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Designing local air pollution policies focusing on mobility and heating to avoid a targeted number of pollution-related deaths: Forward and backward approaches combining air pollution modeling, health impact assessment and cost-benefit analysis

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ABSTRACT

Context: Policies aiming at decreasing air pollutants (e.g., fine particulate matter, $PM_{2.5}$) are often designed without targeting an explicit health benefit nor carrying out cost-benefit analyses.
Methods: We developed a transdisciplinary backward and forward approach at the conurbation level: from health objectives set by local decision-makers, we estimated which reductions in $PM_{2.5}$ exposures and emissions would allow to reach them, and identified urban policies leading to these reductions (backward approach). We finally conducted health impact and cost-benefit analyses of these policies (forward approach). The policies were related to the most emitting sectors in the considered area (Grenoble, France), wood heating and transport sectors. The forward approach also considered the health impact and co-benefits of these policies related to changes in physical activity and CO_2 emissions.
Findings: Decision-makers set three health targets, corresponding to decreases by 33% to 67% in $PM_{2.5}$-attributable mortality in 2030, compared to 2016. A decrease by 42% in $PM_{2.5}$ exposure (from 13.9 $\mu g/m^3$) was required to reach the decrease by 67% in $PM_{2.5}$-attributable mortality. For each Euro invested, the total benefit was about 30€ for policies focusing on wood heating, and 1 to 68€ for traffic policies. Acting on a single sector was not enough to attain a 67% decrease in $PM_{2.5}$-attributable mortality. This target could be achieved by replacing all inefficient wood heating equipment by low-emission pellet stoves and reducing by 36% the traffic of private motorized vehicles. This would require to increase the share of active modes (walking, biking…), inducing increases in physical activity and additional health benefits beyond the initial target. Annual net benefits were between €484 and €629 per capita for policies with report on active modes, compared to between €162 and €270 without.
Conclusions: Urban policies strongly reducing air pollution-attributable mortality can be identified by our approach. Such policies can be cost-efficient.

1. Introduction

Atmospheric pollution has major and proven effects on mortality and morbidity, mainly through cardiovascular and respiratory health (Hamra et al., 2014; Pope et al., 2004; World Health Organization, 2014). With nine out of ten people in urban areas worldwide in 2019

Abbreviations: Δ_{NAC}, difference in the number of attributable cases; LEZ, Low Emission Zones; PM, particulate matter; $PM_{2.5}$, fine particulate matter; RR, risk ratio; VoT, Value of Time; WHO, World Health Organization.

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being exposed to levels of fine particulate matter ($PM_{2.5}$) from outdoor air pollution above the 2005 World Health Organization (WHO) guideline value (annual average $PM_{2.5}$ concentration of 10 μg/m^3) (World Health Organization, 2019), and even more above the current World Health Organization (WHO) guideline value of 5 μg/m^3, air pollution is a major public health issue. Exposure to ambient $PM_{2.5}$ annually causes an estimated 4.2 million (Uncertainty Interval, UI, 3.7, 4.8) deaths worldwide (Cohen et al., 2015) (based on 2015 and 2018 exposure levels, and a counterfactual level of 2.4–5.9 μg/m^3 corresponding to the theoretical minimum risk exposure level) and 417,000 annual death cases in Europe (European Environment Agency, 2020) (based on 2015 and 2018 exposure levels, and a counterfactual level of 0 μg/m^3); in France, about 40,000 people would prematurely die each year due to ambient anthropogenic $PM_{2.5}$ exposure (based on 2016–2019 exposure levels and a counterfactual level of 5 μg/m3) (Medina et al., 2020). The health impacts of air pollution cost an estimated $1.7 trillion in OECD countries in 2010, while specifically in France the annual direct and indirect economic costs amount to €100 billion (Senate, 2015).

Air pollution thus represents one of the biggest controllable environmental risk to health. Public policies are one family of options to reduce the health and economic impacts of air pollution. These policies should target the main sources of atmospheric pollution. Such public policies can combine different instruments: legal instruments (e.g., norms on emissions for vehicles or other sources or on concentrations of specific pollutants, low emission zones), price instruments (e.g., economic incentives to increase the share of low emitting equipment, of non-motorized mobility, of public transports, which emit less per capita, to improve insulation of homes), technological solutions (e.g., development of low emission devices to replace polluting ones), urban planning (e.g., transportation infrastructures), and public awareness. Cities in Europe and elsewhere have undertaken measures to limit air pollution emissions, especially from transportation and heating sources. In cities where ambitious programs were implemented, environmental evaluations have documented decreases. For example, ban of coal sales in Dublin in 1990 led to the reductions in black smoke air concentrations by 70% and in non-trauma death rates by 5.7% (95% CI, 4, 7), when comparing concentration levels over the 72 months before and after the measure came into force (Clancy et al., 2002). Decreases in PM_{10} by as much as 50% were reported in Tokyo between 2001 and 2010 (Hara et al., 1995), and between 5% and 13% in Germany following the adoption of low emission zones (Cyrys et al., 2014; Fensterer et al., 2014). Until now, the adoption of such public policies did not allow to quickly alleviate the above-mentioned societal burden, in particular in France (Cour des comptes, 2020; Court, 2008).

One possible reason is that policies to reduce pollution are often designed without explicit consideration of a targeted health impact. In some cases, they rely on an *ex ante* environmental evaluation ignoring any health consequence. Such an evaluation is even seldom done a posteriori: a review of LEZs in Europe (ADEME, 2018) showed that only in rare cases was the environmental evaluation supplemented with a health impact assessment (HIA) (Cesaroni et al., 2012). In contrast, in the USA, the Clean air act requires the Environmental Protection Agency to periodically estimate the impact of the Clean air act on public health, economy, and environment.

Starting from a target health impact to appropriately dimension urban policies would be a logical and important change of approach for many areas of the world.

Scientifically, this raises the challenge to develop a reverse or backward approach consisting of starting from a target formulated in terms of improvement of health (e.g., reducing by 50% the $PM_{2.5}$-related mortality), and subsequently identifying urban policies allowing to reach such a health target. Specific health co-benefits can arise from policies aiming primarily to reduce air pollution, such as those related to changes in physical activity linked with the promotion of mode shift from cars to e.g., bicycles, and their assessment would be required to fully appraise the health improvements than can be expected from such policies (Kelly et al., 2014; Kyu et al., 2016). Traffic is also a major source of noise, whose exposure has been associated to heart disease and stress (Belojevic et al., 2008; Bodin et al., 2009) as well as decreases in well-being (Gidlöf-Gunnarsson and Öhrström, 2007), as well as a source of greenhouse gas; changes in these factors, which also influence health (Woodward et al., 2014; Kalsch et al., 2014), need to be considered.

If the cost of the targeted policies is estimated, cost-benefit analyses can in addition be conducted. In the USA, analyses of benefits and costs are planned by the Clean Air Act law, and the analyses conducted so far indicate that the benefits exceed costs by a factor of 3 to 90, with a central estimate equal to 30 (US EPA, 2011). No such figure is available in France. Making them available in the French and European contexts, where atmospheric pollution limits are much higher than in the USA (with a regulatory limit of 25 μg/m^3 for $PM_{2.5}$ yearly mean concentration in Europe, compared to 12 μg/m^3 in the USA), would be very relevant for citizens and decision makers. Such estimates should also be provided at the city level, to consider accurately specific local sources and because air pollution mitigation policies are often implemented at this level.

We therefore developed a backward and forward approach at the city level, starting from predetermined health objectives and identifying the corresponding change in the population's exposure to air pollution (focusing on $PM_{2.5}$), then the corresponding $PM_{2.5}$ emission reductions, and finally defining urban policies compatible with these health objectives (Fig. 1, "reverse approach"). We then carried out a cost-benefit analysis of these policies, including climate change and various health co-benefits (Fig. 1, forward cost-benefit analysis). The present study was led in Grenoble urban area, a French middle size city with good characterization of air pollution impacts (Morelli et al., 2019), as well as good knowledge on the main air pollution sources of $PM_{2.5}$, i.e., wood heating and road traffic.

2. Material and methods

2.1. A reverse approach to develop scenarios for achieving specific air pollution-related health objectives

The main steps of our backward and forward approaches are described in Fig. 1. The details are provided below.

2.1.1. From health targets to changes in air pollution exposure

Grenoble conurbation belongs to Auvergne-Rhône-Alpes region, which is in the South-eastern part of France. Grenoble conurbation has a surface of 541 km^2, includes 49 municipalities, and, with 444,000 inhabitants in 2014, is the 11th French largest conurbation in terms of population (Insee, 2017). In Grenoble, emissions from wood heating account for an annual average of 63% of $PM_{2.5}$ emissions (Atmo, 2017), a proportion higher during cold winter days. These emissions come from inefficient equipment such as open fireplaces and stoves with low energy efficiency. This is why Grenoble conurbation has been offering a subsidy for the purchase of efficient wood stoves for the replacement of these installations since 2016. To obtain the wood stove replacement premium, households have to own a fairly old device, destroy it and install a new one with an efficiency label. Road transport accounts for 17% of yearly $PM_{2.5}$ emissions (Atmo, 2017). In 2017, the Grenoble conurbation set up a low emission zone (LEZ) for the goods transport vehicles; only vehicles without a "CritAir" label (the least efficient ones) were concerned. This restriction, which only applied to Grenoble center when it was introduced, has been extended since 2019 to 10 voluntary municipalities bordering Grenoble, and since 2020 to 27 municipalities among the 49 included in the Grenoble conurbation.

