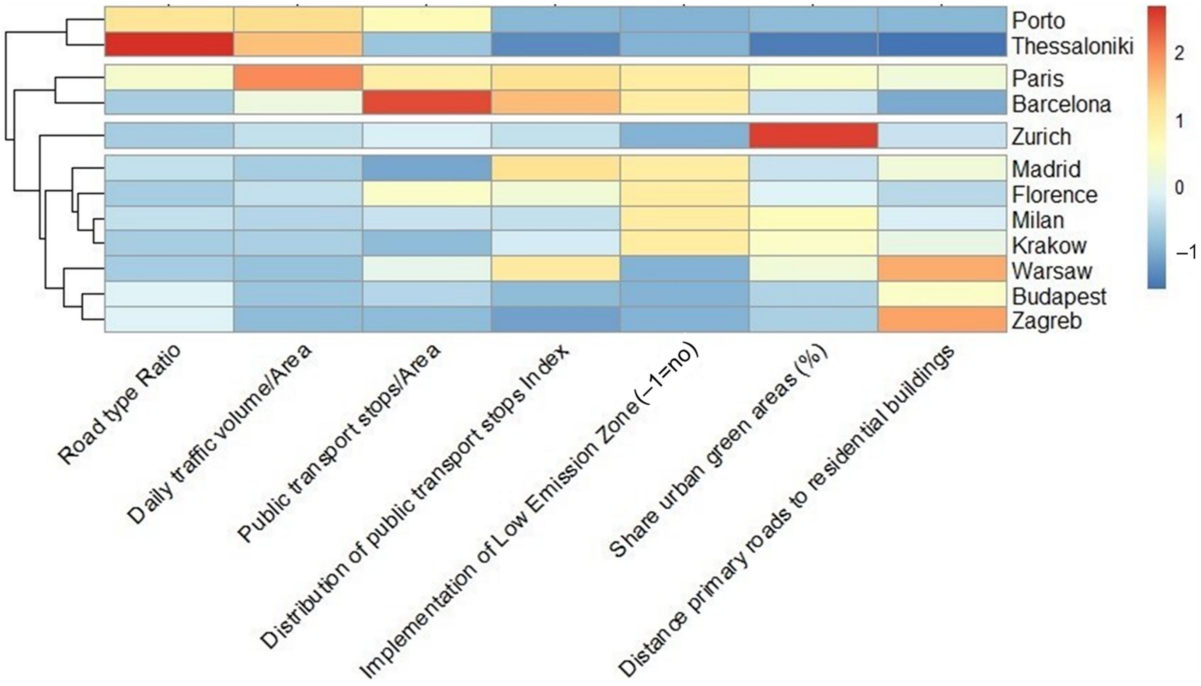

Figure 3. Heatmap of the results of the hierarchical clustering performed for selected city indicators, data values have been transformed to a color scale.

Conversely, some positive aspects should be also highlighted, such as the relatively high number of public transport stops, with a homogeneous distribution, as a proxy of accessibility, in Paris and Barcelona, as well as the relatively high percentage of green and outdoor leisure areas in Zurich, Paris, Milan, Krakow and Warsaw. This percentage shows good agreement with the data available on the percentage of share of journeys to work by bicycle, as reported by Eurostat [64]. Information on commuting modes was available for 8 of the 12 selected cities, and the coefficient of determination between the two referred indicators was >0.90 (p-value < 0.001; Figure 4). This seems to point out that promoting the perception of green routes is fundamental to tapping into the existing potential of active transport modes.

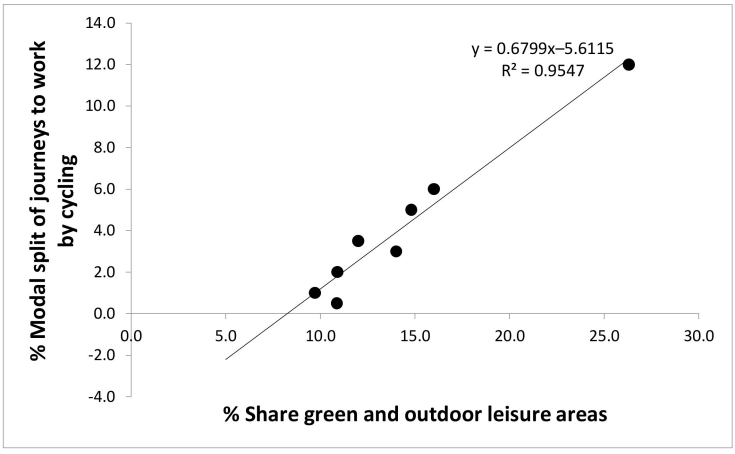

Figure 4. Linear regression between the percentage of green and outdoor leisure areas and the percentage of journeys to work by cycling in 8 of the selected cities.

