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Benefits on public health from transport-related greenhouse gas mitigation policies in Southeastern European cities

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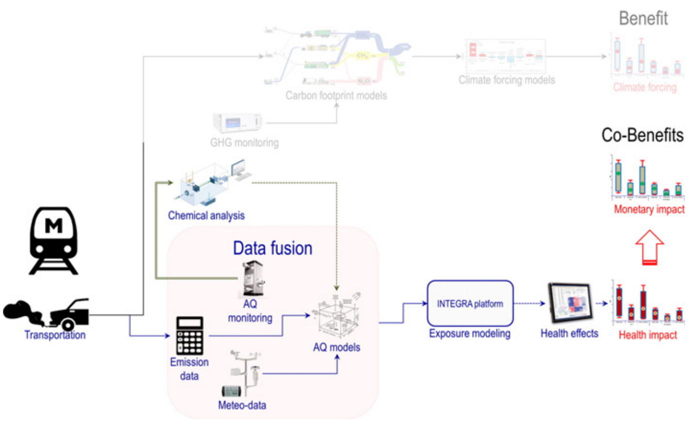
HIGHLIGHTS

- Underground rail reduces health impact attributed to PM_x in cities.
- Changes in traffic composition reduce health impacts attributed to NO_2 and C_6H_6.
- Monetary savings from PM_{10} and $PM_{2.5}$ exposure correspond to 60 and 49 million Euro.
- Monetary savings from NO_2 and C_6H_6 exposure correspond to 41 and 1 million Euro.
- 3–4% reduction in mortality and morbidity from green transport policies.

GRAPHICAL ABSTRACT



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ABSTRACT

Climate change is a major environmental threat of our time. Cities have a significant impact on greenhouse gas emissions as most of the traffic, industry, commerce and more than 50% of world population is situated in urban areas. Southern Europe is a region that faces financial turmoil, enhanced migratory fluxes and climate change pressure. The case study of Thessaloniki is presented, one of the only two cities in Greece with established climate change action plans. The effects of feasible traffic policies in year 2020 are assessed and their potential health impact is compared to a business as usual scenario. Two types of measures are investigated: operation of underground rail in the city centre and changes in fleet composition. Potential co-benefits from reduced greenhouse gas emissions on public health by the year 2020 are computed utilizing state-of-the-art concentration response functions for PM_x, NO_2 and C_6H_6. Results show significant environmental health and monetary co-benefits when the city metro is coupled with appropriate changes in the traffic composition. Monetary savings due to avoided mortality or leukaemia incidence corresponding to the reduction in PM_{10}, $PM_{2.5}$, NO_2 and C_6H_6 exposure will be 56.6, 45, 37.7 and 1.0 million Euros respectively. Promotion of 'green' transportation in the city (i.e. the wide use of electric vehicles), will provide monetary savings from the reduction in PM_{10}, $PM_{2.5}$, NO_2 and C_6H_6 exposure up to 60.4, 49.1, 41.2 and 1.08 million Euros. Overall, it was shown that the respective

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GHG emission reduction policies resulted in clear co-benefits in terms of air quality improvement, public health protection and monetary loss mitigation.

Nomenclature

C	Ambient air concentration
D	Distance from the gas station
RR	Relative Risk
CRF	Concentration response function
Pi	Population size per building block i
AF	Attributable fraction
BR	Background rate of disease
HI	Health impact
YLL	Years of life lost
YLD	Years lost due to disability
DALY	Disability Adjusted Life Years
I	Number of incidence cases
L	Standard life expectancy at age of death in years
DW	Disability weight
L_k	Average duration of the case until remission or death in years

1. Introduction

Under the continuous pressure for climate change mitigation and adaptation measures, there have been several studies over the last years assessing the co-benefits of GHG reduction emission policies in Europe (Perez et al., 2015; Tobollik et al., 2016; Vardoulakis et al., 2015), USA (Galvis et al., 2015; Garcia-Menendez et al., 2015), China (Chen and He, 2014; He and Qiu, 2016; Yang and He, 2016a), Malaysia (Kwan et al., 2016) and Australia (Xia et al., 2015). Public health co-benefits of climate change mitigation policies are observed in a well-defined spatial scale (e.g. an urban agglomeration) and within a shorter time frame (e.g. reduced number of daily respiratory hospital admissions). On the contrary, GHG reduction emission policies produce benefits to the global environment over a longer timescale (Ganten et al., 2010). As a result, public health co-benefits are convincingly presented by the scientific community and easily perceived by policy makers. Considering the significant monetary costs associated with air pollution mortality and morbidity (Alberini et al., 2006; Desaigues et al., 2011), health co-benefits could partly compensate for the costs of tackling climate change.

Urban planning and transportation have been one of the major sectors investigated in terms of public health co-benefits associated to GHG emission reduction measures. It has been found that increased physical activity associated with active transport could generate a large net improvement in population health (Sabel et al., 2016) arising from reduced air pollution, as well as from the improved physical condition of the population (Maizlish et al., 2013). It is noteworthy that a statistically significant negative correlation between active travel and diabetes has been established through a cross-sectional study among 14 countries (Pucher et al., 2010). However, unless additional measures aiming at minimizing pedestrian and bicyclist injuries are considered, health benefits of active transport in terms of DALYs might be countered by traffic injuries (Maizlish et al., 2013). Similar results on the co-benefits on public health from climate change mitigation in transport were obtained in a comparative study (Woodcock et al., 2009) between London, UK and Delhi, India. That study identified that irrespectively of the existing status, policies aiming at increasing the acceptability, appeal, and safety of active urban travel, and discourage travel in private motor vehicles would provide larger health benefits than would policies that focus solely on lower-emission motor vehicles. Similar are the results obtained from a health-effectiveness comparison study exploring different transport-related measures to mitigate climate change in Basel Switzerland (Perez et al., 2015) and of a parallel study assessing the health impact of transport policies in Rotterdam, the Netherlands (Tobollik et al., 2016). Indeed, adding physical activity and well-being among the health effect attributes seems to provide a wider context of the assessed policies. Despite the widely recognised co-benefits arising from GHG emission reduction policies, systematic consideration of the suitability of model assumptions, of what should be included and excluded from the model framework, as well as handling of uncertainty are essential in order to better quantify the active estimates (Remais et al., 2014).

Urban transport accounts for 40% of the CO_2 emissions produced by European road transport (EC, 2007). Furthermore, not only CO_2 but also other traffic-related emissions affect climate change. “Soot particles” (i.e. a mixture of elemental carbon or “black carbon”, and organic compounds from e.g. diesel transport) have a net warming effect on the climate (Bond et al., 2004; Jacobson, 2001). Contrary to CO_2, which has a residence time of decades in the atmosphere, soot particles and ozone, are short-lived pollutants with residence times in the order of days to weeks. Hence, reducing these short-lived GHGs provides opportunities to reduce the rate of warming in the short run.

The EU CO_2 reduction targets that apply for Greece include the EU-wide 21% reduction from 2005 to 2020 for all emissions within the Emission Trading System (EC, 2009b) and national non-ETS targets of 4% CO_2 reduction from 2005 to 2020 (EC, 2009a), and an 18% to be attributed to the renewable energy. For the area of Thessaloniki, a number of measures have been proposed (Moussiopoulos et al., 2009; Sarigiannis et al., 2015; Vlachokostas et al., 2009; Vlachokostas et al., 2011), differentiated by area of implementation, application type (direct/indirect measure) and emission sources (transport, industry and domestic heating). Some of the proposed policies include engine retrofits in conventional vehicles, provision of benefits in favor of bio-fueled and electric vehicles, expansion of the public bus and bus-lane network, withdrawal of old private vehicles, creation of a city-centre traffic ring, increased parking spaces and intense police control for compliance monitoring. Other proposals include changes in the city infrastructure that could influence road transport, including the construction of an underground rail network in the city, a tram network, an outer ring road, sea coast transportation and an underground vehicle highway. These measures are part of urban GHG reduction policies, directed to changing emission factors and/or volume of urban road traffic. This would result in reduced emissions (which are the product of emission factor, volume and activity) of traffic related CO_2 and air pollutants (e.g. PM_x, NO_x, CO and VOC). The impact on health and well-being of the urban population depends on the location of these emissions (e.g. inner urban roads, urban motorways) and dispersion of the emissions (e.g. air pollutants). Environmental stressors (and thus health impacts) are often worse in areas of high density housing and deprived neighbourhoods (WHO, 2011).