Based on exposure levels from 2015 to 2017, we previously estimated that the population density-weighted long-term average exposure to anthropogenic $PM_{2.5}$ in Grenoble conurbation corresponds to 145 (95% , CI, 90–199) attributable premature death cases each year

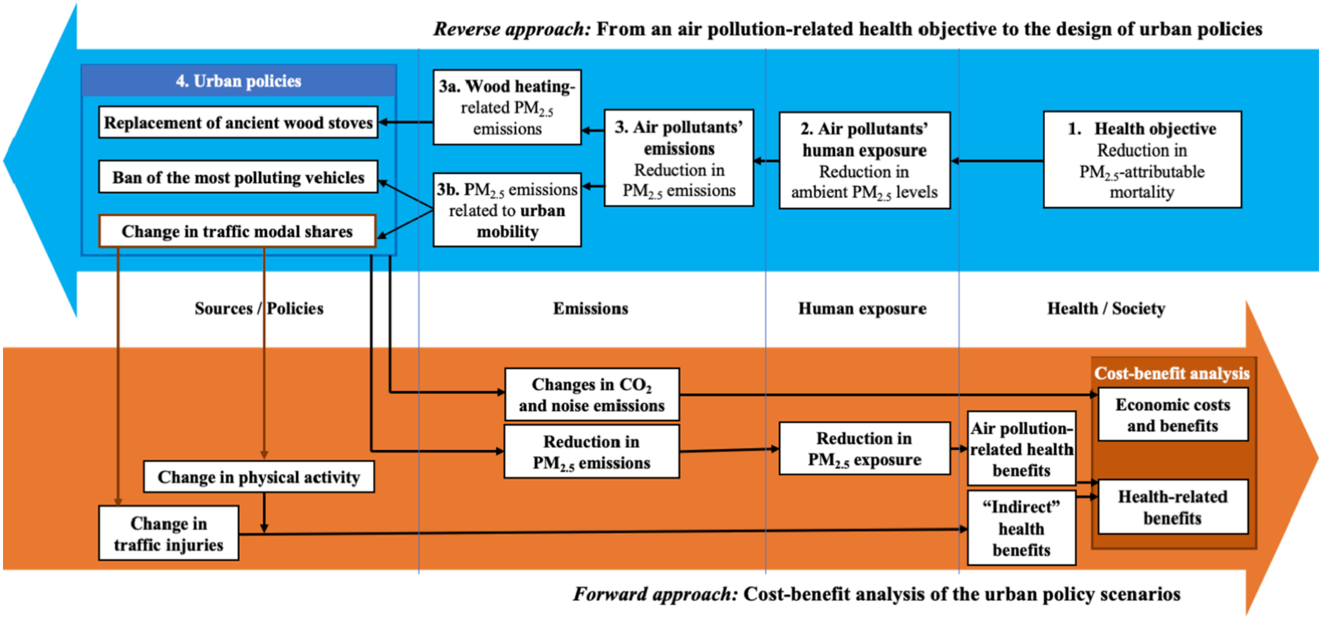

Fig. 1. Overview of the study, showing the reverse approach from an air pollution-related health improvement objective to the identification of the corresponding urban policies as well as the cost-benefice analysis of the designed urban policy scenarios.

(Morelli et al., 2019). We also previously showed that achieving a decrease by 33%, 50%, and 67% of the premature mortality attributable to anthropogenic $PM_{2.5}$ exposure by 2030, compared to the 2015–2017 average (baseline), would require to reach the yearly average $PM_{2.5}$ exposure of 11.0, 9.6, and 8.0 $\mu g/m^3$, respectively, starting from the baseline population-weighted yearly level of 13.9 $\mu g/m^3$ (Morelli et al., 2019). These health objectives were defined by the elected officials of Grenoble metropolitan area.

The study area population's yearly average exposure to $PM_{2.5}$ was assessed coupling the modeled $PM_{2.5}$ concentrations with information on population density, as previously described (Morelli et al., 2019). Atmospheric pollutant concentrations were modeled at a 10-meter spatial resolution combining two models: CHIMERE, a mesoscale chemistry-transport model (Menut et al., 2013), and SIRANE, a proximity scale air pollutant-dispersion model (Soulhac et al., 2011). Population density by sex and five-year age classes was available for 2014 at the same spatial resolution (10-meter), based on data from the National Institute of Statistics and Economic Studies (Insee, 2017) and the National Institute of Geographic and Forestry Information (IGN, 2017). All assumptions made throughout this study are listed in Table S1 (*see supplement*).

2.1.2. *From air pollution exposure changes to PM emissions reductions*

Many studies use forward-looking emission reduction modelling, in which each scenario is evaluated independently. The MECANO approach that we developed is an alternative way of carrying out this assessment using the capacity of models to perform source tracking. We used a model nesting to track the mass of pollutants emitted into the atmosphere with the Comprehensive Air Quality Model with Extensions (CAMx) and SIRANE models. These two models allow to trace emissions at the regional level and identify their local sources (*see supplement*, Figure S1).

CAMx model (Ramboll Environ, Arlington, Virginia, USA) is a Eulerian chemistry-transport model able to simulate atmospheric concentrations of particulate and gaseous pollutants. The regional domain was bounded to the Rhône-Alpes Region using a 3x3-km grid resolution. Boundary conditions on this domain were given by CHIMERE modelling at the 27x27-km scale over Europe. Meteorological fields come from a simulation with the Weather Research and Forecast (WRF) model (NCAR, Boulder, Colorado, USA) configured on 3 nested domains of 27x27, 9x9 and 3x3 km. Emissions within the Rhône Alpes Region were provided by Atmo Auvergne-Rhône-Alpes inventory. Outside this area, emissions were retrieved from the EMEP database (Simpson et al., 2012).

CAMx and SIRANE were both used in a source apportionment approach for $PM_{2.5}$. The contributions of emission sources from different sectors of activity and geographical areas were identified and followed during the simulation. The flagged emissions sources were grouped in CAMx according to five activities (industry, road traffic, residential heating, agriculture, and others). An interface was developed to apply coefficients to the different areas and activity sectors. In parallel, SIRANE was launched with traffic emissions only. Given the better spatial resolution of SIRANE model (to the road scale) compared to CAMx (1-km grid), traffic sector-related emissions from CAMx were not considered and were substituted by SIRANE model's estimates.

We then combined the models' estimates, assuming linearity between the emissions of all pollutants related to a given activity (traffic or urban heating) and the concentrations followed in the PSAT module of CAMX. This approach allowed to drastically reduce the calculation time of each scenario, from almost one week to less than one hour. This approach therefore made it possible to quickly screen various reduction scenarios. The limitations of this approach and its possible domain of validity are discussed in supplementary material (Box S1). To check the most ambitious scenario (67% decrease in PM2.5-related mortality), we made a forward estimation of this emission scenario using CAMX. The population-weighted difference between this estimate and the backward estimate from MECANO approach was 0.01 $\mu g/m^3$.

2.1.3. *From emission reduction to urban policy scenarios*

The definition of urban policies to achieve health objectives focused on traffic and urban heating, the two main local sources of $PM_{2.5}$. The traffic scenarios explored different hypotheses of modal shift towards modes alternative to the private car in order to reach the reduction of vehicle.km consistent with the health objectives.

To identify the potential modal shift in the Grenoble conurbation, we relied on the Grenoble-area Household Travel Survey (2010), which describes all trips (travel time, mode of transport, purpose…) performed by a representative sample of the conurbation inhabitants. For each trip of the household, we enriched the database with data on travel distances and times by car (calculated with *Odomatrix* (Hilal et al., 2018)) and urban public transit (calculated with the Grenoble multimodal model). We first defined, as a reference scenario, the transport modal share of the main transport modes in 2010 (Table 1). We then developed three orientations of modal shift (later called sub-scenarios) from motorized vehicles (cars, taxis, motorized two-wheelers, vans, tractors…): one with an emphasis on public transport, one with an emphasis on active modes (walk and bicycle), and a third with an emphasis on active modes including also electrically-assisted cycling (E-bikes). The two latter sub-scenarios also considered carpooling, a mode of transport favored by local mobility policies, for which a shift was considered possible depending on the number of single drivers making the same trip (same origin and destination).

We considered the behavior of people using alternative modes to the car as a basis for describing which modes could be used by current car users, based on the time or distance of the trip and loop (i.e., trip series from home-to-home); from this we derived a potential mode shift. We considered the home-to-home loop because a trip that could be replaced by an active mode when considered alone could not be done by the same mode of transportation when regarded as part of a loop (for instance, a 1-km trip to bring children to school followed by a 20-km trip to go from the school to work). For the potential of modal shift to public transportation, we considered the ratio of public transport travel time and car travel time, for the trip and for the loop, while for the potential of modal shift to the active modes (walking and cycling), we considered the distances of the trip and the home-to-home loop.