Relationships between the city indicators described and the corresponding mean concentrations of NO_2 and $PM_{2.5}$ traffic contribution will be discussed in the following section.

On the other hand, although it is outside the scope of this work, it is worth mentioning that the socioeconomic sector can play a very important role during the urbanization process of a city and, thus, in the transportation plans. Previous studies suggest that good sustainability performance during urbanization is characterized by several indicators such as a high GDP level and stable economic condition [84,85]. Figure S3 shows a correlation matrix of GDP (PPP) in the selected cities against the described city characteristics. GDP (PPP) seems to partly determine the percentage of green and outdoor leisure areas and also the considered public transport indicators. Further research on how inequalities bear on sustainability should be addressed as an environmental challenge.

3.3. Road Traffic Contributions to $PM_{2.5}$ and NO_2 Concentrations

$PM_{2.5}$ source contributions reported in the literature for the different cities are shown in Figure 1 and Figure S4 (references in Table 1). A total of 9 studies was finally selected out of 38 works reviewed. Causes for rejection were: (1) reported data was collected prior to 2005, (2) no clear information of total $PM_{2.5}$ concentrations was available, (3) the chemical composition of the traffic source was not clearly described, and/or (4) mortality statistics were not available for the corresponding city. For better comparability, source classification was unified as traffic, sea salt, dust, industry, and biomass burning/residential, with the rest of the mass being considered as "Others + Unaccounted". Traffic-$PM_{2.5}$ concentrations refer to annual averages comprising from 1 to 3 years and spanning across the period 2007–2016.

The traffic contribution to $PM_{2.5}$ concentrations in the selected cities ranged between 1.9 and 13 μgm^{-3}, representing relative contributions of 8.3–39%. Concentrations of this source show a moderate negative linear relationship against the mean percentage of green and outdoor leisure areas at each city (Pearson's $r = 0.66$; $R^2 = 0.44$; p-value < 0.05; Figure S5). Traffic was the main source of $PM_{2.5}$ in most of the cities, except in Zagreb, Warsaw, Milan and Budapest, with a high contribution of biomass burning/residential heating. In Budapest and Zurich, the contribution of the dust source was also higher than that reported for traffic. Bulk $PM_{2.5}$ concentrations showed high variability, ranging between 13 and 40.5 μgm^{-3}. The highest concentrations were recorded in Thessaloniki (40.5 μgm^{-3}), followed by Krakow (31 μgm^{-3}), and Milan (30 μgm^{-3}). According to the present categorization, the highest $PM_{2.5}$ percentage of unaccounted mass was reported in Zurich. As reported in Section 2.6, it should be noted that traffic contributions, NO_2 and PM mass concentrations may be significantly different at present.

Concentrations of NO_2 for the same periods, and for all the traffic and urban background stations in each city, were obtained from the European Environment Agency database [54]. Mean concentrations ranged between 18 and 56 μgm^{-3} (2.5th percentile: 17; 97.5th percentile: 84), with the highest mean concentrations reported for Madrid (56 μgm^{-3}), followed by Milan (53 μgm^{-3}), and Paris (43 μgm^{-3}). Mean NO_2 concentrations at each city did not show agreement with the corresponding $PM_{2.5}$ traffic concentrations, which could be due to: (a) the presence of other sources probably affecting NO_2 concentrations, such as industrial emissions, (b) mean NO_2 concentrations were calculated considering both, traffic and urban background measurement sites, and/or (c) a more distinct local pattern of NO_2 compared to $PM_{2.5}$. This more marked local influence could be evidenced by the significant linear relationship of mean NO_2 concentrations at each sampling site and the mean distance of each site to the primary roads of the city ($R^2 = 0.36$, p-value < 0.001; Figure S6). This relationship was not significant when considering $PM_{2.5}$ traffic contributions at the different monitoring stations (Figure S6). Thus, the NO_2 concentrations considered, with a higher number of sampling points, seem able to better trace the complex urban-scale air pollution.

