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Health benefits of traffic-related air pollution reduction in different socioeconomic groups: the effect of low-emission zoning in Rome

Giulia Cesaroni,1 Hanna Boogaard,2 Sander Jonkers,3 Daniela Porta,1 Chiara Badaloni,1 Giorgio Cattani,4 Francesco Forastiere,1 Gerard Hoek2

ABSTRACT

Objectives Few studies have assessed the effects of policies aimed to reduce traffic-related air pollution. The aims of this study were to evaluate the impact, in terms of air quality and health effects, of two low-emission zones established in Rome in the period 2001–2005 and to assess the impact by socioeconomic position (SEP) of the population.

Methods We evaluated the effects of the intervention on various stages in the full-chain model, that is, pressure (number and age distribution of cars), emissions, PM10 and NO2 concentrations, population exposure and years of life gained (YLG). The impact was evaluated according to a small-area indicator of SEP.

Results During the period 2001–2005, there was a decrease in the total number of cars (−3.8%), NO2 and PM10 emissions and concentrations (from 22.9 to 17.4 g/m³ for NO2 and from 7.8 to 6.2 µg/m³ for PM10), and in the residents’ exposure. In the two low-emission zones, there was an additional decrease in air pollution concentrations (NO2: −4.13 and −2.99 g/m³, PM10: −0.70 and −0.47 µg/m³). As a result of the policy, 264 522 residents living along busy roads gained 3.4 days per person (921 YLG per 100 000) for NO2 reduction. The gain was larger for people in the highest SEP group (1387 YLG per 100 000) than for residents in the lowest SEP group (340 YLG per 100 000).

Conclusion The traffic policy in Rome was effective in reducing traffic-related air pollution, but most of the health gains were found in well-off residents.

The literature on the detrimental effects of traffic air pollution on health has grown considerably in the last decade.1 Recently, the debate on the possible differential effects of air pollution exposure in different socioeconomic groups of the population has raised environmental justice concerns.2–4 In American and European cohort studies, educational level has been shown to modify the effect of exposure to particulate matter on mortality, with higher risks among people with lower educational level.2–11 According to the Italian Institute for Environmental Protection and Research, motorised road traffic is the source of 44% of the NO2 and 26% of the PM10 emissions in Italy.12 In the city of Rome, these percentages raise to 80% and 52%.13 The European Union has set standards for ambient air quality to protect the health of European citizens. National policies related to air quality are focused on economic instruments like fuel taxation and subsidies to replace old with new less-polluting vehicles. At the local level, traffic measures are being implemented like congestion charges, environmental zoning designed to limit traffic of polluting vehicles, monetary subsidies to accelerate replacement of old cars and measures to promote public transport and cycling.

Studies that have evaluated the effects of traffic policies are still limited; the majority of them indicate a decrease in emissions or concentrations of air pollutants, but only a few have analysed the effects on both air quality and health.14–21 The traffic congestion reduction during the 1996 Olympic Games in Atlanta was associated with a decreased traffic density, a reduction in ozone concentrations, lower rates in childhood asthma events and a small decrease in emergency department visits.17,18 Similar results were reported during the 2002 Summer Asian Games in South Korea.19 Using modelling and GIS data, Tonne et al.14 estimated a small reduction in NO2 and PM10 concentrations and a gain of 188 years of life per 100 000 people after the Congestion Charging Zone (CCZ) introduced in London in 2003. After the implementation of road pricing policy in Stockholm, there was a 8.5% decrease in NO2 emissions, a 13% decrease in PM10 emissions and a gain of 206 years of life per 100 000 people.20 Assuming the same concentration–response function (CRF) for low and high socioeconomic groups, the study conducted in London indicated that the

What this paper adds

- Few studies have evaluated the impact of traffic policies on both air quality and health.
- Policies affect the intervention zones, and reductions in NO2 are larger than those in PM10.
- In Rome, the low-emission zoning had a small impact on years of life gained at the city level but had a large impact in the intervention area.
- The high socioeconomic position population benefited more from the policy than low socioeconomic groups.
- The low-emission zone in Rome was beneficial from a public health point of view for all socioeconomic groups of the population, but it also exacerbated social inequalities.

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congestion charging scheme was associated with a small reduction in socioeconomic inequalities in exposure to traffic-related air pollution and in mortality.14

The aims of this study were to evaluate the impact, in terms of air quality and health effects, of the intervention implemented by the City Council of Rome (two low-emission zones) in the period 2001–2005 to reduce traffic-related air pollution and to examine whether the impact was different by socioeconomic position (SEP). We evaluated the sensitivity of the results by the use of a single or SEP-specific CRFs.