The objective of this study is to present the health co-benefits associated with realistic climate change policies with long-term beneficial impacts on the urban carbon footprint, namely the operation of an underground rail network and changes in the traffic fleet by the year

2020. These climate change mitigation measures have been updated to reflect the target of 1.5 °C increase of the global atmospheric temperature set in Paris in December 2015. For this assessment, an integrative modelling framework was developed, aiming at estimating ambient air concentration levels, population exposure, health impact and the associated monetary cost estimates at very high spatial resolution (building block level). A baseline in year 2010 and three future scenarios by year 2020 were considered, a business-as-usual and two GHG mitigation scenarios employing the series of measures outlined above.

2. Methodology

2.1. Overview of the area under study

The city of Thessaloniki, located in the northern part of Greece, is the second largest of the country with more than a million inhabitants (EL.STAT, 2011). The Thessaloniki area stretches over 20 km, looking upon a bay that opens to Thermaikos gulf. Its complex orography is formed from the particular coastal formation and mountainous area, which favor local circulation systems of various kinds (sea-land breeze, valley-mount winds), as well as wind channeling phenomena (Moussiopoulos et al., 2009). The studied area includes the Thessaloniki Metropolitan Area and the Greater Thessaloniki area. Municipalities historically associated with the Thessaloniki Metropolitan Area are (Fig. 1a): Thessaloniki, Kalamaria, Evosmos, Sykies, Stavroupoli, Ampelokipoi, Polichni, Neapoli, Pylaia, Eleftherio-Kordelio, Menemeni, Triandria, Agios Pavlos and the community of Efkarpia. In this area, the main determinants of air pollution are domestic heating (Sarigiannis et al., 2014), traffic, and to a lesser extent the city's harbor. Transportation is the main determinant of ambient noise. Emission characteristics differ between east and west in the Greater Thessaloniki area (GTA). The western side of the GTA comprises an extended industrial complex. Major industrial emission sources involve activities such as oil refining, petrochemical, acid and fertilizer production, cement production, ceramics, non-ferrous metal smelting, iron and steel manufacture, scrap metal incineration, etc. and fossil fuel burning (Samara and Voutsa, 2005). This industrial complex contributes approximately 30% of primary PM_{10} found in the western suburbs of the city whereas only about 7% in the city centre. In the eastern side of the GTA road transport and domestic heating are the main determinants of air pollutant emissions. The international airport of Thessaloniki is primarily responsible for CO_2, HC, CO and NO_x emissions (Tsilingiridis, 2009). Urban transport in the city of Thessaloniki is characterized by a very heavily trafficked and densely built city centre (attracting a large share of commercial, hospitality, and financial services), extending to the north and south through large traffic arteries and via a ring road connecting peripherally the northern suburbs to the south and to the Macedonia international airport. The coastal road going through the city is very heavily trafficked and currently an underground metro system expected to be completed by 2020 is being built. Based on the latest transportation study conducted between 2010 and 2013, the average daily private vehicle traffic on the main roads of the city reaches 1.300.000 vehicle-trips (Mitsakis et al., 2013), while the total number of vehicles in the city exceeds 777.544, including private cars, heavy vehicles and motorcycles (EL.STAT, 2011). In addition to that, 622 buses serve the public transportation network of Thessaloniki.

To accurately model and validate air pollution estimates in the GTA, 13 air quality monitors were used, as depicted in Fig. 1b, described in detail in section A4 of the Supplementary material.

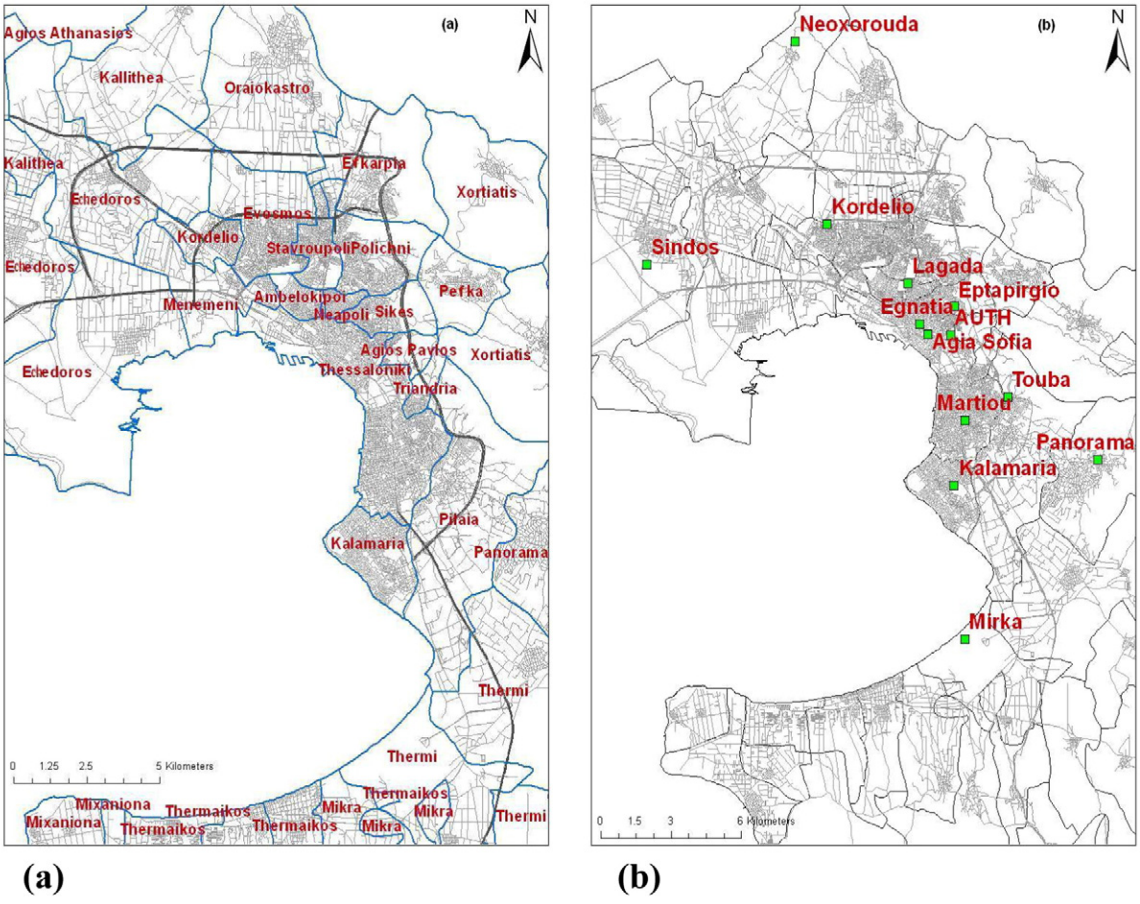

Fig. 1. (a) The city of Thessaloniki, the Great Thessaloniki Area and (b) the location of the air quality monitors used in this study.

2.2. Exposure modelling framework

The exposure modelling framework employed for estimating urban transport-related greenhouse gas emissions and air pollution in Thessaloniki consists of a computation chain that uses an Origin-Destination (OD) matrix for a typical week-day in year 2010; the OD matrix was imported in the transport model VISUM (PTV, 2014), whereby the hourly variation in traffic flow and speed for the Thessaloniki road network was reckoned. For the scenarios regarding implementation of climate change mitigation policies in the future, changes in traffic flow and speed are in accordance to the implementation of measures considered. For the business as usual (BAU) scenario, changes in traffic flow were in accordance with the projected increase in vehicle registrations, described in section *A*1 of the Supplementary material, whereas for greenhouse gas (GHG) mitigation (MIT) scenarios, the impact of the operation of the city underground rail on traffic flow and velocity were based on traffic modelling results.