3.4. Health Impact Assessment

Figures 5 and 6 summarize the HIA findings in terms of estimated premature mortality per year and per 100,000 inhabitants, in the intervention and baseline/control scenarios,

for long- and short-term exposures. The intervention scenario simulated 4–50% reductions in traffic contributions, as estimated in Section 3.1.

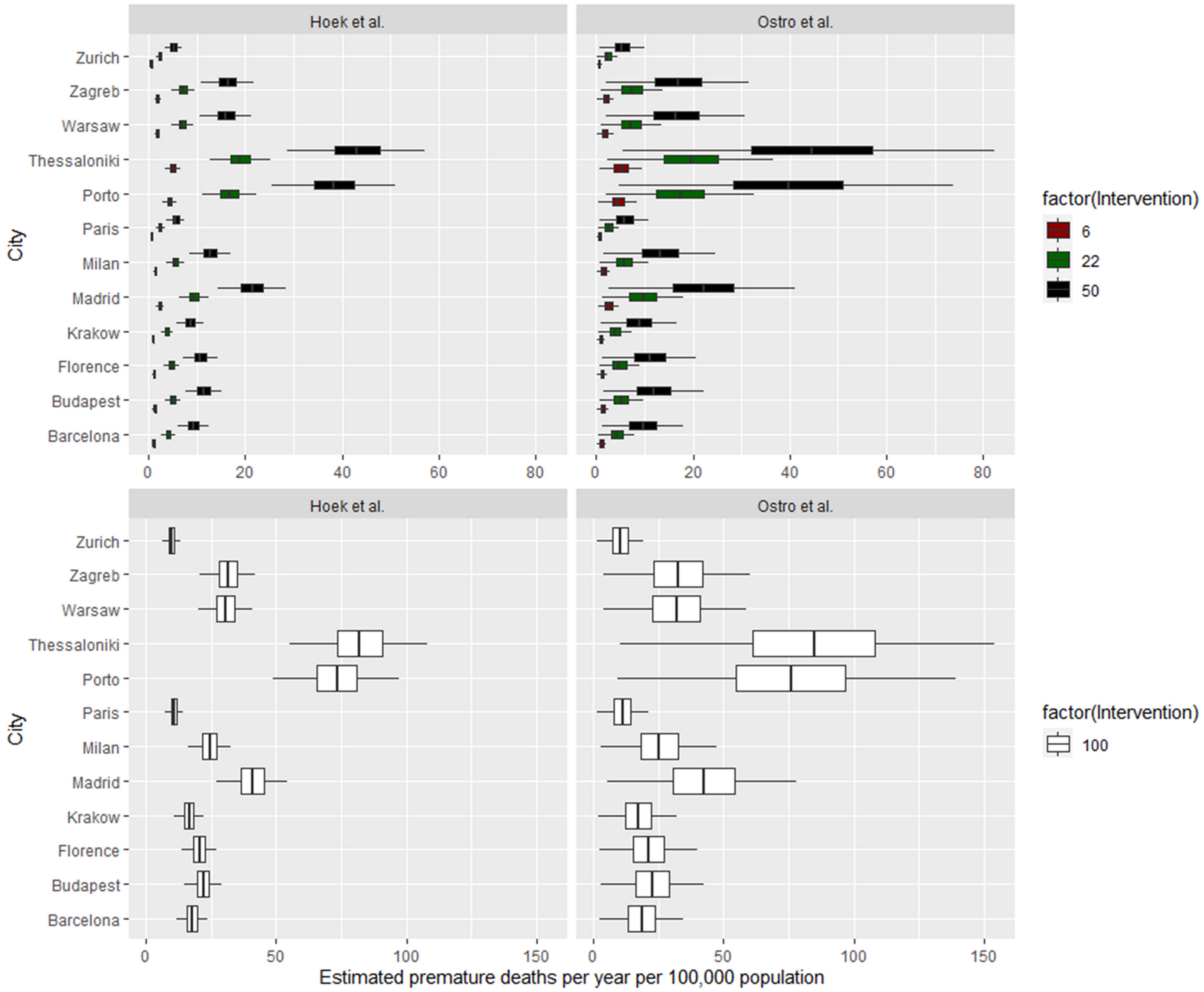

Figure 5. Estimated premature mortality/year per 100,000 population due to exposure to traffic-related $PM_{2.5}$ (baseline scenario) in the study cities, using two different risk estimates (as reported by Ostro et al. [45] and Hoek et al. [68]), and applying three different intervention scenarios (5, 22 and 50% reduction in concentrations). It is shown in comparison with the baseline/control scenario (100% reduction). The line within the box plots shows the median concentrations, while the box bottom and top represent the 25th and 75th percentiles, respectively. The whiskers represent the lower (2.5th percentile) and the upper (97.5th percentile) bounds. Note on the different x scales.