METHODS
This study was conducted within the INTARESE (Integrated Assessment of Health Risks of Environmental Stressors in Europe) project.22 Briefly, INTARESE uses a full-chain approach to assess the effects of policies on indicators of health. Policies are evaluated on the basis of mean population health gain and also on indicators of the social distribution of that gain. We evaluated the effects of policy intervention on various stages of the full-chain model, that is, pressures (number of cars, age distribution of cars, number of kilometre driven), emissions, PM10 and NO2 concentrations, population exposure to PM10 and NO2 by SEP of the residents and health effects.

The urban layout of Rome
Rome is the largest Italian city, with 2.7 million inhabitants in a 1285 km² area. The urban area is divided into five concentric circular zones, corresponding with different levels of urbanisation, population density and transportation. The historical centre, which corresponds to the limited traffic zone (LTZ) (55 000 inhabitants over an area of 6 km²), shows the highest concentration of business activity in Rome. The central railway ring area (597 000 inhabitants, 59 km²) has the highest population density and represents a great deal of business activity. The semi-central Green Strip area (944 000 inhabitants, 111 km²) is characterised by medium business density and high population density. The peripheral area covers the rest of the city that falls within the external ring road (Main Ring Road) (729 000 inhabitants, 189 km²). Business and residential density are lower than in the previous areas. The last area includes all the districts outside the main ring road (626 000 inhabitants). Unfortunately, the radial system of public transportation has not been sufficiently developed. In 2001, pedestrian and public transport shared only 40% (20% each) of the total mobility, while 60% of the trips were by private transport; in the historical centre, traffic is 34% pedestrian, 29% public transport and 37% private transport (including cars, motorcycles and mopeds). The map of Rome indicating the circular zones and high-traffic roads (HTRs) (>10 000 vehicles per day) is shown in figure 1.

The intervention
The intervention was implemented in two city areas: the central LTZ and the railway ring. Driving in the LTZ, since October 2001, has been prohibited to all vehicles from 06:30 till 18:00 on Monday through Friday and from 14:30 till 18:00 on Saturday. The system uses fully automatic checks with cameras that record vehicles that enter and exit the zone, with expensive fines automatically issued to those who enter illegally. Only authorised vehicles (residents’ cars, commercial vehicles and public transport vehicles) can enter at any time.

In the railway ring area, the intervention was implemented between 2002 and 2003 and enforced using expensive fines. Starting in January 2002, old diesel vehicles were not allowed in the area (during the daytime); starting in July 2002, only vehicles with a catalytic converter were allowed in the area (during the daytime), and from January 2003 at any time of day.

The overall goal of the policy was to reduce the number of private vehicles in the centre, to encourage the use of public transport and to facilitate replacement of old heavily polluting vehicles. The intervention has been coupled with national policies to provide monetary incentives to buy new less-polluting vehicles.

Pressures
The impact of the policy on number and type of vehicles was evaluated using data from 2001 to 2005 derived from the national automobile association (http://www.aci.it). The data were of total number of vehicles by type (moped, motorcycles, cars, buses, light duty vehicles, heavy duty vehicles), type of fuel (gasoline, diesel, LPG or methane) and Euro classification categories (Euro 0, 1, 2, 3, 4) city-wide. The Euro classification category corresponds to the level of emissions of motor vehicles indicated by European directives.23 To evaluate whether these indicators changed because of the intervention or due to autonomous time trends, we have compared the Rome indicators with regional statistics (central Italy without Rome).

Policy evaluation
The evaluation of the policy was made by considering a diverse traffic composition in the area of intervention compared to the other areas of the city. This was done because the intervention prohibited access of the most pollutant vehicles to the low-emission zones. First, a ‘without policy scenario’ was considered on the basis of the known car fleet of the city, without taking into account the policy. Second, an ‘optimistic scenario’ was evaluated assuming that there would no longer be any Euro
0 cars in the railway ring area, all would be replaced with Euro 4 cars. Finally, a ‘pessimistic scenario’ was evaluated that considered 10% of the Euro 0 cars were still circulating within the railway ring area, and 90% of the Euro 0 cars in the target area were replaced by Euro 1–4 type cars (according to the proportion of the city car fleet in 2005).