The methodological workflow is depicted in Fig. 2. First, using the COPERT IV model (Ntziachristos et al., 2009), the hourly variation in emissions for PM, NOx and VOC for a typical day were computed, based on the hourly fleet composition (differentiated between passenger cars, lorries, buses and motorbikes) for a large number of streets in the city. Fleet data were provided by the Hellenic Institute of Transportation through a survey that took place in 2009, whereby the country aggregated variation in engine size, type of filter and fuel type used and the typical distance covered in a year were reckoned.

Hourly emissions of PM, VOC and NO_x were computed per road and motorway segment for the baseline and the different scenarios considered (BAU and MIT). Secondly, pollutant dispersion from traffic sources at predefined receptor points was computed using two models:

(a) the parameterized street pollution model OSPM (Berkowicz, 2000; Berkowicz et al., 2008), which was used to compute concentration within street canyons and
(b) the California Puff Model, CALPUFF (Scire et al., 2000b; Scire et al., 2000a) in order to model the pollutant dispersion from motorways (treated as line sources).

Ground and upper air meteorological data were used from stations in the Great Thessaloniki area including monitors at Mikra airport (a sub-urban area with upper air data), Panorama (a sub-urban area), Kalamaria (an urban area), Sindos (a sub-urban area) and Neohorouda (a rural area), including hourly data on wind speed and direction, humidity and temperature. These data were used as input to the meteorological model CALMET to generate a 3-D grid for modelling the wind and temperature fields and a 2-D grid for mixing height, surface

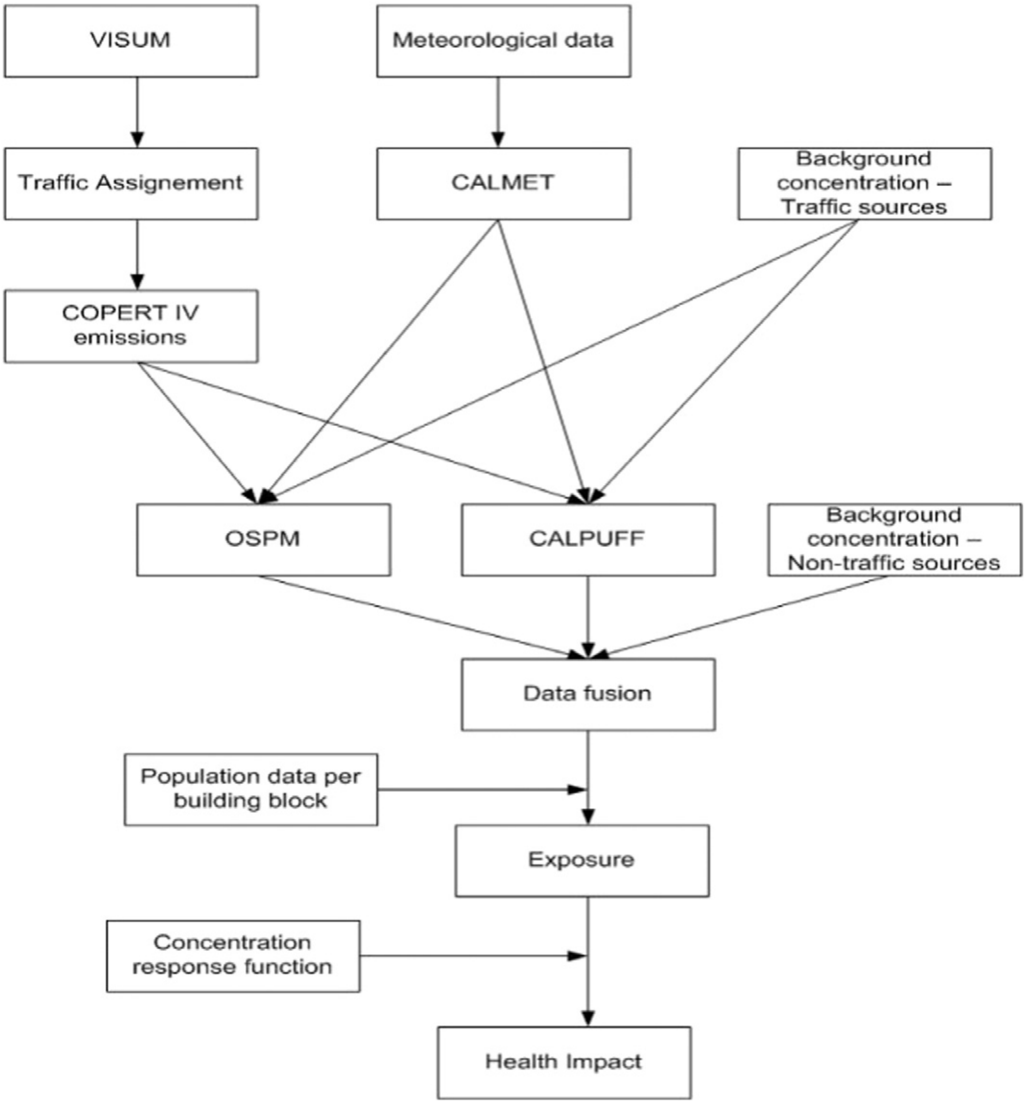

Fig. 2. Health impact assessment flow chart followed in this study.

characteristics and atmospheric dispersion properties above the city of Thessaloniki. Road segments were given as input to CALPUFF. Each road link was divided into *n*-segments surrounded by a buffer. Non-traffic pollution maps per pollutant were generated via spatial interpolation using as input the measuring data from the predominantly non-traffic stations employing ordinary krigging and bias removal of the computed map. For benzene, as it is primarily attributed to vehicle transportation, gas filling stations were considered as the main non-traffic sources within the urban fabric (Correa et al., 2012; Karakitsios et al., 2007; Morales Terrés et al., 2010). In order to estimate the dispersion of benzene concentration C (in $\mu g/m^3$) around filing stations, Eq. 1 was derived based on the concentration gradient identified experimentally in an earlier study by Karakitsios et al. (2007).

$$C = \frac{90}{D^{1.12}} \tag{1}$$

where D is the distance from the gas station (expressed in meters).

Furthermore, to evaluate the benzene concentration from all filling stations mapped within the Thessaloniki GMT, a focal sum methodology was employed as follows:

A single station was used as proxy for the remaining filling stations. A kernel file was generated deduced from the multiple buffers of varying radii starting from 10 m up to 1 km. Concentration within each buffer was evaluated via Eq. 1 and divided by the maximum computed concentration. This kernel file was used as input to a raster file containing the grid of the available gas stations. Going through the computational domain of interest and applying the kernel functions throughout, the concentration of benzene due to the gas stations operating in Thessaloniki was calculated (see Supplementary material section A5.3.1).

Data interpolation techniques were used to generate the annual average concentration maps stemming from each model. These concentration maps were then added vectorially to produce the final predicted concentration. The concentration estimates per station were validated using observations from ground control points in accordance with the Council Directive 1999/30/EC air quality requirements (EC, 2008).

Population exposure to the pollutants studied herein was computed by coupling pollutant concentrations with population residence and workplace data per building block using zonal statistics. The exposure estimates were used as input to exposure-response functions to estimate mortality attributable to PM_{10}, $PM_{2.5}$ and NO_2 and morbidity (leukaemia incidence) attributable to benzene using urban background health data (EUROSTAT, 2011; WHO, 2008).

2.3. Health impact assessment and monetary cost

The health impact attributed to PM_x and NO_2 pollution was estimated through concentration- response functions that were used as acceptable proxies of exposure-response functions. Relative risk $\boldsymbol{RR}$ is calculated for a yearly average concentration $\boldsymbol{C}$, using Eq. 2, based on a log-linear, regression model:

$$RR = CRF^{\left(\frac{C}{10}\right)} \tag{2}$$

where $\boldsymbol{CRF}$ is the concentration-response function.