Long and short-term health impacts and potential reductions of traffic-derived $PM_{2.5}$ concentrations.

Health impacts from traffic were estimated using the Hoek et al. [68] risk estimates, obtained from an extensive review of epidemiological studies on long-term exposure to bulk fine and coarse particles. The risk estimates from Ostro et al. [45] were used for comparison and to assess the sensitivity of the HIA model, given that Ostro et al. [45] reports risk estimates for short-term exposure specifically to traffic-derived $PM_{2.5}$.

Using the source-specific risk estimates from Ostro et al. [45], short-term exposure to traffic emissions (baseline/control scenario) accounted for 10–90 (CI: 4–150) premature deaths per 100,000 inhabitants, annually. Similarly, when the risk ratio for long-term exposure to bulk $PM_{2.5}$ was used [68] the results were 10–85 (CI: 7–108) premature deaths due to traffic. Thus, significant differences between long-term and short-term estimates were not observed, due to the fact that health impacts were estimated for bulk $PM_{2.5}$ for long-term exposures, as opposed to traffic-related $PM_{2.5}$ for short-term exposures. The

estimated health impacts using source-specific risk ratios were expected to be higher than those for bulk $PM_{2.5}$, given the differential toxicity of traffic aerosols (containing mostly black carbon and organic aerosols) when compared to bulk $PM_{2.5}$ (a mix of chemical components including mineral matter and inorganic salts). In relative terms, the premature mortality due to exposure to traffic-$PM_{2.5}$ accounted for between 0.9% and 8.2% of the baseline mortality (due to all causes), with an average of 3.5%.

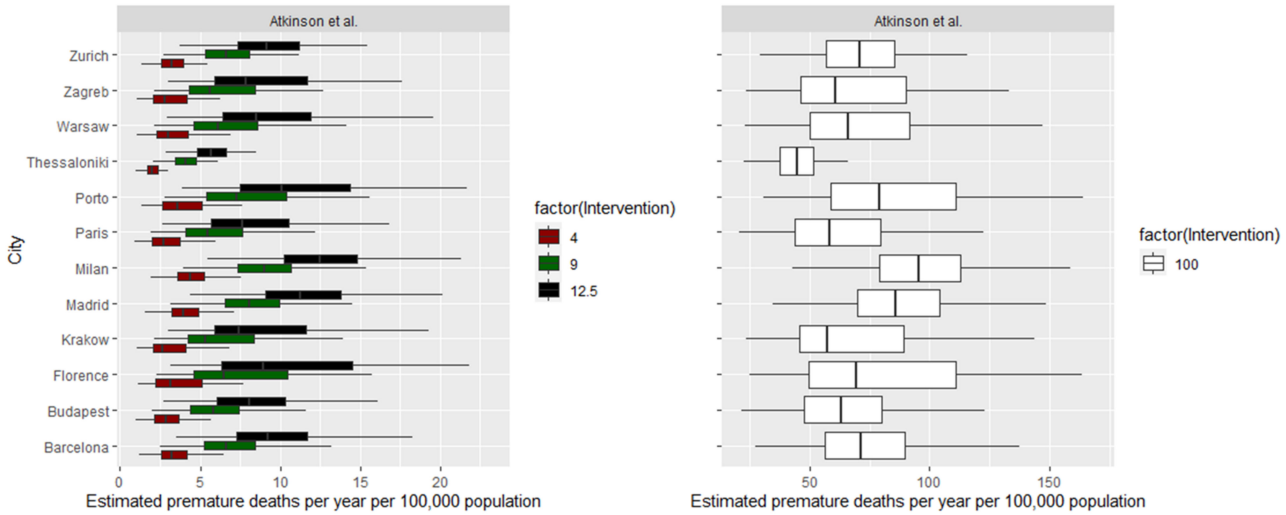

Figure 6. Estimated premature mortality/year per 100,000 population due to exposure to NO_2 concentrations (baseline scenario) in the study cities, using risk estimate by Atkinson et al. [69], and applying three different intervention scenarios (4, 9 and 22% reduction in concentrations). It is shown in comparison with the baseline/control scenario (100% reduction). The line within the box plots shows the median concentrations, while the box bottom and top represent the 25th and 75th percentiles, respectively. The whiskers represent the lower (2.5th percentile) and the upper (97.5th percentile) bounds. Note on the different x scales.