### Emissions

A software program (Copert III) developed for the European Environmental Agency was used for the calculation of emissions from the road transport sector. Air pollution emission factors were applied to all vehicles in circulation between 2001 and 2005 in order to determine average emission values for each year. For the year 2005, three sets of average fleet emission values were estimated: the without policy scenario emissions, the optimistic scenario emissions and the pessimistic scenario emissions. In appendix 1 (online only), we describe in detail the methods used to estimate these emission factors.

### Concentration of air pollutants

Concentrations were calculated only for HTRs (>10 000 vehicles per day) using a local-scale dispersion model. We assumed that background concentrations were not affected by the policy. Emission factors, traffic volume and street geometry properties were used as input for the dispersion modelling of PM10 and NO2 at the street level with the CAR-2 model. The CAR-2 model assesses the contribution of traffic on a specific street for each pollutant. The model does not take nearby streets into account. The NO2 contribution is calculated from the NOX contribution, using the background ozone concentration and an empirical chemical conversion formula. To calculate the concentration contribution from road traffic, the CAR-2 model was applied to calculate the normalised concentration contribution, that is, the average concentration contribution per vehicle. It was then multiplied by the number of vehicles per day on a specific street in order to get the concentration contribution in micrograms per cubic metre, and it was calculated for 1560 distinct road characteristics (5 road types, 3 tree densities, 26 widths and 4 traffic compositions).

The City Council of Rome provided the traffic data for all major roads in Rome as of 2005 (6585 road segments, 26% of all roads in Rome), including the HTRs (2228 segments, 9.7% of all roads in Rome). For each HTR segment, we had data on the number of vehicles circulating, the circular zone and the neighbourhood in which it is located, the segment’s width, length, the street type and tree density. More detailed methods are available in appendix 2 (online only).

We collected and stored all geographical variables using ArcGis 9.1 (ESRI, Redlands, California, USA). We used the Word Geodetic System of 1984 with the Universal Transverse Mercator 33N as the coordinate system and map projection (http://www.teleatlas.com).

### Population exposures

Data on residents of Rome in 2001 and 2005 were obtained from the Municipal Registry Office. We geocoded each residential address using the Italian road network (Tele Atlas, Italy), and for each address, we measured the distance to the nearest HTR. We considered the 264 522 residents living at a distance of ≤50 m to the nearest HTR as the study population. We also assessed the exposure of the 1077 460 subjects who live at a distance ≤150 m to the nearest HTR. For each subject, we assigned the exposure estimate to traffic-related PM10 and NO2 produced by the CAR-2 model.

As an index of SEP, a 5-level index by census block (average population: 500 subjects) was used. The study population was divided by the residential zones and by SEP.

### CRFs for PM10 and NO2

We assumed a linear relationship between the air pollutants and associated health effects since most epidemiological studies on large populations have been unable to identify a threshold concentration below which ambient air pollutants have no effect on morbidity and mortality. CRFs were derived from cohort studies from both the USA and Europe. Estimates were derived from a meta-analysis with a fixed-effects inverse-variance weighted method. See online table 1 for the individual studies. Summary CRFs expressed per 10 µg/m3 for PM2.5 and NO2 were 1.06 (95% CI 1.03 to 1.09) and 1.06 (95% CI 1.04 to 1.08), respectively. As the policy affects tailpipe emissions only, which are in the fine particle mode, the change in PM10 modelled by the dispersion involves particles smaller than 2.5 µm. We therefore used the CRF for PM2.5 directly and multiplied that with the change in modelled PM10 (the model did not calculate PM2.5).

In addition, we calculated three different CRFs based on three educational levels (primary school, secondary school, and post secondary). The summary estimates were based on the original extended ACS study, the reanalysis of the six-city study and the Dutch cohort study (see online table 2). The summary CRFs expressed per 10 µg/m3 for PM2.5 and NO2 were 1.10 (95% CI 1.05 to 1.16), 1.08 (95% CI 1.05 to 1.15) and 1.05 (95% CI 1.02 to 1.09) for low, average and high SEP categories, respectively. There were insufficient studies to derive SEP-specific CRFs for NO2.

### Quantification of mortality impacts

The impact the traffic policies had on mortality in 2005 according to the optimistic and pessimistic scenarios were estimated in terms of years of life gained (YLG). We applied CRFs to all ≥50-year-old residents who live at a distance ≤50 m from HTRs. Baseline mortality rates by 1-year age groups of the Rome population were used. When the analysis was conducted by SEP, the SEP-specific mortality rates for Rome were considered. Population exposure to traffic-related PM10 and NO2 in 2001 and in 2005 (with and without application of the policy) was calculated by circular zone and SEP group. For the purpose of comparing circular zones and SEP groups, YLG were calculated per 100 000 people over 15 years following the implementation of the intervention (2006–2020).