For the first sub-scenario, thresholds concerning time and distance of the trip and the loop were set at the median of the observations in the Household Travel Survey. From this, we then deduced a potential reduction in terms of motorized vehicle-km (cf. 3.1.2).

The thresholds under the two other sub-scenarios were chosen to achieve the same level of reduction in motorized vehicle.km as in the first sub-scenario, while remaining compatible with people's practices (in terms of time spent in transportation and distance to be traveled on foot or by bicycle) and the conurbation layout.

Table 1 displays the motivation for each modal shift sub-scenario, as well as the time and distance thresholds used. When a trip was potentially transferable to more than one mode of transport, the mode report hierarchy was as follows: i) walking; ii) cycling; iii) E-biking; iv) public transportation; v) carpooling.

Lastly, for each mode of transport, we estimated the change in the number of travelled kilometers between the reference scenario (2010) and each modal shift sub-scenario. On the basis of the Grenoble-area Household Travel Survey, we also assessed the travelers' age distribution under the reference and each sub-scenario, for each transport mode.

Analyses were performed using R software version 3.6.3 (R Foundation for Statistical Computing, Vienna, Austria).

2.2. *Health and economic evaluation of urban policies*

2.2.1. *Health impact assessment*

Several long-term health effects likely to be linked to $PM_{2.5}$ exposure, and also to physical activity for most of them, were considered: all-cause non-accidental mortality (ICD10: A00-R99), lung cancer incidence (ICD10: C33-34), ischemic heart disease incidence (ICD10: I20-25), and cerebrovascular disease incidence (ICD10: I60-69). All-cause non-accidental mortality data were obtained from the Epidemiological center on causes of death (CépiDC, Inserm) for people aged 30 years and older, at the municipality scale. Lung cancer incidence in the study area was

Table 1
Definition of the modal shift sub-scenarios of *Traffic_3* scenario.

Sub-scenario		**Reference**	**"Public transport" sub-scenario**	**"Active modes" sub-scenario**	**"E-bike" sub-scenario**
Description		Observations of the Household travel survey (2010). Transport modal share of the main transport modes (in % of passenger.km): −57% are drivers of cars and of two wheelers, −12% are passengers in cars and two wheelers, –22% corresponds to public transport, −7% for walk −2% for bicycles.	Starting from the reference scenario, this scenario implements a modal shift from motorized vehicles for all trips or loops whose distances or ratios of travel time are below the median of the observations concerning the mode towards which the shift is done.	Favors the active modes to reduce the mode share of public transport. Introduces carpooling.	Introduces E-biking in addition to carpooling. The modal share of public transport is close to the level it has in the reference scenario.
Threshold values of trips entailing a shift from the car	**Walking (distance)**		< 0.7 km (trip) < 2 km (loop)	< 2 km (trip); corresponds to the stated objective of the local urban mobility plan) < 5 km (loop)	< 2 km (trip); corresponds to the stated objective of the local urban mobility plan < 5 km (loop)
	Cycling (distance)		< 1.8 km (trip) < 5.1 km (loop)	< 5 km (trip); corresponds to the 9th decile currently observed in trips performed by bike < 12.5 km (loop)	< 3 km (trip) < 7.5 km (loop)
	E-biking (distance)				< 7.8 km (trip) < 19.5 km (loop)
	Public transportation (ratio with car travel time)		< 1.7 × car travel time (trip and loop)	< 1.5 × car travel time (trip and loop)	< 1 × car travel time (trip and loop)
	Carpooling		Not considered	Drivers may become passengers if their origin–destination trip was made in a driver's car at least 400 times a day; we then randomly allocated 4 out of every 10 trips in a driver's car to a passenger car.	Drivers may become passengers if their origin–destination trip was made in a driver's car at least 400 times a day; we then randomly allocated 4 out of every 10 trips in a driver's car to a passenger car.
Motorized vehicle.km		3.18 M. vehicle.km	2.05 M. vehicle.km	2.05 M. vehicle.km	2.07 M.vehicle.km
Motorized person.km		3.85 M person.km	2.44 M. person.km	2.44 M. person.km	2.45 M.person.km

NB: Loop threshold distances are equal to about 2.5 times trip threshold distances, which is approximately the number of trips in a loop. M: million.

estimated using regional data from the French National Cancer Institute (data 2007–2016) (INCa, 2019). Numbers of new beneficiaries from the “long duration diseases” database of the French health insurance system (ALD$_{30}$) (French health insurance system, 2018) were used as incidence data for ischemic heart disease and cerebrovascular disease.

From the literature, we selected concentration–response functions between PM$_{2.5}$ exposure or physical activity and each health outcome; robust risk-ratios, such as those from *meta*-analyses, were preferred (Table 2).

The expected “direct” health benefits related to the reduction of air pollution were estimated for each health outcome and each policy plan as the difference in the number of attributable cases (Δ_{NAC}) between the baseline (2015–2017 period) and a counterfactual situation under which the policy is assumed to be implemented. Differences in attributable cases $\Delta_{NACi,j}$ were first estimated at each 10-m air pollutant model grid point before being added to estimate the Δ_{NAC} for the whole area (Morelli et al., 2019). We also expressed health gains in terms of number of life-years in people aged 30 years and older. A cessation lag before obtaining complete health benefits was applied: 30% of the total health gain the first year after implementation, 50% distributed over years two to five, and 20% through the following fifteen years (US EPA, 2010).

We also evaluated “indirect” health benefits such as those subsequent to the increase in physical activity under scenarios supporting active mobility, through the difference of the average metabolic equivalent hours (MET.hours) per week and inhabitant between the situation with the scenario and that without implementation of the scenario (at the same period). Increase in walking in link with shift to public transport was also considered. To that end, traveled kilometers were firstly converted in MET.hours considering an average speed of 4.8, 15.1 and 18.3 km.h^{-1} and 3.5, 5.8 and 4.5 METs for walking, cycling, and E-bikes respectively (Ainsworth et al., 2011; Berntsen et al., 2017). Like for health benefits related to air pollution decreases, we assessed for each modal report scenario the number of preventable death cases, and the corresponding number of years of life saved, as well as the number of preventable cardiovascular disease cases.

Table 2

Concentration-response functions used to estimate the long-term effects of air pollution exposure to fine particulate matter (PM$_{2.5}$) and physical activity on health. A relative risk below one indicates a protective effect.

Health event	Study source	Meta-analytical relative risk (95% CI)	Unit
Effects of PM$_{2.5}$ exposure			
Non-accidental mortality	World Health Organization (2014) (World Health Organization, 2014)	1.066 (1.040 – 1.093)	For a 10 µg/m^3 increase
Lung cancer incidence	Hamra et al. (2014) (Hamra et al., 2014)	1.09 (1.04 – 1.14)	For a 10 µg/m^3 increase
Ischemic heart disease incidence	Cesaroni et al. (2014) (Cesaroni et al., 2014)	1.28 (0.96 – 1.69)	For a 10 µg/m^3 increase
Cerebrovascular disease incidence	(Stafoggia et al., 2014) (Stafoggia et al., 2014)	1.42 (0.77 – 2.62)	For a 10 µg/m^3 increase
Effects of physical activity			
Non-accidental mortality (for walking)	(Kelly et al., 2014) (Kelly et al., 2014)	0.89 (0.83 – 0.96)	For 11.25 MET.hour.week^{-1} of walking
Non-accidental mortality (for cycling)	(Kelly et al., 2014) (Kelly et al., 2014)	0.90 (0.87 – 0.94)	For 11.25 MET.hour.week^{-1} of cycling
Ischemic heart disease incidence	(Kyu et al., 2016) (Kyu et al., 2016)	0.860 (0.796 – 0.926)	For 10.0 MET.hour.week^{-1} of activity
Cerebrovascular disease incidence	(Kyu et al., 2016) (Kyu et al., 2016)	0.862 (0.780 – 0.954)	For 10.0 MET.hour.week^{-1} of activity

NB: MET.hours: metabolic equivalent hours.

“Indirect” effects also included those related to traffic injuries. Total number of incidents was obtained at the municipality scale by sex and transportation mode for the 2008–2012 period, from the National interministerial road safety observatory (ONISR, 2018). For each transportation mode, the injury risk (fatal, serious, or light) per km traveled was estimated as the ratio of the annual average number of incidents to the total number of kilometers traveled in the study area in 2010 (*see supplement*, Table S2). The number of traffic injuries expected by mode under each sub-scenario was then estimated applying these injury risks. The increase in injuries in walkers in relation with shift to public transport was also considered (public transport users have to reach their bus/tram on foot). Concerning fatal injuries only, the associated life-year loss was estimated by comparing, by sex and mode, the average age at death among victims under the considered scenario to the life expectancy at age 40 (i.e., the average age of Grenoble conurbation commuters), which was equal in France to 40.6 years in men and 46.2 years in women in 2014 (Insee, 1994).

Analyses were performed using Stata version 15.1 (Stata Corp., College Station, TX, USA) while geographical data were handled with QGIS version 3.4 (OSGeo Foundation, Beaverton, OR, USA).