When analyzing the data spatially, the highest impacts estimated were obtained for Thessaloniki and Porto (with >80 premature deaths/year per 100,000 inhabitants due to traffic emissions in each city, based on Ostro et al. [45]), and the lowest for Zurich, Krakow and Paris (with <15 premature deaths/year per 100,000 inhabitants in each city). A negative correlation between latitude and avoidable premature mortality can be deduced, with higher numbers in the south of Europe, regardless of the measurement year, highlighting the special need for effective actions to decrease traffic emissions in these cities. The negative correlation found between the concentrations of the traffic contributions to $PM_{2.5}$ and the mean percentage of green and outdoor leisure areas may be seen as an opportunity to incentivize more sustainable land use management.

The intervention scenario was set to a range of 6–50% reduction in traffic-derived $PM_{2.5}$ concentrations, according to the described literature review (Section 3.1). Given that the mean annual traffic-$PM_{2.5}$ in the baseline scenarios in the different cities ranged between 1.9 and 13 $\mu g/m^3$, the proposed reductions would range between 0.1–6.5 $\mu g/m^3$ in the mean annual traffic-$PM_{2.5}$ concentrations. If the maximum proposed reduction in traffic-$PM_{2.5}$ were achieved in the different cities, by implementing measures such as those reported in Table S1, the premature mortality avoided per year could range between 5–48 per 100,000 inhabitants (CI: 1–72), according to Ostro et al. [45], and between 5–44 per 100,000 inhabitants (CI: 1–54), according to Hoek et al. [68] (Figure 5). This would account for a 1.7% reduction in premature mortality on average. Given that traffic contributions accounted on average for 3.5% of the baseline mortality, a 1.7% improvement could seem adequate; however, more ambitious targets should probably be set when aiming to significantly improve public health.

Long-term health impacts and potential reductions of NO_2 concentrations.

A similar analysis was carried out for long-term exposures to NO_2. In this case, the risk ratio used was from Atkinson et al. [69]. It is important to mention that authors conclude on an important heterogeneity between studies, depending on the spatial resolution of pollution estimates, and adjustment for smoking and body mass index, among other specifications. An accurate review is therefore required before conducting health impact assessments, so that the reported results comprise a representative range of values, accounting for the inherent uncertainties of the analysis and the specific population characteristics.

Using the risk estimates from Atkinson et al. [69] (Figure 6), long-term exposure to NO_2 emissions (control scenario) accounted for 42–122 (CI: 20–170) premature deaths per 100,000 inhabitants, annually. These values are relatively higher but in the range of those deduced from traffic-derived $PM_{2.5}$ exposures. In relative terms, the premature mortality due to exposure to NO_2 in the selected cities accounted for between 3% and 15% of the baseline mortality (due to all causes), with an average of 8.5%.

The intervention scenarios (4–12.5% reduction in NO_2 emissions) would result in reductions of 0.7–7 $\mu g/m^3$ in the mean annual NO_2 concentrations. Hypothesizing that the most ambitious reduction is achieved, the premature mortality avoided per year would account for 1.0% on average (Figure 6).

Comparing results achieved with the different approaches (based on exposure to NO_2 and to traffic-related $PM_{2.5}$), the distribution of percentages of reduction in premature mortality is generally similar for all the cities (Figure 7), except for Madrid, Porto and Thessaloniki, where the avoided premature mortality associated with reductions in traffic-derived $PM_{2.5}$ concentrations would be significantly higher. In that sense, presenting results from the HIA of traffic-related $PM_{2.5}$ could be more encouraging to impulse decisions from authorities on land-use management and traffic policies. Nonetheless, the generally higher spatial availability of NO_2 concentrations provides an appropriate tool to investigate the variability within a city and to identify hotspots, where urgent measures should be taken, as well as those areas poorly monitored but highly populated. In our study, differences in the percent of baseline within a city range between 0.1 to 1.2% (see examples in Figure 8). It is here also important to briefly discuss how changes in NO_2 concentrations would impact O_3 behavior, due to the ever-changing interplay between both pollutants. Assuming a decrease of O_3 linked to a decrease in NO_2, this would lead to higher health benefits than described, as O_3 has been well linked to severe lung damage in previous works [86].