The attributable fraction $\boldsymbol{A}$F is estimated based on Eq. 3 which is multiplied by the background rate of disease $\boldsymbol{BR}$, in order to derive the estimated health impact $\boldsymbol{HI}$ expressed in number of cases expected for the population of interest $\boldsymbol{P_i}$, as seen in Eq. 4.

$$AF = \frac{(RR-1)}{RR} \tag{3}$$

$$HI = AF * BR * P_i \tag{4}$$

where $\boldsymbol{BR}$ is the background rate of disease and $\boldsymbol{P}$ the population per building block i.

Demographic data for mortality and morbidity rates for several age groups are obtained from EUROSTAT (2011) and the background rate of disease and mortality are obtained from WHO (2008). The CRFs used with regard to the selected health endpoints are given in detail in table A20 of the Supplementary material.

Disability Adjusted life Years or ***DALYs*** for a disease or a health condition are used as a metric of overall impact; it is defined as the sum of the Years of Life Lost (***YLL***) due to premature mortality and the Years lost due to Disability (***YLD***) for people living with the health condition or its consequences, i.e.

$$DALY = YLL + YLD \tag{5}$$

where ***YLL*** corresponds to the number of deaths multiplied by the standard life expectancy at the age at which death occurs and ***YLD*** to the number of incident cases in that period, multiplied by the average duration of the disease and a weight factor that reflects the severity of the disease on a scale from 0 (perfect health) to 1 (dead), as defined in Eqs. 6 and 7,

$$YLL = N * L \tag{6}$$

where $\boldsymbol{N}$ is the number of deaths and $\boldsymbol{L}$ the standard life expectancy at age of death in years.

$$YLD = I \ * \ DW \ * \ L_k \tag{7}$$

where $\boldsymbol{I}$ is the number of incident cases, $\boldsymbol{DW}$ is the disability weight and L_k is the average duration of the case until remission or death in years.

For mortality incidence, DALYs were computed solely from the YLL, whereas for morbidity YLD is used with appropriate adjustment for disability weight and illness duration.

The starting point for the valuation of health end-points is the identification of the components that comprise changes in welfare. These components should be added to reckon the total welfare change, assuming no overlap between impact categories. The three components include: a) resource costs i.e. medical costs paid by the health service in a given country or covered by insurance, and any other personal out-of-pocket expenses made by the individual (or family), b) opportunity costs i.e. the cost in terms of lost productivity (work time loss (or performing at less than full capacity)) and the opportunity cost of leisure (leisure time loss) including non-paid work, c) dis-utility i.e. other social and economic costs including any restrictions on or reduced enjoyment of desired leisure activities, discomfort or inconvenience (pain or suffering), anxiety about the future, and concern and inconvenience to family members and others.

The welfare changes represented by components (i) and (ii) can be approximated using market prices that exist for these items. This measure - in best practice - needs to be added to a measure of the affected individual's loss of utility, reflected in a valuation of the willingness-to-pay/accept (WTP/WTA), to avoid/compensate for the loss of welfare associated with the illness. For the endpoints mentioned above, we used values derived in the EU project HEIMTSA (UBath, 2011), presented in Table A21 of the Supplementary material. These values are the result of both an evaluation of the evidence available in the existing literature and ad hoc population surveys in several European countries.

2.4. Uncertainty assessment

Uncertainty associated with the health impact calculations was identified in emission estimation, air quality modelling, exposure and health impact assessment. Uncertainty in emissions was attributed to the systematic errors of the emission calculation methodology and may include errors in the determination of the emission factors, emission-related elements (e.g. cold start modelling etc.) and variations in activity data. Uncertainty in air quality models was quantified from the actual model fit to the ground observations, after correcting for systematic bias, assuming normal distribution where mean is the observed concentration and the standard deviation was deduced from the standard error to the observations. Exposure uncertainty was deduced from the extent to which the existing measurements and model-based estimates of the pollutants considered characterize the general population. To this end, zonal statistics was used to extract the average concentration per pollutant per building block and the associated standard deviation. Lastly, uncertainty in health impact was attributed to: (a) the concentration response functions used; (b) the potential nonlinear interactions among pollutants to which the population is co-exposed; and (c) the baseline rates of the considered health outcome in the studied population.

2.5. Climate change mitigation scenarios

The first scenario considered (MIT-1) included an optimal combination of two measures: the operation of a metro in the city-centre and changes in traffic composition i.e. a high share (22%) of diesel fuelled vehicles and an economically feasible penetration (2%) of electric vehicles. Using the SIBYL model projections as seen in appendix *A*1 (see Supplementary material), diesel-fueled vehicles increased significantly in comparison to the BAU scenario. This was the result of the reduced cost of transportation (fuel cost) and service, durability and endurance in comparison to the gasoline fueled vehicles. Similarly, the introduction of electric vehicles was considered to follow a conservative penetration of 0.5% of Battery Electric Vehicles - BEV types and 1.5% of Extended Range Electric Vehicles - EREV and Plug-in Hybrid Electric Vehicles - PHEV types. The construction of a metro, expected to be completed by 2018, will be 9.6 km long with 13 terminals. The use of diesel fueled vehicles in Thessaloniki was prohibited until 2011 (Hellenic, 2011); this provision has since been modified. Per Law 4030/2011, diesel-fueled passenger vehicles are allowed into the city if new Euro 5 and Euro 6 type particulate filters are used. Simulations show that these diesel-fueled vehicles dominate the new registered passenger vehicle market, due to very low consumption (30–50% to the gasoline vehicles depending on the vehicle type) and lower fuel price (15–20% to gasoline), as illustrated in appendix A2 in the Supplementary material.

The second scenario (MIT-2) was based on high market penetration of electric vehicles. Starting from the BAU scenario flows the following changes in traffic composition were assumed: 50% electric cars, followed by 45.5% gasoline cars, 0.5% for the diesel cars and 4% for the hybrid cars. This 50% change in market share for electric cars would arise from retrofits over the older gasoline fueled vehicles if consumers are attracted by a series of benefits that could be provided by the central government. Such benefits could be in the form of VAT and registration tax waivers and other fiscal incentives to make the acquisition and use of electric vehicles affordable.

3. Results

3.1. Traffic flow variation

For the baseline scenario, the variation in traffic flow was simulated via VISUM using an origin-destination matrix for a typical day. The hourly variation in flow and car speed for all road segments in the Thessaloniki area were estimated by the model. The daily flow in the motorways surrounding the city varies between 40,000 and 70,000 vehicles. The highest throughput is observed in the Moudania-Thessaloniki motorway and the northeastern part of the ring road influencing the municipalities of Pilaia, Triandria, Thermi, Thessaloniki and Agios Pavlos. The corresponding daily average velocities in these roads are in the range of 80 to 100 km/h. Flow in the Thessaloniki-Malgara motorway located in the southern part of the GTA is in the range of 30,000–38,000 veh/day and the average daily speed is close to 100 km/h. Lastly, daily flows in the western part of the ring road, are in the range of 15,000 to 35,000 vehicles and the corresponding average speeds in the range of 80 to 100 km/h. Focusing on the traffic corridors in the city of Thessaloniki, traffic flow ranges between 45,000 veh/day (Tsimiski street and King George Boulevard) and 15,000 veh/day (Nea Egnatia street). Almost all other main traffic corridors have a daily flow of ca. 20,000–25,000 veh/day.

The highest reduction in flow between the business-as-usual and the first mitigation scenario MIT-1, as depicted in Fig. 3, was observed in Tsimiski street (45%), Egnatia and Nea Egnatia street (35%). Overall, reductions in traffic flow ranged between 20% and 50% compared to the BAU, affecting for the most part roads close to the metro line.