2.2.2. *Cost-benefit analysis*

The perspective of the cost-benefit analysis is societal at the local level, so that we did not consider costs to the general economy, such as possible lost incomes in the car manufacturing industry or gains for public transport or bike manufacturers, for example. In order to consider all health gains and lag effects, the cost-benefit analysis covered the period 2017–2045. All amounts were expressed in Euros 2021. We considered the time profiles of the costs and benefits of the urban policies over a period of 29 years from 2017 to 2045. We assumed a discount rate equal to 4% for both costs and benefits (Haute Autorité de Santé, 2011).

2.2.2.1. Health benefits induced by pollution reduction. For each scenario, we estimated the avoided costs associated with all-cause non-accidental mortality, lung cancer incidence, and cerebrovascular disease incidence due to pollution alleviation. We considered direct and indirect tangible costs as well as intangible costs. Direct costs refer to medical costs, indirect costs to loss of productivity due to sick leave and intangible costs to grief and loss of quality of life. The assessment methods for all-cause non-accidental mortality and lung cancer incidence relied on *Aphekom project* methodology and values (Chanel, 2011). These intangible costs, based on a literature review of contingent valuations, corresponded to €103,592 per year of life saved (69,054–138,120; the extreme values corresponding to variations of 33% around the central value) (Chanel, 2011). For cerebrovascular disease incidence, we estimated direct medical costs by considering the differences between patients admitted in nursing home or not (Chevalier et al., 2014) and we assumed a seven-year life expectancy (de Pouvourville, 2016); unit health costs are given in Table S3 (*see supplement*). Due to a lack of reliable data on costs associated with ischemic heart disease incidence, no economic valuation was provided for this health outcome.

2.2.2.2. Other externalities specific to the transport sector. In addition to the health benefits related to pollution exposure reduction, we considered five indirect health impacts specific to the transport sector. Firstly, we considered the cost related to the change in the frequency of road traffic accidents. Concerning fatal injuries, intangible costs of corresponding life years were the same as above, i.e., €103,592, whereas costs of serious and light injuries were respectively equal to 12.5% and 0.5% of the value of a statistical life, which is 3.458 M€ per case (ONISR, 2017). Secondly, we monetized the years of life gained from the additional physical activity generated by the shift to active modes of transport, using the same value of 103,592€ per year of life saved. Thirdly, the composition of the vehicle fleet and modal share can also affect the exposure of the population to noise pollution in the vicinity of traffic. We relied on an average cost of noise per vehicle.km from a published study (Quinet, 2013), and we applied a noise pollution cost 50% lower for electric cars (CGDD, 2017). Fourth, we considered non-health benefits related to greenhouse emission decrease. The fleet regulation and the growth of active mobility decrease greenhouse gas (GHG) emissions due to road traffic. GHG emission reductions were monetarized following the recently computed global social cost of carbon equal to US$417 per ton of CO_2 (Ricke et al., 2018). Lastly, we considered benefits related to the value of time spent in transport. The global journey time variation was assessed, assuming an average speed based on the literature for the active modes (Kelly et al., 2014; Ainsworth et al., 2011; Berntsen et al., 2017) and on local transport data for motorized modes. We then applied perceived Values of Time (VoT) per mode of transport to convert these changes in journey duration into Euros (Bouscasse and de Lapparent, 2019; Litman, 2008; Le Papon, 2013; Litman, 2019).

2.2.2.3. Public costs and private expenditures specific to mobility-related policies. We also estimated the costs engaged by the public actors under each scenario. The implementation of a LEZ in itself does not require significant investment, contrarily to the development of infrastructures to facilitate cycling and the development of public transport. In the following, we rely on the estimated budget for the realization of the mandatory urban mobility plan (SMTC, 2018), provided by the Grenoble conurbation to define its transport policy. The budgets required into the estimation for each scenario were thus deduced by multiplying the urban mobility plan costs associated to each mode of transport by the ratios of vehicle.km of each mode in all scenarios, compared to that of the urban mobility plan. A portion of the costs remained constant through all scenarios because of their low sensitivity to changes in infrastructure plans.

The change in mobility behavior induced by the traffic policies also affects household expenditures for mobility. We estimated private total costs integrating the investment cost and the cost of use of each transport mode per vehicle.km to estimate the impact of the modal report on the cost for the users concerned. The total cost per kilometer were respectively from €0.32 to €0.51 for cars (depending on the type of motorization), €0.15 for public transport, and from €0.12 to €0.22 for bikes (depending on the share of E-bikes and the use intensity).

2.2.2.4. Public costs and private expenditures specific to policies in the heating sector. Public costs related to the wood stove replacement premium include subsidies and operating costs (communication and animation costs supported by the conurbation to convince inhabitants to replace their wood burning facilities by less polluting ones). The subsidies are the premium itself (which amounts to €1600 for most households and €2000 for the most deprived ones) and national grants aimed at promoting the energy transition. Operating costs include communication and animation costs supported by the conurbation. Private costs are the expenses incurred by households for installing a new heating system after deduction of public subsidies, which are more important for the most deprived people. We also considered that household saved €300 on energy bills each year due to more efficient heating devices.

3. Results

3.1. Reverse approach: Identification of policies allowing to reach the health targets

3.1.1. Scenarios combining actions on wood heating and traffic

As already mentioned, based on exposure levels from 2015 to 2017, we previously estimated that the population density-weighted long-term average exposure to anthropogenic $PM_{2.5}$ in Grenoble conurbation corresponds to 145 (95% CI, 90, 199) attributable premature death cases each year (Morelli et al., 2019). Our previous study (Morelli et al., 2019) identified the air pollution decrease required to reach the three health targets we selected, namely –33%, −50%, and −67% of this $PM_{2.5}$-attributable mortality. Fig. 2 shows these air pollution decreases and allows identifying combinations of emission reduction targets in each sector expected to achieve each of the three health objectives. A large number of combinations allow to reach these targets, and for practical reasons, we decided to consider three global scenarios (one for each target) each combining one policy in the transport sector and one policy in the wood heating sector; these policies are detailed in Table 3. The most ambitious health target (-67% of the $PM_{2.5}$-attributable mortality) could be achieved in 2030 by replacing all inefficient wood heating equipment by pellet stoves and by reducing by 36% the traffic of private motorized vehicles.

3.1.2. Sub-scenarios implementing shifts in mode share in the −67% scenario

We selected three sub-scenarios of modal shift under the scenario *Traffic_3*, which led to a 36% reduction in the number of vehicle.km travelled using motorized vehicles compared to the baseline situation (2010). We estimated that a 36% reduction in the number of vehicle.km travelled in motorized vehicles was required to reach the $PM_{2.5}$ exposure decrease due to traffic changes identified for the scenario allowing the 67% decrease in $PM_{2.5}$ mortality.

In the first sub-scenario (Fig. 3), the modal shift from car to alternative modes is then possible if the distances travelled (for active modes) or the time ratios (car/public transport) are below the median of these same indicators observed for current users of these alternative modes (median threshold). In this sub-scenario, named *Public Transport* due to the strong modal shift to public transport, the modal share of motorized modes dropped to 44% (i.e., −36% compared to the baseline of 69%), whereas public transport and cycling modal shares doubled (from 22% to 45% and from 2.3% to 4.5%, respectively).

The second sub-scenario was named *Active modes* due to the strong increase of the modal share of walking and cycling while the third sub-scenario was named *E-Bikes* due to the introduction of this electric mode. In the *Active modes* and *E-bikes* sub-scenarios (Fig. 3), the shares of cycling (including E-Bikes) reached 12% and 23%, respectively. The walking share rose to 9.6%, against 6.6% in the baseline and 6.7% in the *Public Transport* sub-scenario. The public transport modal shares were lower in these scenarios than in the first one and reached respectively 34.4% and 23.1%.

3.2. Forward approach: cost-benefit analysis of the identified urban policies

3.2.1. Health impact assessment

On average, 2,601 people aged 30 years and more non-accidentally died each year in Grenoble urban area under the baseline situation. There were 219 new lung cancer annually diagnosed, 568 new ischemic heart disease cases, and 325 new cerebrovascular disease cases.