Results were compared to the studies available in the literature. Reductions in premature mortality estimates were found to be generally in the same order of magnitude, although it should be noted that studies are relatively scarce, and most of them do not use source apportionment data based on actual observations as input data. To the authors' knowledge, Isley et al. [44] is the only study grounded on an estimation of the traffic contribution to $PM_{2.5}$ by a source apportionment method. According to these authors, the annual benefit resulting from a 100% reduction of road traffic emissions would be 20 (15–36) premature deaths, in the city of Suva (on the isle of Fiji, with a population of 100,000 inhabitants). In Europe, Malmqvist et al. [42] estimated that 29 premature deaths/100,000 inhabitants could be prevented annually by completely removing exhaust emissions in the city of Malmö (Sweden). Pérez et al. [87] calculated 66 prevented deaths under the assumption that 50% of the private car fleet would be based on electric vehicles in the city of Basel (170,000 inhabitants, Eurostat [64], resulting in 39 premature deaths avoided/100,000 inhabitants). Castro et al. [43] quantified the health benefits of implementing a clean air plan in the agglomeration of Lausanne-Morges (Switzerland), which would prevent 26 premature deaths annually. In Madrid, Izquierdo et al. [29] concluded that 88 (57–117) premature deaths could be associated with $PM_{2.5}$ reductions (mainly, from traffic) from the implementation of the local air quality plan, a comparable result to that obtained in the present work. In contrast to the studies above, Tobollik et al. [88] found no health benefits related to air pollution, when applying two separate interventions (10% reduction of private vehicle kilometers and a share of 50% electric-powered private vehicle

kilometers) in the city of Rotterdam, with only small benefits being related with noise reduction. It is relevant to highlight that, as expected, the health impacts estimated for the vehicular traffic source in urban environments were higher on average than reported in the literature for other sources [46] (e.g., shipping emissions, accounting for 5 premature deaths/100,000 inhabitants per year in Mediterranean coastal cities).