3.2. Changes in emissions

Using the COPERT IV model PM_x, VOC, NO_x, CO and other pollutant emissions were computed. These estimates were made for each road segment taking into account road length and width, hourly traffic flow and velocity profiles, total daily traffic flow, ambient temperature and traffic fleet composition. Vehicles were grouped as follows: gasoline-fueled passenger vehicles, diesel-fueled passenger vehicles, LPG-fueled passenger vehicles, motorbikes, diesel-fueled TRC-1 lorries, diesel-fueled TRC-2 lorries, gasoline-fueled TRC-1 lorries and buses. Changes in traffic fleet (i.e. penetration of diesel-fueled passenger vehicles and electric vehicles) per mitigation scenario were evaluated with respect to business as usual (BAU), considering changes in end-of-pipe emission control technology in all three categories.

Between BAU and MIT-1, the share for the gasoline fueled passenger drops from 59% to 36% for PM_{10} (Fig. 4a), 55% to 28% for $PM_{2.5}$ (Fig. 4b), 43% to 32% for VOC (Fig. 4c) and 36% to 19% for NOx (Fig. 4d). Changes in traffic fleet (i.e. penetration of electric vehicles) in the 2nd mitigation scenario (MIT-2) were also evaluated with respect to BAU (Fig. 4). Between BAU and Scenario MIT-2 scenarios, the share for the gasoline fueled passenger drops from 59% to 42% for PM_{10}, 51% to 35% for $PM_{2.5}$, 45% to 29% for VOC and 32% to 19% for NO_x. In the case of motorbikes and lorries changes in emissions between BAU and Scenario MIT-2, compensate the reduction in emissions from the passenger vehicles as shown by the increase in the respective emission shares.

3.3. Change in traffic-related air pollution

The variation in the annual average concentration of PM_{10}, $PM_{2.5}$, NO_2 and C_6H_6 in the traffic corridors in the city of Thessaloniki and the Great Thessaloniki area is calculated by fusing the results of CALPUFF (for motorways) and OSPM (for street canyons). The baseline PM_{10} concentration in the municipality of Thessaloniki is in the range of 10–25 $\mu g/m^3$ due to the low contribution of the ring motorway to the air pollution (i.e. in the metropolitan area the contribution of the ring motorway to air pollution is in the range of 1–5 $\mu g/m^3$). In the municipality of Kalamaria, PM_{10} ambient air concentration is in the range of 14–30 $\mu g/m^3$, associated with the high contribution of the motorway to the residential area. Municipalities with high pollution levels are identified in the western part of the city and the respective PM_{10} concentration levels ranged from 8 to 20 $\mu g/m^3$. Significant differences between BAU, MIT-1 and MIT-2 are identified: in the city centre the reduction in PM_{10} is in the 2–8 $\mu g/m^3$ (BAU – MIT-1) and 2–12 $\mu g/m^3$ (BAU – MIT-2) range. Similarly, in the surrounding municipalities, reduction in PM_{10} are in the 3–6 $\mu g/m^3$ (BAU – MIT-1) and 3–8 $\mu g/m^3$ (BAU – MIT-2) range. Similar variations in $PM_{2.5}$, NO_2 and C_6H_6 concentration are presented in the Supplementary material, section A5 in Figs. A9, A13 and A16.

3.4. Change in non-traffic-related air pollution

To evaluate non-traffic air pollution sources, an extensive review of existing datasets from ground control points was conducted. Air

Fig. 3. Traffic flow in the BAU (a) and MIT-1 2020 (b) scenarios for the city of Thessaloniki.

pollution monitoring stations close to traffic corridors were identified and their data excluded from further analysis. The pollution data from the remaining stations were used to generate a pollution map for which the associated standard error comparing the map estimates to the ground observations is minimized. In the western (industrial) area of the GTA only three stations are available and distant from each other; thus, artifacts are generated during spatial interpolation. This was fixed through an iterative algorithm introducing two virtual stations in locations that fill the observed spatial data gaps. Per our algorithm first the concentration at the location of the virtual stations was calculated by spatial interpolation of the data coming from the actual existing monitors; these concentration estimates were used to re-run the spatial interpolation algorithm including now the virtual station data in the dataset. This resulted in updating the concentrations reckoned at the virtual stations. The procedure continued iteratively until the standard error at the ground control points was minimized across the computational domain. The procedure was repeated for both $PM_{2.5}$ and NO_2. The fitted kriging models that minimized the standard error of the generated pollution map and the resulting concentration maps of PM_{10}, $PM_{2.5}$ and NO_x are given in the Supplementary material. The highest concentrations of both PM_{10} and $PM_{2.5}$ were found in the western area of the GTA where concentration reaches 46 $\mu g/m^3$ for PM_{10} and 25 $\mu g/m^3$ for $PM_{2.5}$ respectively.

3.5. Predicted annual average concentration maps – air pollution data fusion

Rigorous comparison of the model fusion output against ground monitoring showed model over-prediction in the GTA and under-prediction in the city centre. To remove the observed computation bias, an iterative procedure was implemented utilizing all ground control points available, as follows:

(a) compare the predicted concentration of a pollutant to the ground control points and estimate the prediction error;

(b) using the prediction error at the ground control points create an error map by spatial interpolation, add the error map to the predicted concentration map vectorially and compare the resulting estimate to the values of the concentrations at the control points;

(c) remove artifacts in concentration that were generated because of the interpolation method; for this, virtual stations are introduced. Two virtual stations were included close to the Egnatia and the Agia Sofia stations, taking an initial concentration extracted from the corrected concentration maps and updated per the procedure described in step (b) above; and

(d) complete the iterative procedure, which ends when prediction error is below 10% of the measured levels at all ground control points throughout the computational domain.

The spatial distribution of error was variable in the GTA: positive error (i.e. overestimation) was found in the city centre and negative error (i.e. underestimation) extends from the city to the entire surrounding area. The error compared to the ground control points for $PM_{10,}$ varied from − 15 $\mu g/m^3$ to 3 $\mu g/m^3$. In the Supplementary material, section A5.4 the Tables A6, A7 and A8 present the prior and posterior error to the pollutants considered. In addition, Figs. A16 and A17 demonstrate variation in PM2.5 and NO_2 concentration for the baseline and the scenarios.

Lastly, using the bias adjusted map, error in pollution was removed for each pollutant considered in this study. By way of example, Fig. 5