Table 4 shows the number of death and disease cases which could be prevented yearly under each policy, because of changes in $PM_{2.5}$ exposure, physical activity, or traffic injuries, while Table 5 presents the benefits of the policy combinations and Table S4 (*see supplement*) details the expected changes in mortality and morbidity for the distinct modal

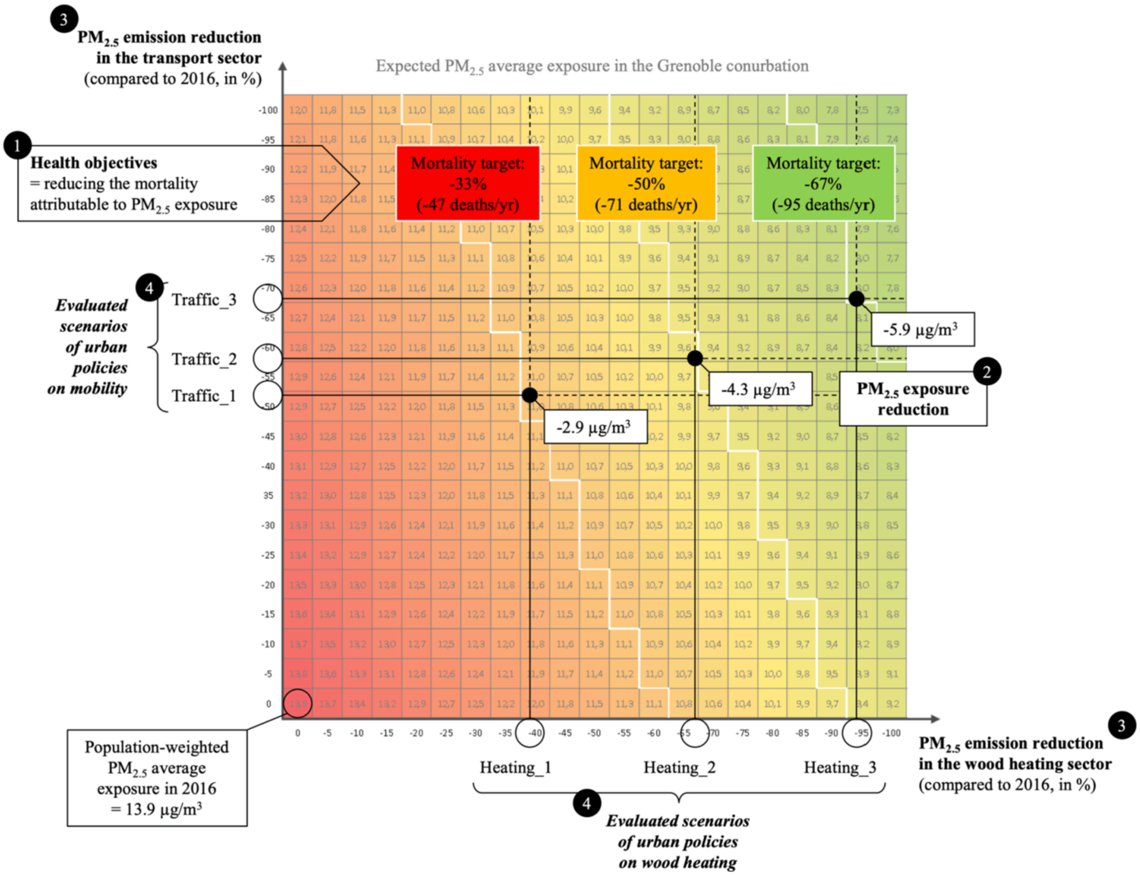

Fig. 2. Expected $PM_{2.5}$ annual average exposure in the Grenoble conurbation population with regard to the combination of urban policies in the wood heating sector and in the transport sector (in µg/m^3). Following our reverse approach: ❶ starting from health objectives seeking to reduce the PM2.5-attributable mortality; ❷ then assessing the reduction in PM2.5 exposure needed to reach these health objectives (symbolized by zigzagging white lines); ❸ assessing the corresponding reduction in PM2.5 emissions in the wood heating and the transport sectors; ❹ and designing compatible urban policy scenarios that will be evaluated though a cost-benefit analysis.

shift sub-scenarios. Reaching the –33% $PM_{2.5}$-attributable mortality objective by combination of the *Heating_1* and *Traffic_1* policies prevented, additionally to the targeted decrease of 47 (95% CI, 29, 65) death cases a year, 5 (95% CI, 2, 8) incident lung cancer cases, 31 (95% CI, 0, 82) strokes, and 39 (95% CI, 0, 81) incident ischemic heart disease cases each year. Combination of *Heating_2* and *Traffic_2* policies (50% decrease in $PM_{2.5}$-attributable mortality) avoided 70 (95% CI, 43, 97) death cases, and also 8 (95% CI, 4, 12) incident lung cancer cases, 46 (95% CI, 0, 118) strokes, and 57 (95% CI, 0, 118) incident ischemic heart disease cases each year. Lastly, *Heating_3* plus *Traffic_3* policies led to “direct” health gains equal to 93 (95% CI, 58, 130) death cases, 10 (95% CI, 5, 16) incident lung cancer cases, 60 (95% CI, 0, 150) strokes, and 76 (95% CI, 0, 154) incident ischemic heart disease cases annually prevented. In addition, under the third transport modal shift sub-scenario (“E-bikes”), the “indirect” health benefits (related to the increase in physical activity and the changes in fatal traffic injuries) corresponded to 179 (95% CI, 85, 257) death cases (192% of the number of deaths directly avoided), 2 (95% CI, 1, 4) incident lung cancer cases, 37 (95% CI, 12, 62) strokes, and 66 (95% CI, 34, 99) incident ischemic heart disease cases prevented each year.

3.2.2. *Economic analysis*

3.2.2.1. Heating-related measures. All the measures aimed at replacing wood heating equipment led to a positive net annual balance (benefits - costs) from the very first years, rapidly generating each year between 60 M€ (for *Heating_1*) and 140 M€ (for *Heating_3*) in net benefits (Fig. 4). Almost all of this balance was made up of the health benefits linked to the reduction of atmospheric pollution. When expressed as a benefit/cost ratio of values averaged over the whole 2017–2045 period, for each Euro invested by the public policy, the benefits generated were higher than 25€ (Table 4, *see supplement*, Table S5).

3.2.2.2. Traffic-related measures. For traffic policies (Fig. 5), *Traffic_1* and *Traffic_2* led to annual net benefits from 50 M€ to 100 M€ as early as 2025, comparable to the heating-related measures. *Traffic_3* sub-scenario focusing on the development of public transport resulted in an initially negative balance sheet, with a net cost around €200 million per year on average until 2030. Thereafter, costs and benefits were broadly balanced until the end of the period. In contrast, the other *Traffic_3* sub-scenarios based on the development of active modes and E-bikes led to a positive net annual balance almost from the beginning of the period, and above 200 M€ after 2030. When expressed as a ratio, one Euro invested in traffic-related measures led to benefits of 19.6 for *Traffic_2*, and respectively 1.1, 3.1 and 4.7 for *Traffic_3* alternatives focusing on public transport, active modes and E-bikes (Table 4, *see supplement*, Table S5).

In terms of structure of benefits, the traffic-related benefits mainly consisted of health benefits related to pollution reduction, reduction of the impact on climate change and savings by households on the investment and operating costs of cars. The time profile and structure of the cost-benefit analysis of *Traffic_3* differed between *Traffic_1* and *Traffic_2* in three ways. First, the implementation of modal shifts in *Traffic_3* required substantial investments in infrastructure, contrarily to the first two traffic scenarios. Second, health benefits related to increased physical activity represented more than half of the benefits

Table 3
Description of the heating- and traffic-related policy scenarios, and their combinations, aiming at reducing fine particulate matter ($PM_{2.5}$) exposure and improving public health.

Health target	**–33% of the mortality attributable to $PM_{2.5}$** **(-47 deaths/year)**		**−50% of the mortality attributable to $PM_{2.5}$** **(-71 deaths/year)**		**−67% of the mortality attributable to $PM_{2.5}$** **(-95 deaths/year)**	
Corresponding decrease in $PM_{2.5}$ exposure	−2.9 μg/m^3		−4.3 μg/m^3		−5.9 μg/m^3	
Combination of policy scenarios allowing to reach the health target	**Heating_1**	**Traffic_1**	**Heating_2**	**Traffic_2**	**Heating_3**	**Traffic_3**
Description of the policy scenarios	Replacement of one-third of non-efficient wood stove appliances over the 2016–2020 period, as planned by the wood stove replacement premium plan. (Grenoble Alpes Métropole, 2018)	The already planned LEZ avoiding goods transport vehicles labeled *CritAir 2* or above.	Once the wood stove replacement premium target has been reached in 2020 (*Heating_1*), replacement of all inefficient wood heating equipment between 2021 and 2030 through a subsidy by efficient wood stoves.	Extension of the LEZ to all vehicles (including passenger cars) labeled *CritAir 2* or above, without modal shift compared to the modal distribution observed in 2010 (Grenoble-area Household Travel Survey); in this scenario, only the technological lever is considered (i.e., the share of cars in the overall mobility remains unchanged compared to the reference year).	Once the wood stove replacement premium target has been reached in 2020 (*Heating_1*), additional subsidy to replace *all* inefficient wood heating equipment between 2021 and 2030 by pellet stoves, which currently are the least polluting wood heating facilities.	In addition to *Traffic_2*, we assumed a modal shift, corresponding to a decrease by 36% in the number of motorized vehicle.km compared to 2016; the *Traffic_3* measure was broken down into 3 sub-scenarios, which differed in terms of the modes (public transport, actives modes, car-sharing) towards which the decrease in the vehicle. km of motorized vehicles were dispatched.
Decrease in $PM_{2.5}$ emissions in the considered sector	−39%	−52%	−67%	−58%	−94%	−68%
Corresponding decrease in $PM_{2.5}$ exposure	−1.8 μg/m^3	−1.0 μg/m^3	−3.1 μg/m^3	−1.1 μg/m^3	−4.4 μg/m^3	−1.3 μg/m^3

LEZ: Low emission zone.