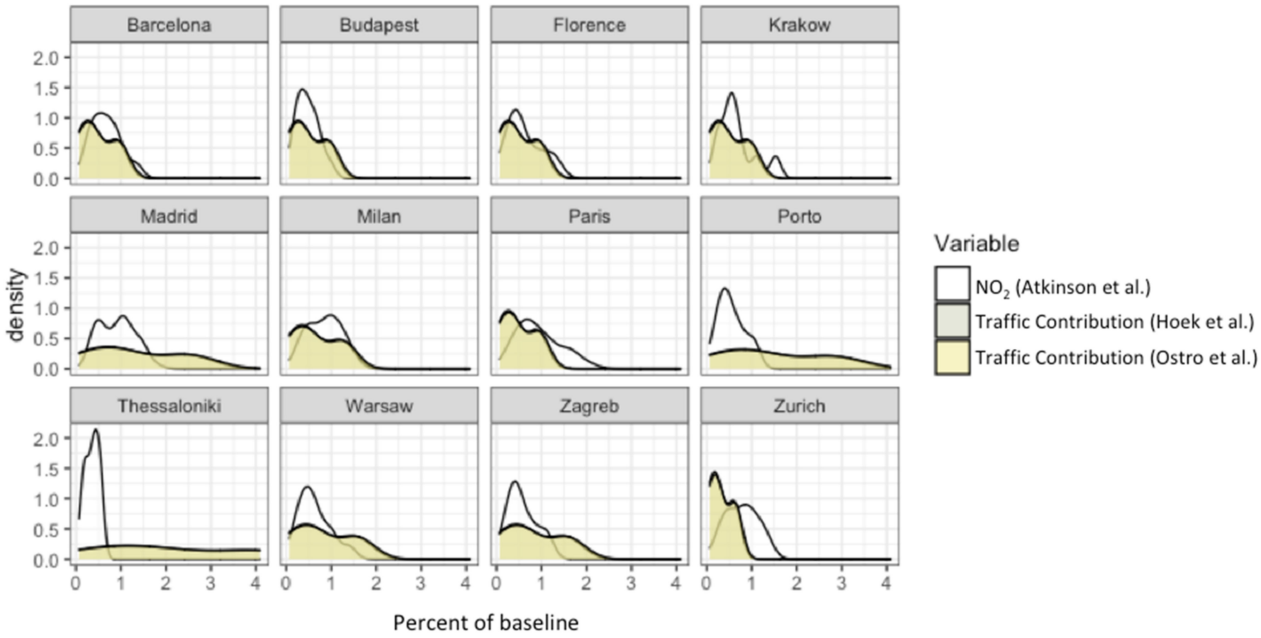

Figure 7. Probability density functions of percent of avoided mortality. Plots compared results based on both selected approaches, exposure to traffic-derived $PM_{2.5}$ concentrations and NO_2 concentrations, according to the different selected risk ratios (as reported by Atkinson et al. [69], Hoek et al., [68] and Ostro et al. [45]).

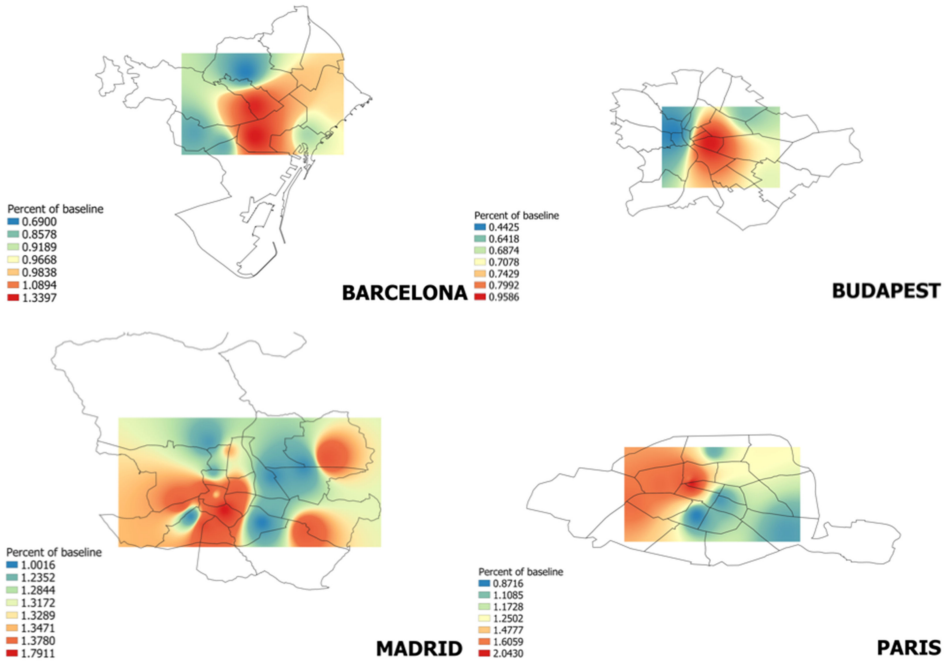

Figure 8. Spatial distribution of percentages of avoided premature mortality within selected cities due to exposure to NO_2 concentrations.

4. Summary and Conclusions

Traffic is the key source of air pollution in most European environments. It is a complex source, emitting a combination of primary and secondary pollutants, with air pollution impacts that depend on urban characteristics (density, % of green areas, etc.) and on societal uptake of the different mitigation measures available (from congestion charges to incentivizing active transport modes). As a result, reducing health impacts from exposure to traffic air pollutants is an especially challenging task. This work aimed to address traffic-related air pollution in urban areas, with a focus on urban indicators and estimating the health benefits of traffic mitigation strategies, for 12 urban environments across Europe.