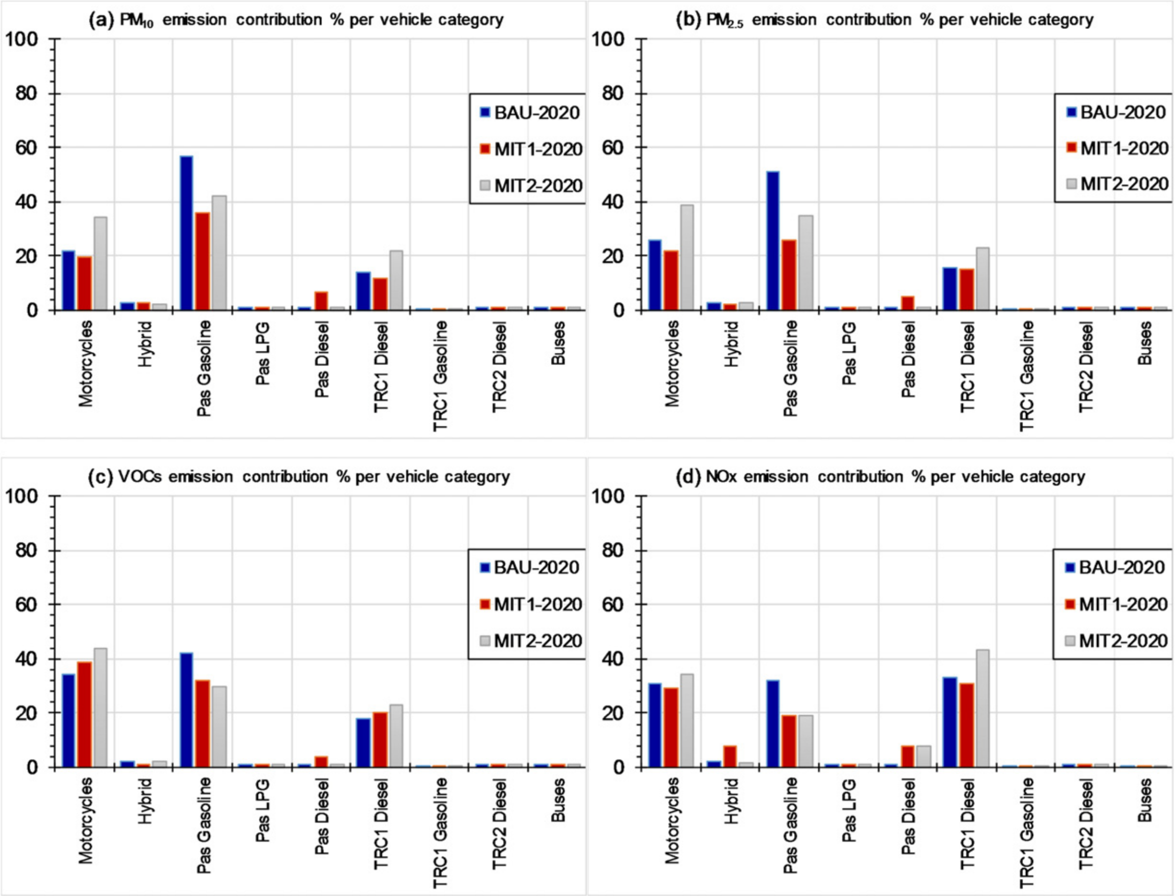

Fig. 4. Change in the % contribution in emissions per vehicle class between BAU, MIT-1 and MIT-2 for PM_{10} (a), $PM_{2.5}$ (b), VOCs (c) and NO_x (d).

shows the variation in ambient air PM_{10} between the baseline, the BAU and the policy scenarios considered herein. Variation in concentration between BAU and MIT-1 in the city centre was up to 5 μg/m^3 and in the municipality of Eukarpia up to 3 μg/m^3. Variation in concentration between BAU and MIT-2 (up to 6 μg/m^3) was most noticeable in high pollution areas (busy roads and motorways). (See Figs. 6a–d and 7a–b.)

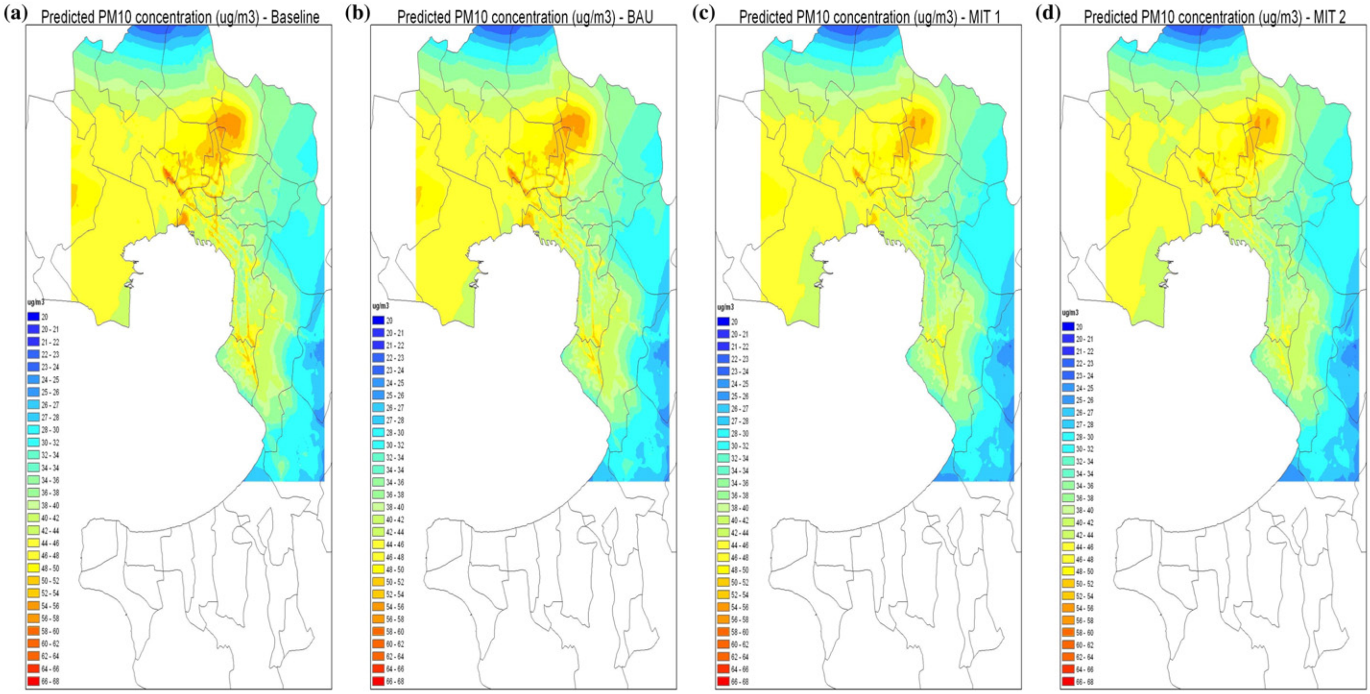

Fig. 5. Ambient air PM_{10} levels for the baseline; BAU (2020); and the two climate change mitigation scenarios.

3.6. Health benefits of air pollution reduction

Using the health impact pathway methodology, attributable mortality and morbidity are computed per building block and reported per municipality. The reduction in the attributable mortality between BAU and MIT-1 and BAU-MIT-2 ranges from 0.001 to 0.07 cases per building block. Mortality risk is also computed, defined as the number of mortality cases per 10^5 people. For the baseline and BAU scenarios, the mortality risk is in the range of 60 to 160 in the city centre, whereas for the MIT-1 and MIT-2 scenarios risk is lower, ranging from 60 to 140. Fig. 6 shows the respective changes in mortality attributed to PM10, between the baseline, the BAU and the policy scenarios MIT-1 and MIT-2.

Mortality estimates were originally reckoned for each building block and then aggregated per municipality, thus allowing us to distribute the related impacts spatially. In the Supplementary material section A7 (Tables A9–A12) the associated uncertainty to the computed health impact is presented, together with the computed DALYs - section A8 (Tables A13–A12) and A9 (Tables A15–A16). The variation in DALYs between scenarios taking into account mortality (deaths due to PM_{10}, $PM_{2.5}$ and NO_2 exposure) and morbidity (PM_x related morbidity and C_6H_6–induced leukaemia) in the GTA municipalities are presented in Table A15 of the Supplementary material (section A9).

The highest DALY values were estimated in the western suburbs (Fig. 7), where high pollution is measured based on the available observations. In these areas climate change mitigation policies considered in this study will bring the largest health benefit to the local population.

4. Discussion

In this paper the public health co-benefits of GHG emission reduction policies in the city of Thessaloniki were investigated. Both local policies affecting a few municipalities (e.g. the construction of an underground railway in the municipality of Thessaloniki and Kalamaria) and national policies affecting all the municipalities in the greater metropolitan area (e.g. allowing new diesel passenger vehicles entering the cities and promotion of electric vehicles) were considered. They were ranked with respect to the reductions in mortality and morbidity, which resulted due to improved air quality. Two main policy scenarios were assessed considering (a) construction and operation of the underground rail and (b) changes in traffic composition.

The annual mortality rate attributed to PM_{10} and $PM_{2.5}$ exposure was differentiated spatially across the municipalities of the GTA: in the densely populated municipality of Thessaloniki, mortality due to PM_{10} and $PM_{2.5}$ is 407 and 316 respectively corresponding to 3571 and 2766 DALYs per 10^5 people.

For BAU-2020 the gradual increase in vehicle numbers and simultaneously the renewal of passenger vehicles with newer end-of-pipe emission control technology improves air quality. This results in a slight reduction in DALYs to 3512 and 2720 per 10^5 people respectively. The slight increase in mortality compared to 2010 levels is due the 3% increase in population numbers expected from 2010 to 2020 in the Greater Thessaloniki Area.