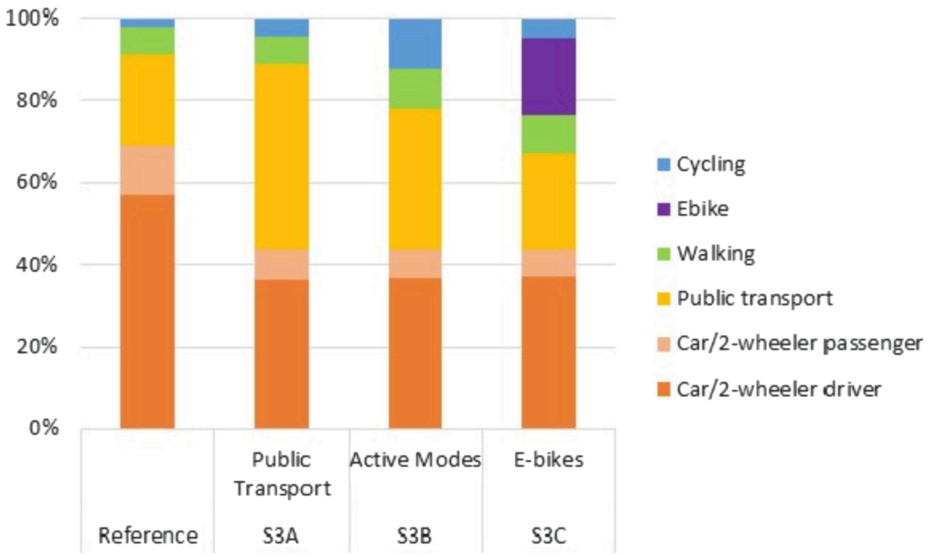

Fig. 3. Transport mode share under the reference situation (2010) and the 3 traffic sub-scenarios of the scenario *Traffic_3* (expressed in percentages of passenger. kilometers travelled).

generated by each *Traffic_3* alternative; these benefits linked to physical activity corresponded to about ten times the value of the health benefits linked to the pollution reduction *per se*. Third, the losses related to the value of time and the increase in travel time due to modal shifts represented a significant net cost.

3.2.2.3. Cost-benefit analyses of scenarios combining heating and traffic-related measures. The discounted sum of costs and benefits of the various combinations of wood heating and mobility measures targeting a 67% decrease in $PM_{2.5}$-related mortality is presented in Fig. 6. Over the whole period, the two sub-scenarios favoring modal shifts towards

Table 4
Changes in air pollutant exposure, mortality and morbidity for each scenario of urban policy related to wood heating and road traffic.

	Wood heating-related policies			**Road traffic-related policies**				
	Heating_1	**Heating_2**	**Heating_3**	**Traffic_1**	**Traffic_2**	**Traffic_3**		
						"Public transport" sub-scenario [b]	**"Active modes" sub-scenario** [b]	**"E-bike+" sub-scenario** [b]
Change in: [a]								
Premature deaths	−30	−52	−72	−16	−18	−79	−179	−201
	(-42, −19)	(-72, −32)	(-100, −45)	(−23, −10)	(-25, −11)	(-117, −38)	(-260, −86)	(-287, −98)
						−58	*−158*	*−179*
						(-87, −24)	*(-230, −73)*	*(-257, −85)*
Corresponding years of life	+958	+1647	+2308	+516	+575	+2602	+6096	+6890
	(587, 1335)	(1009, 2297)	(1412, 3221)	(316, 718)	(353, 801)	(1235, 3860)	(2851, 9027)	(3280, 10087)
						+1928	*+5421*	*+6216*
						(821, 2920)	*(2437, 8088)*	*(2866, 9147)*
Lung cancer incidence	−3	−6	−8	−2	−2	−2	−2	−2
	(-5, −2)	(-9, −3)	(-12, −4)	(-3, −1)	(-3, −1)	(-4, −1)	(-4, −1)	(-4, −1)
Stroke incidence	−20	−34	−46	−11	−12	−25	−46	−52
	(-53, 0)	(-85, 0)	(-112, 0)	(-30, 0)	(−33, 0)	(-56, −3)	(-90, −10)	(-100, −12)
						−11	*−31*	*−37*
						(-18, −3)	*(-52, −10)*	*(-62, −12)*
Ischemic heart disease incidence	−25	−42	−58	−14	−15	−37	−73	−84
	(-52, 0)	(-86, 0)	(-117, 0)	(-29, 0)	(−32, 0)	(-66, −10)	(-120, −29)	(-136, −34)
						−19	*−55*	*−66*
						(-29, −10)	*(-83, −29)*	*(-99, −34)*
Cumulated and discounted net benefits (in M€ over the whole period 2017–2045)	1300	1902	2545	1466	2228	197	4399	6329
Benefit/cost ratio (over the period 2017–2045)	26.8	26.7	35.4	67.0	19.8	1.1	3.1	4.7

[a] Estimate and 95% confidence interval (95% CI) of the number of cases annually prevented, and corresponding gain (estimate, 95% CI) in years of life for prevented death cases.

[b] In black: Total change, combining changes related to the decrease in air pollutant exposure, the increase in physical activity, and, if relevant, the changes in fatal traffic injuries; in italic grey: change related to modal shift only (i.e., related to the increase in physical activity and, if relevant, the changes in fatal traffic injuries; *see supplement*, Table S4).

active modes or electric bicycles were the most interesting economically, generating annual net benefits equal to €6.7 billion (i.e. €468 per capita each year) and €8.6 billion (i.e. €615 per capita each year) respectively over the whole period, i.e., 2 to 4 times more than the –33% and −50% scenarios (Table 5 and Fig. 7). All scenarios presented a positive cumulative balance almost from the first years, except for the sub-scenario based on public transport, which required a very high public investment and generated fewer health benefits related to physical activity than the two other *Traffic_3* alternatives.

The overall gain is shown by the red diamond shape while surfaces indicate the structure of costs and benefits.

4. Discussion

We used a backward modelling approach to define policies to achieve air pollution mortality reduction targets set by local decision-makers, and then used a forward modelling approach to assess their health and economic impacts, including indirect benefits not considered in the backward approach. The most ambitious health target (-67% of the $PM_{2.5}$-attributable mortality) could be achieved in 2030 by replacing all inefficient wood heating equipment by pellet stoves and by reducing by 36% the traffic of private motorized vehicles. Assuming no change in distance travelled, such a reduction in motorized traffic would require identical increases in active modes share (walking, biking…); these would also induce, thanks to the increase in physical activity, additional health benefits beyond the initial target. Wood heating system replacement and strategies maximizing active mobility by other means than the development of public transport were the most cost-effective policies. At the scale of this urban area of 444,000 inhabitants, over a 25-year period, reaching the −67% $PM_{2.5}$-attributable mortality target by promoting active modes would generate at the conurbation level cumulated net benefits of around €7-9 billion in 2045 whereas the –33% $PM_{2.5}$-attributable mortality target, reachable with policies already planned, would lead to a net benefit equal to €2.7 billion.

4.1. Policy recommendations

Policies to be implemented for wood heating are easily identified. Subsidizing the most performing appliances can be particularly effective from both a health point of view (since they drastically reduce emissions related to wood heating compared to old appliances) and from an economic point of view, since the leverage effect is very important (a benefit of around 30€ for each euro invested by public authorities). In practice, the implement. Banning the most polluting appliances (in particular

Table 5

Changes in mortality and morbidity for each combination of policies related to wood heating and road traffic, allowing to reach the pre-defined health targets.

Health target	**−33% of the mortality attributable to $PM_{2.5}$** **(-47 deaths/year)**	**−50% of the mortality attributable to $PM_{2.5}$** **(-71 deaths/year)**	**−67% of the mortality attributable to $PM_{2.5}$** **(-95 deaths/year)**		
Combination of policy scenarios	**Heating_1 + Traffic_1**	**Heating_2 + Traffic_2**	**Heating_3 + Traffic_3 "Public Transport"**	**Heating_3 + Traffic_3 "Actives modes"**	**Heating_3 + Traffic_3 "E-bikes+"**
Change in: [a]					
Premature deaths	−47 (-65, −29)	−70 (-97, −43)	−151 (-217, −83)	−251 (-360, −131)	−273 (-387, −143)
Lung cancer incidence	−5 (-8, −2)	−8 (-12, −4)	−10 (-16, −5)	−10 (-16, −5)	−10 (-16, −5)
Stroke incidence	−31 (-82, 0)	−46 (-118, 0)	−71 (-168, −3)	−92 (-202, −10)	−98 (-212, −12)
Ischemic heart disease incidence	−39 (-81, 0)	57 (-118, 0)	−95 (-183, −10)	−131 (-237, −29)	−142 (-253, −34)
Cumulated and discounted net benefits (in M€ over the whole period 2016–2045)	2,767	4,130	2,742	6,944	8,875
Net benefit per year and per capita (over the period 2016–2045)	162	270	168	484	629
Benefit/cost ratio (over the period 2016–2045)	39.3	22.5	2.1	4.2	6.0

[a] Estimate and 95% confidence interval (95% CI) of the number of cases annually prevented, and corresponding gain (estimate, 95% CI) in years of life for prevented death cases.