The main conclusions extracted were:

- Practical initiatives to achieve sustainable city design, in terms of transport, include the creation of LEZ, fostering active transport modes, redistribution of public space, promotion of public transport, traffic policies/taxes, and technological improvement/roads management. These measures are known to be able to translate into a reduction of traffic-related air pollutants, which would in turn decrease associated premature mortality. The need for the different measures was proposed to be guided by key city indicators. In this study, the evaluation of urban indicators showed two main trends. On the one hand, cities with the most heterogeneous distribution of public transport stops, as an indicator of poor accessibility, are also those with the lowest proportion of km dedicated to cycleways and footways. This highlights the need in these cities for more sustainable mobility management. On the other hand, the percentage of green and outdoor leisure areas may influence the share of journeys by bicycle, pointing out that promoting the perception of green routes is relevant to enhancing the potential of active transport modes.
- The influence of city indicators on air quality parameters was elucidated for the selected cities. The traffic contribution to $PM_{2.5}$ showed a moderate negative linear relationship with the mean percentage of green and outdoor leisure areas, while NO_2 concentrations, available for a higher number of measurement sites, showed a significant linear relationship with the mean distance of each site to the primary roads of the city. This highlights that citizens' exposure to air pollution is to a large degree dependent on urban planning decisions.
- Using the source-specific risk estimates, short-term exposure to $PM_{2.5}$ traffic emissions accounted for 10–90 (CI: 7–130) premature deaths per 100,000 inhabitants per year. When the long-term risk ratio for bulk $PM_{2.5}$ was used the results were very similar (10–85 premature deaths). Accordingly, premature mortality due to exposure to traffic-$PM_{2.5}$ accounted for between 0.9% and 8.2% of the baseline mortality. These results were comparable to the literature [42,44].
- Long-term exposure to NO_2 was estimated to account for 42–122 (CI: 20–170) premature deaths per year. These results correspond to percentages between 3% and 15% of the baseline mortality.
- The intervention scenarios proposed could result in up to a 1.7% reduction in premature mortality due to exposure to traffic-derived $PM_{2.5}$, and up to a 1.0% due to exposure to NO_2, as the mean for all the cities. The relatively low reductions estimated indicate that more ambitious abatement measures should be targeted. Some recent studies point out that combining these measures with optimistic fleet renewal and demand reductions is the only way to achieve relevant global emission reductions [89]. It is also worthy to mention the research revealing the importance of focusing efforts on heavy goods vehicles [90], as well as on the high contribution of secondary compounds to $PM_{2.5}$ and on the need to identify major precursor reduction targets [91].
- While HIA results from traffic-derived $PM_{2.5}$ are expected to be more accurately showing the effects of the reviewed intervention measures, the higher spatial availability of NO_2 is useful to study the complexity of the urban scale air pollution.

- Analysis performed within this study evidenced that a sensitivity analysis is highly recommended when selecting risk ratios and air pollution descriptive variables as input for the HIA models. Efforts are needed to provide mortality risk estimates associated with specific aerosol sources and their related chemical components.
- Despite the limitations and uncertainties of this work, this study illustrates the importance of continued air pollution controls to reduce air pollution-related mortality.
- This work is based on open source databases. Open data should be promoted as an essential tool for comprehensive studies, aiming to raise environmental awareness in citizens and empower them to participate in urban governance, encouraging policymakers to constantly reevaluate city plans.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos13040598/s1, Supporting Information SI1: Review of traffic emissions abatement measures; Figure S1: Methodology steps and the input data files required to run BenMAP-CE; Figure S2: Boxplot of the distribution of different indicators in the selected cities considered relevant from an air quality perspective; Figure S3: Correlogram of GDP (PPP) in the cities under study against selected city indicators. Correlation coefficients represent the Pearson's correlation coefficients (r); Figure S4: $PM_{2.5}$ source contributions reported in literature for the selected cities; Figure S5: Correlation matrix including selected city indicators and $PM_{2.5}$ traffic contribution and $PM_{2.5}$ concentrations in μgm^{-3}; Figure S6: Linear regression between mean NO_2 and $PM_{2.5}$ traffic contributions in μgm^{-3} against mean distance to primary roads of the different measurement points; Table S1: Review of selected studies analyzing the effectiveness of different abatement measures, aimed to reduce the exposure to traffic emissions; Table S2: Review of traffic-related air pollution abatement measures which have proven to be successful in the selected European cities. Adapted from: http://fairmode.jrc.ec.europa.eu/measure-catalogue/.

Author Contributions: Authors' individual contributions were: C.R.: Data curation, Formal analysis, Methodology, Writing—Original draft, Review and Editing; M.V.: Conceptualization, Methodology, Writing—Original draft, Review and Editing, Supervision; A.T.: Writing—Review & Editing. All authors have read and agreed to the published version of the manuscript.

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