The first traffic scenario considered (MIT-1) illustrated the optimal combination of the measures considered, namely (a) the introduction of a metropolitan underground rail, which primarily influences traffic flow and velocities leading to reduced emissions in the municipalities of Thessaloniki and Kalamaria; and (b) changes in vehicle composition, the greater benefits of which will come from the large number of newly registered diesel vehicles.

It should be noted that the transition of the vehicle fleet composition from gasoline-based into a diesel-fuelled fleet is of great concern in European cities and could potentially offset the benefits of policies that encourage integrated transport among some of the proposed solutions. On the other hand, the limited penetration of electric passenger vehicles will not influence air quality in Thessaloniki significantly, despite generation of zero emissions locally. Overall, simulations showed a noticeable improvement in air quality in the city centre (municipality of Thessaloniki) as the result of the reduced traffic load. Comparisons against the BAU scenario for PM_{10} and $PM_{2.5}$ show reduction in mortality and in the corresponding DALYs. Municipalities with the highest reduction in mortality cases include Kalamaria (5%), Thessaloniki (4%) and Pilaia (4%). MIT-1 will bring savings from the reduction in PM_{10} and $PM_{2.5}$ exposure, which correspond to 62 and 49 million Euros respectively. Reductions in NO_2 and C_6H_6 exposure will lead to savings

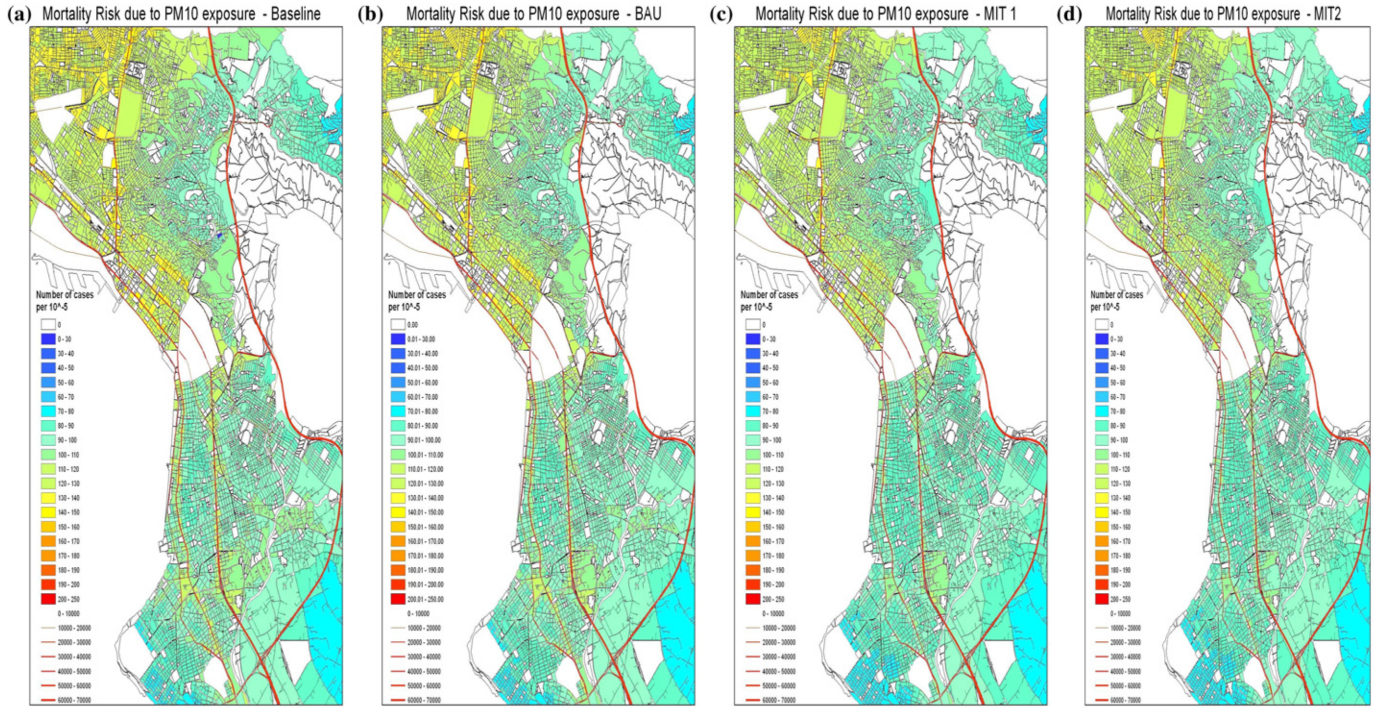

Fig. 6a–d. Spatial distribution of mortality risk attributed to PM_{10} under the various scenarios.

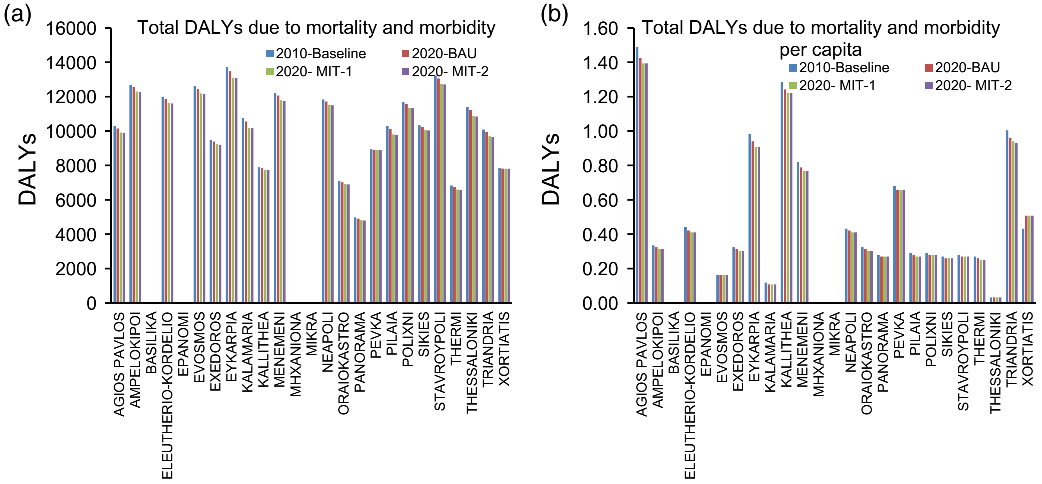

Fig. 7a–b. Total DALY and total DALY per capita for each municipality in the GTA.

of 38 and 1 million Euros respectively. Overall, 150 million Euros per year will be saved by the public health system due to the introduction of these climate change mitigation policies.

The MIT-2 scenario solely simulates the drastic change in vehicle fleet in favor of electric vehicles. Reduction in mortality and morbidity attributed to PM_x pollution in the municipality of Thessaloniki, is 4% for PM_{10} and $PM_{2.5}$. For the other municipalities in the greater Thessaloniki area, the observed differences are related to the relative fleet composition. MIT-2, i.e. the promotion of 'green' transportation in the city via the widespread use of electric vehicles will bring savings resulting from the reduction in PM_{10} and $PM_{2.5}$ exposure up to 66 and 54 million Euro respectively. Similarly, reductions in NO_2 and C_6H_6 exposure will lead to savings of 41 and 1 million Euros respectively. The total savings to the public health system rise to 162 million Euros on an annual basis.

From the above it appears that the introduction of electric vehicles is a very efficient measure for reducing airborne pollutants and most importantly PM and NO_x. Changes in benzene emissions and reduction of benzene-attributable leukaemia are insignificant. This can be explained by the fact that diesel vehicles have negligible benzene emissions. Penetration of diesel vehicles will result in lower health and monetary benefits compared to policies that favor the use of zero emission vehicles. A combination of fiscal, technological policy scenarios and infrastructural interventions would maximise the expected benefits, as identified in a similar study carried out in China (He et al., 2016), where the combined use of bio-fuels with the increased market share of hybrid cars was proven as the most efficient policy. Data on the monetary cost per municipality and pollutant are given in section A10 (Tables A17–A18) of the Supplementary material.