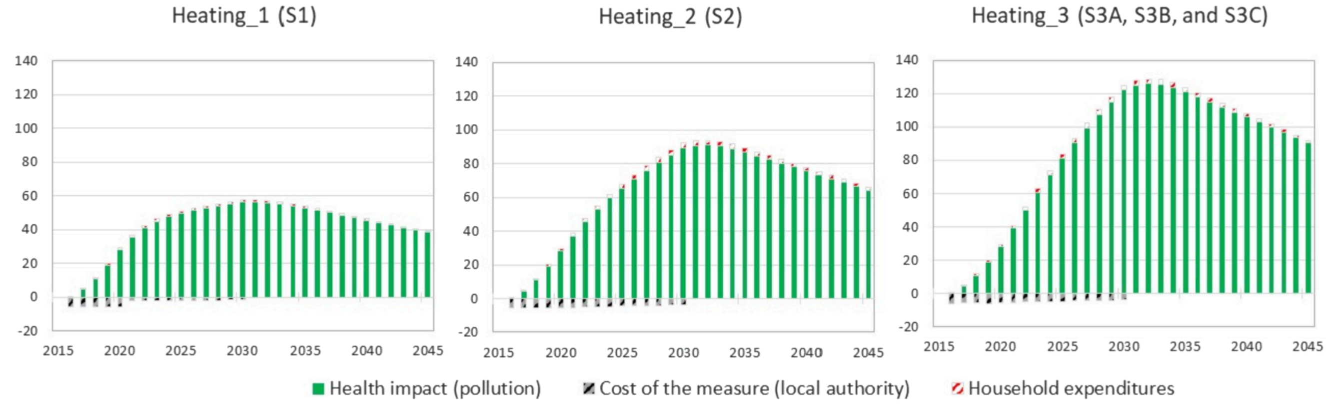

Fig. 4. Annual flow of costs and benefits generated by wood heating-related measures (Million €).

open fireplaces) is worth considering as, in the considered area, these were responsible for 63% of $PM_{2.5}$ emissions in 2016. When it comes to the transport sector, the health impact of $PM_{2.5}$ emission reductions was less important because of lower emission levels, but the modal shifts considered produced indirect health benefits adding to than those directly related to pollution reduction, particularly through the increase in physical activity, the decrease in greenhouse gas emissions, and the reduction of noise, representing respectively 91%, 15%, and 3% of net benefits in the −67% scenario including a modal shift toward E-bikes (S3C). The deployment of cycling appeared particularly interesting for several reasons: first, because of its co-benefits, but also because the investments in infrastructure and facilities needed to promote cycling (bike lines, facilities that make cycling enjoyable, bicycle parking, showers in the workplace) can be easily implemented through light changes in the existing urban infrastructures. In the future, electric bicycles are expected to be in great demand as an alternative for medium-distance journeys made today by private car. The electric bicycle pushes back the limits in terms of distance of the modal shift from the private car and can be adopted by people reluctant to ride a muscle-powered bicycle.

One challenge is the development of ambitious programs to encourage the practice of conventional and electric bicycles. Beyond economic incentives (subsidies for bicycle purchase, reimbursement by employers) and dedicated facilities, it is also important that policies and programs target the psychological levers (perception, intention, altruism, social norms…) allowing to promote cycling share (Bamberg, 2012).

4.2. *Methodological strengths and limitations*

4.2.1. *4.2.1 mobility behavioral changes*

We made several assumptions worth being discussed. Concerning the sub-scenarios of transportation mode shift, we considered the behavior of people using alternative modes to the car as a basis for describing which modes could be used by current car users. This hypothesis is restrictive because mode choice is multi-factorial and other factors come into play, such as age, gender or number of children. However, we considered that only car trips with distance or travel time characteristics less than the median of the distances and travel times achieved in the alternative modes could shift to those modes. The potential shift could actually be much greater if we considered the characteristics of a larger share or even of all cyclists and other users of alternative modes to the

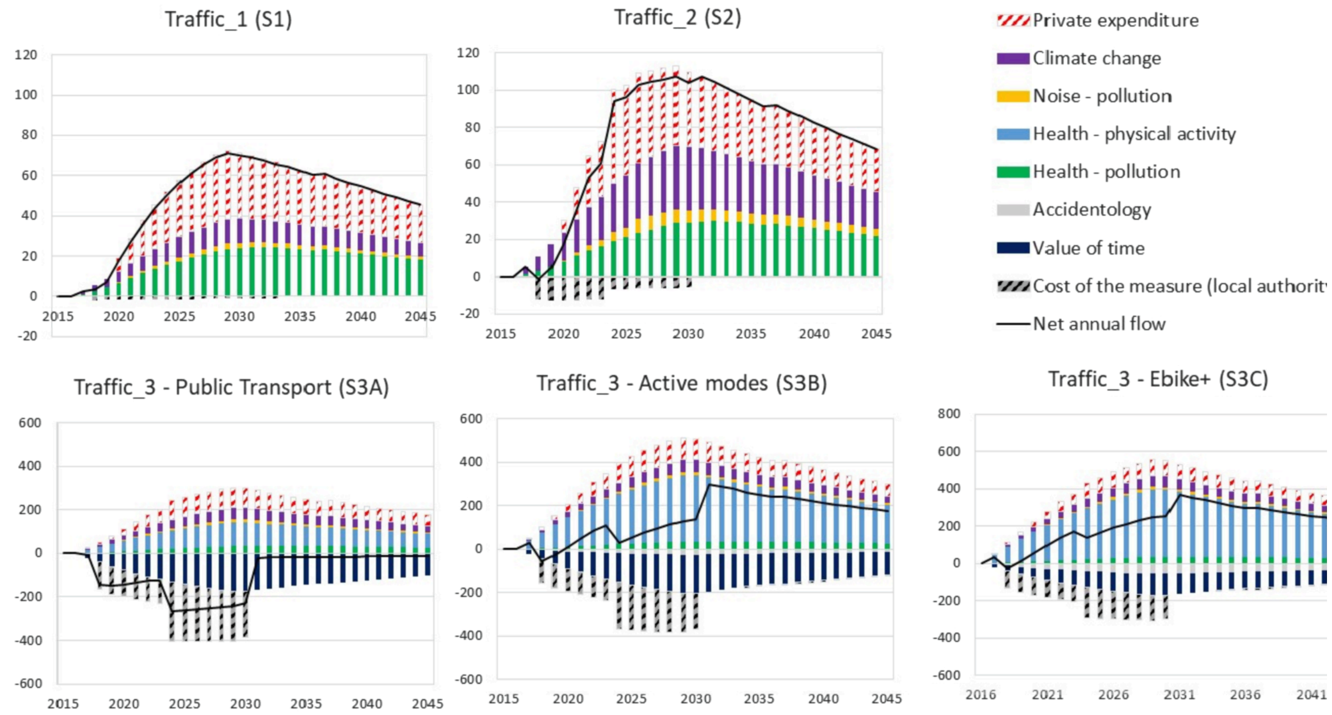

Fig. 5. Annual flow of costs and benefits generated by measures in the transport sector (Million €).

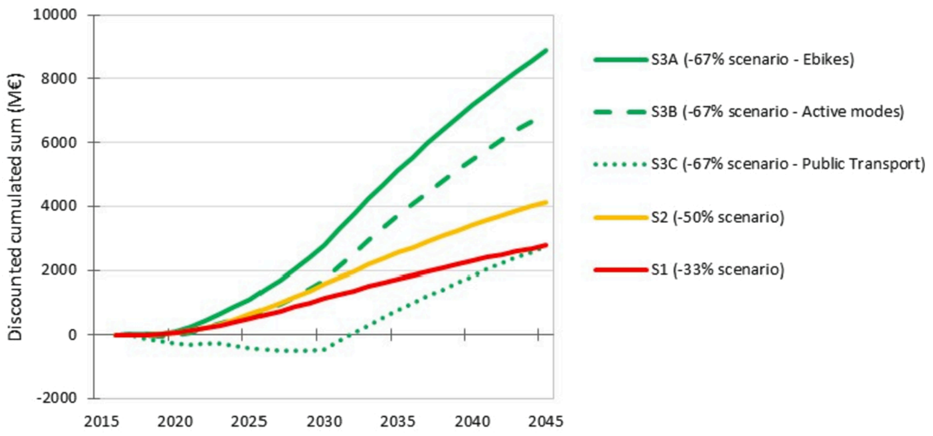

Fig. 6. Time profile of the discounted sum of benefits and costs for each of the five considered scenarios (Million €, 2017–2045 period).