From the methodological point of view, results show that the very high spatial resolution (building block level) of the assessment presented here, allows a more detailed evaluation of the actual benefits from improved air quality in different parts of the urban agglomeration. Such benefits are associated with urban planning as well as different socioeconomic determinants or modifiers of exposure. Based on our knowledge, ours is one of a very limited number of studies worldwide, which succeeded in differentiating air quality, exposure and health impact assessment at such a high spatial resolution. Fusion of different models and data allowed us to overcome the data paucity that usually hampers other analogous studies. The use of OSPM allowed the calculation of traffic contribution in each single traffic segment, tacking also into account the refined emission modelling provided by COPERT. Thus, changes in traffic emissions were evaluated at very high spatial resolution feeding into high resolution air quality maps. This is of importance when assessing real-life traffic scenarios, since their effect on traffic flow and composition is not equally distributed. The construction of a metropolitan underground railway is a typical scenario of this type. In that case changes in traffic flow (and, thus, in emissions) are not proportional in all areas of the urban agglomeration. Use of a comprehensive traffic flow and composition model (VISUM) was necessary for an as much as possible accurate projection of traffic change per road segment under the investigated scenarios. Another very important aspect of the methodology is that differences between the scenarios considered are estimated based on the overall air quality levels and not only on the traffic-related air pollution. This was the result of the use of different air quality modelling tools for re-estimating jointly both the traffic contribution and urban background levels. Although box models are generally considered sufficient for analysis of scenarios reflecting changes in emissions on the urban scale, they are insufficient for the assessment of policies that have spatially variable environmental and health impacts. Our method allowed us to identify partial health effects in areas where traffic is not the dominant component of air quality. This type of spatially resolved assessment is of importance especially in areas where socioeconomic determinants of exposure to air pollution contribute to significant environmental inequity. A detailed analysis like the one described herein allows us to identify the sub-areas that will benefit mostly from the planned interventions that target climate change drivers and to quantify the extent of such benefit. The spatial distribution of climate change mitigation co-benefits on urban air quality and public health would thus support the efficient dialogue among all stakeholders to explore the plausible, feasible and societally acceptable optimal policy options.

A data and model fusion methodology like the one described herein that utilises both air quality monitoring data and modelling tools to derive high resolution spatially resolved air quality concentration and population exposure maps could be a valuable tool for spatial epidemiology and environmental health policy assessment. Potential re-analysis of registered mortality and morbidity data in urban settings worldwide using high spatially resolved air quality maps will reduce significantly the exposure misclassification bias hampering population-based studies and enhance the relevance and robustness of their results.

The methodological advances highlighted above could provide significant insights in similar studies aiming to assess the health benefits of GHG emission mitigation policies stemming from the consequent reduction of air pollution in cities. This is not meant only in terms of methodology, but also in terms of identifying win-win solutions towards GHG and air pollutant emission mitigation. Our study shows that the development of a key public transportation means (such as underground rail) results in a cascade of changes in the overall urban function, land use and traffic emissions; the public health co-benefits of scenario

MIT1 (although lower compared to scenario MIT2), indicate the effectiveness of large scale policies such as the introduction of metropolitan underground rail. Yet, the introduction of underground rail alone brings only limited benefits, constrained by distance of population residence from the actual rail lines and the main stations/nodes of the metropolitan rail network. Our results show that to allow underground rail networks to generate the full benefits they are capable of they should be combined with infrastructure supporting multimodal transport such as park-and-ride sites and adaptation of the public bus network to connect with all metro stations. This would enlarge the spatial radius of benefits that underground rail has on the reduction of air pollutants and their health impacts on the urban population.

On the other hand, the significant co-benefits obtained by MIT-2 scenarios, indicated the importance of the transition to zero-emission vehicles (ZEVs) in terms of improving public health and well-being. These results agree well with the findings of other similar studies carried out in Europe (Perez et al., 2015; Tobollik et al., 2016), and China (He et al., 2016; Yang and He, 2016b), highlighting the importance of disruptive technological advances in the private vehicle sector. ZEVs are more effective than diesel vehicles in reducing GHG and toxic pollutants released into the urban atmosphere. Uptake of GHG emission abatement measures follows the socio-economic gradient in the urban population; it can be further limited by dire financial conditions and recession.

Overall ours is an innovative method based on data and model fusion that can produce spatially resolved impact assessments with increased accuracy, providing new insights in future environmental inequalities and their alleviation options. We focused on traffic-related GHG abatement measures as the latter are highly relevant for many cities in Europe and worldwide. The results presented above met our objectives, which included:

(a) the identification of win-win solutions that cater to both climate change mitigation and improved urban air quality; and
(b) the evaluation of these solutions within a ten-year time frame regarding their plausibility and the associated co-benefits in terms of public health and related economic burden on the healthcare system.

Concluding remarks

Potential co-benefits from the implementation of climate change mitigation policies affecting urban traffic between 2010 and 2020 have been estimated. A full-chain impact pathway methodology was followed employing different models to address the source-to-health outcome continuum. These policy scenarios were compared against a business-as-usual scenario (BAU) to assess the effect of the policies considered on human health expressed in terms of mortality and morbidity and their translation into associated monetary costs. All policy bundles considered in this study will bring noticeable benefits to public health and would be expected to significantly reduce the cost of medical care associated with air pollution-attributed mortality and morbidity. Overall the MIT-2 scenario (i.e. penetration of ZEVs into the public and private vehicle market) presents slightly higher benefits with respect to the MIT-1 scenario (i.e. introduction of underground rail and transition towards diesel-fueled vehicles) for all stressors considered when assessing the heath impact and the associated monetary valuation. Based on our results the following recommendations were issued towards the smooth implementation of the policies considered:

(a) the operation of an underground rail network in the city of Thessaloniki should be part of a sustainable transport system, via the promotion of energy efficient multi-modal transport systems, clean fuels and vehicles. Towards the development of the unique opportunity to develop an integrated system, the improvement of the public transport system is essential, accompanied by technological improvements that will result in cleaner buses (e.g. buses fuelled with LPG). This type of integrated approach could also be pursued at the national, regional and local level.
(b) the use of electric vehicles should be promoted via a series of benefits and fiscal incentives provided by the central government. Retail cost could be reduced via VAT and registration tax removals and series of other fiscal incentives could be put in place to make the acquisition and use of electric vehicles affordable. Although the question of fleet renewal and disposal of older vehicles, as well as the provision of financial incentives in a country facing tremendous economic difficulties seems a challenge, the health and monetary co-benefits in the long run provide the impetus for win-win solutions towards the concurrent mitigation of GHG emissions and urban air pollution.

In closing, it should be underlined that the use of active transport (although beyond the scope of this study) could benefit the urban population health through multiple channels including (a) benefits of physical activity and (b) mitigation of air pollution, accompanied with GHG emission mitigation.

One key result of our study is the comprehensive methodology we have developed that incorporates a unique data fusion algorithm that integrates efficiently environmental monitoring data and modelling. This method resolves problems of data paucity that hamper the detailed impact assessment of climate change mitigation interventions in many a city around the world. Thessaloniki is a typical case in this regard and the fact that we succeeded in obtaining spatially refined and robust results paves the way for similar applications in other urban settings worldwide. Certainly, many cities in Europe and the Americas are of similar size and face similar problems regarding data availability and intervention options. Thus, our results bear significant relevance to many cities globally.

The Thessaloniki case study presents yet another type of specific scientific interest, since it refers to an urban area that faces a large financial crisis. From this perspective, exploring options that pave the way towards a green city is of interest, since cost effectiveness of policies that target mitigation of both GHG emissions and air pollution in cities is of importance in other parts of the world as well. In our opinion the conclusions and lessons learned from our study as well as the methodology outlined can be readily used in other mid-size cities in Southeastern Europe (our region) and the world.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2016.11.142.

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