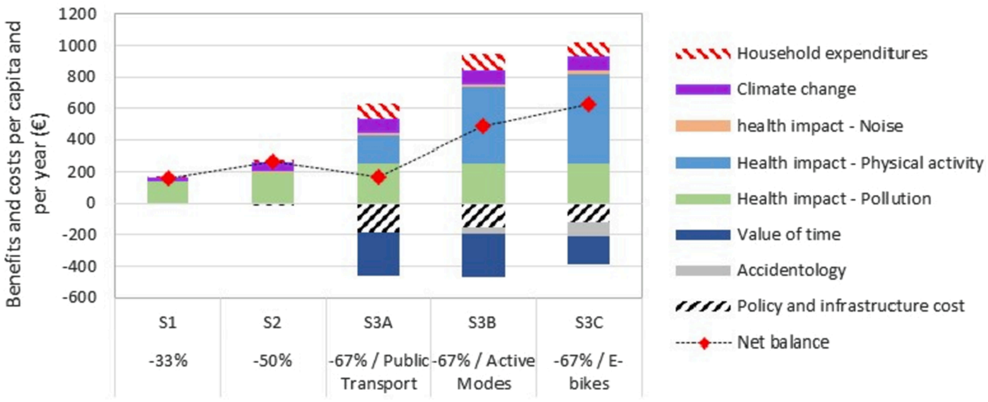

Fig. 7. Result of the cost-benefit analysis per year and per capita for each of the five considered scenarios (S1: –33% in $PM_{2.5}$-related mortality, S2: −50%; S3: −67%; see Table 3 and Fig. 3 for the definition of scenarios).

car. Even though some trips considered transferable to alternative modes are not transferable because of characteristics such as age or reason for travel, other trips that we did not consider transferable because we have limited ourselves to the median threshold are in fact transferable. The objective here was not to give one single good answer but a range of possibilities to achieve a substantial reduction (-36%) in motorized vehicle.km, anchoring the alternatives on one or other of the modes of transport (active modes, E-bikes).

The public transport scenario led to a strong modal shift to public transport, which could not be absorbed by current or even possibly future infrastructure, due to financial and land-use constraints, according to the local stakeholders. This sub-scenario, purely based on a statistical description of the Household Travel Survey (2010), also did not include the fast-developing E-bikes, nor carpooling. To address these limitations, the two alternative scenarios were constructed and evaluated, in particular, one interesting feature of the E-bikes sub-scenario is the stability in the public transport modal share compared to the reference, which helps limiting infrastructure costs.

Finally, it would be useful to complement the definition of alternative modal distribution scenarios induced by the implementation of a LEZ with an impact assessment on the utilization rate of transport infrastructures.

4.2.2. *Validity of health impact assessment*

The validity of health impact assessment studies strongly depends on input parameters, namely exposure data, concentration–response functions, and health outcomes data. Concerning the exposure data, we used the fine-scale (10-m grid) air pollutant-dispersion SIRANE model, based on a network street approach allowing to evaluate air pollutant concentrations inside streets in urban canopy. In addition to the primary validation of the SIRANE model (Soulhac et al., 2012), a validation of model estimates is routinely conducted with Delta Tool (EU's Joint Research Centre, 2019). The very fine spatial resolution is a major strength, as relying on less fine models can lead to underestimating of health impacts (Morelli et al., 2016). We developed a specific approach (MECANO) allowing to estimate the impact of various reductions of emissions in the traffic and residential heating sectors on the $PM_{2.5}$ population-weighted exposure, as illustrated Fig. 2. This approach allowed to quickly provide a set of combinations of emission reductions in each sector entailing a given change in $PM_{2.5}$ exposure, and thus likely to reach the targeted health improvement, or beyond. We have checked its validity for the most ambitious scenario considered by running the dispersion model with the emission reductions identified by MECANO, and obtained a very low difference (0.01 $\mu g/m^3$), not raising concern regarding the validity of MECANO approach.

We exclusively relied on *meta*-analytical risks, which reflect the whole evidence of the literature and are likely to be more robust and less biased than relative risks from individual studies. We assumed these concentration–response functions to be linear, which seemed to be reasonable for air pollution effects within the exposure range in this study (Burnett et al., 2018). Woodcock et al., 2011 showed that the slope of the relationship of physical activity to mortality flattened for long durations of physical activity; with regard to the increases in physical activity expected under our mobility scenarios, we used the relative risks estimated in starting ranges of MET.hours. In the absence of specific dose–response functions regarding E-bikes, we applied the relative risks established for cycling while using E-bikes-specific MET and speed.

Another strength of our health impact assessment consists in the reliability of the health data sources, namely national institutions for public health and for road safety as well as the national health insurance system. Although non-accidental mortality rates and traffic injury cases could be obtained at the municipality scale, lung cancer and cardiovascular diseases incidence data were available at the local scale (the *department*), which might give more weight to random spatial fluctuations than for the formers. Lastly, we focused on the main health outcomes related to air pollution exposure; given the existence of other health conditions possibly associated with air pollution (e.g., breast cancer, mental disorders, diabetes mellitus…) (White et al., 2018; Buoli et al., 2018; Eze et al., 2015), the total health benefit and related economic savings are probably underestimated.

4.2.3. *Assumptions related to the cost-benefit analysis*

Several assumptions should be subjected to a sensitivity analysis: the intangible costs, in particular the value of human life, whose values vary considerably in the literature (Chanel et al., 2020), the value of time (VoT) specific to each mode of transport, the external costs for noise, climate change (since the social value of carbon is the subject of lively academic debates (Pindyck, 2019) and the discount rate suitable to deal with environmental issues, whose choice has a significant impact on the valuation of future benefits (Guesnerie and Stern, 2012).

The promotion and deployment of alternatives to the car will profoundly change the context in which the determinants of mobility choices will apply. The values of a certain number of behavioral and economic parameters used in this study will evolve under the effect of a change in context. The aggregate impact of modal shifts on the valuation of time spent in transport is a key determinant of the results of the cost-benefit analysis. The values taken here are based on literature and on the current valuation of this time as it is perceived today with urban transport infrastructures that are still largely oriented towards the private car and not very well adapted to cycling. It is likely that the adaptation of infrastructures and the development of bicycle paths truly separated from the roadways reserved for cars and of bicycle highways will change the perception of the time spent cycling, and thus decrease its valuation. Therefore, the perceived value of time can vary significantly between individuals, depending on their relationship to active modes of transport. Furthermore, in the sub-scenarios in which the modal shift toward active modes was highest, we can reasonably assume that the last people to adopt these modes are those who enjoy it least, and thus who have a higher value of time when traveling by active modes. However, we also assumed a learning effect of active modes of transport and a reduction in car traffic, and thereby a growing pleasure, which will reduce the perceived value of time spent cycling. The two effects could compensate each other and lead to average time values for cycling not very far from the current values found in the literature.

4.3. *Involvement of local decision-makers in the definition of health objectives used to define urban policies*

The participatory approach developed as part of the MobilAir project has made it possible to involve the elected representatives of the local urban authority in the project, with the aim of encouraging the appropriation of the study results by decision-makers, and the implementation of the necessary urban policies. In particular, local decision-makers defined the health objectives. This was done as part of a process of exchange between the research consortium and the services and elected officials of the local authority. The smooth running of the project and its success required interactions with decision-makers to identify and discuss the relevance of sectoral measures on an urban scale on road traffic or wood heating. This took the form of a committee including high-level decision-makers that met once a year, in addition with more frequent meetings of the scientists with lower-level technical staff. During the first decision-makers' committee, we presented the health impact of air pollution in the urban area, the general objectives of the project as well as the first results on the contribution of the main sectors emitting PM and their geographical origin. Following the first committee, the decision-makers asked the research consortium to study in detail three health objectives (the –33%, −50% and −67% reductions in $PM_{2.5}$-related mortality). On this basis, an exploration of sectoral measures in relation to these health objectives was carried out and presented to the second committee of decision-makers. Following this, the elected representatives asked to explore and evaluate the scenarios of urban policies presented here.

4.4. *Interactions between climate change and air pollution*

Interactions between climate change and PM-related air pollution are complex and numerous (von Schneidemesser et al., 2015). Synergies and antagonisms exist between policies to reduce pollution and policies to reduce greenhouse gases. It is important that policies implemented to reduce PM-related pollution do not lead to increases in greenhouse gases, and vice-versa. The case of wood heating, using a renewable energy but emitting fine particulate matter if old stoves are used, provides an illustration of the related challenges.

5. Conclusion

This inter-disciplinary work between epidemiologists, air pollution modelers and economists aimed at defining and evaluating scenarios of urban policies to significantly reduce air pollution and its impacts. To our knowledge, such a reverse and forward approach has not previously been carried out at the city or national level.

We showed that the most ambitious scenarios in terms of targeted health improvement were also the most interesting from an economic point of view, particularly if the urban policies lead to strong increases in active mobility, the health benefits thereof proving to be much greater than those directly induced by the reduction of air pollution. The policies allowing to achieve these objectives were realistic, relying on behavioral mobility changes that are also realistic.

Policies simultaneously relying on the full replacement of highly polluting wood-heating facilities and shifts from private car to bike mobility for short trips are likely to allow benefits of 4.2 to 6 Euro for each Euro invested and generate net annual benefits per person of €484 to €629.

CRediT authorship contribution statement

Hélène Bouscasse: Conceptualization, Formal analysis, Writing – original draft. **Stephan Gabet:** Conceptualization, Formal analysis, Writing – original draft. **Glen Kerneis:** Formal analysis, Writing – original draft. **Ariane Provent:** Methodology. **Camille Rieux:** Methodology. **Nabil Ben Salem:** Methodology. **Harry Dupont:** Methodology. **Florence Troude:** Methodology, Writing – original draft. **Sandrine Mathy:** Conceptualization, Writing – review & editing. **Rémy Slama:** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2021.107030.

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