Sensitivity analyses were conducted to evaluate the robustness of the results. First, we used different CRFs by SEP for PM10 exposure. Then, we considered not only the subjects living along the HTRs (for whom exposure assessment was more straightforward with the CAR-2 model) but also for the entire population who live at a distance of ≤150 m of an HTR. We estimated exposure to traffic-related PM10 and NO2 as follows:

1. For people living at a distance of ≤30 m of an HTR, we assigned the value exactly estimated with the CAR-2 model.
2. For people living at a distance between 30 and 100 m of an HTR, a factor of 0.7 was applied to the estimated contribution of the CAR-2 model. This was done based on experimental observations of the rapid decay of these pollutants from the source.
3. For people living at a distance between 100 and 150 m of an HTR, a factor of 0.5 was applied to the estimated contribution of the CAR-2 model of the closest HTR.

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RESULTS

Traffic composition 2001—2005 in Rome

The total number of cars decreased slightly in Rome between 2001 and 2005 (−3.8%), but this was also observed in central Italy excluding Rome (−15.1%) and hence is likely not a result of the policy. The decrease of Euro 0 petrol cars and the increase of Euro 5 cars were substantially greater in Rome than in central Italy, which may be an effect of the policy or may reflect other differences between Rome and central Italy (online table 3).

Emission factors

We calculated emission factors by vehicle type and year according to the two scenarios (online table 4). In the Without policy scenario, the average emission factors for the fleet of public buses, heavy and light duty vehicles, mopeds, motorcycles and passenger cars decreased in Rome between 2001 and 2005, and the effect was stronger for NO\textsubscript{2} (for cars: from 1.06 to 0.78 g/km) than for PM\textsubscript{10} (for cars: from 0.079 to 0.067 g/km). As a result of the policy, under the optimistic scenario in 2005, there was a further reduction of the emission factors for passenger cars in the railway ring area (NO\textsubscript{2}: 0.45 g/km, −58%; PM\textsubscript{10}: 0.053 g/km; −53%).

Changes in concentrations

When emission factors were used in the CAR-2 model, the traffic-related contribution to PM\textsubscript{10} and NO\textsubscript{2} was estimated for each circular zone (Table 1). The traffic contribution to NO\textsubscript{2} and PM\textsubscript{10} decreased from 2001 to 2005 (without policy) by 24% and 21%, respectively. In 2005, there was an additional small reduction in the average concentration of NO\textsubscript{2} (−2%) and PM\textsubscript{10} (−1%) related to the intervention (both under the optimistic and pessimistic scenarios) across the city, assuming no changes outside the intervention area. The impact was sizeable when considering the intervention area, with a further 25% reduction in NO\textsubscript{2} and 10% in PM\textsubscript{10} in the railway ring area, under the optimistic scenario.

The difference between the two scenarios was slight. This was due to the large difference in Euro 0 emission factors compared to Euro 1−4. Therefore, the main impact on concentration contributions resulted from the removal of Euro 0 vehicles from the roads. The class of the replacement car was of lesser importance.

Changes in population exposure and related health effects

Table 2 shows the average population-weighted annual exposure to traffic-related NO\textsubscript{2} and PM\textsubscript{10} for 264,522 subjects living along HTRs and their impact in terms of YLG.

Due to the changes in the car fleet, without taking account of the policy, the average exposure decreased from 2001 to 2005 (from 24.1 to 18.4 μg/m\textsuperscript{3} for NO\textsubscript{2}, and from 8.7 to 6.8 μg/m\textsuperscript{3} for PM\textsubscript{10}). This decrease affected much of the central part of the city (residents along an HTR outside the main ring road had a decrease of only 3.17 μg/m\textsuperscript{3} of exposure to NO\textsubscript{2} compared to an average of 5.54 μg/m\textsuperscript{3} for residents in the city centre).

The intervention had an impact on the exposure of the residents in Rome living along HTRs: in the optimistic scenario for NO\textsubscript{2}, there was a further overall decrease of 0.78 μg/m\textsuperscript{3} due to an additional decrease of 3.27 and 4.02 μg/m\textsuperscript{3} in the railway ring and in the LTZ areas, respectively.

In Rome, 22% of residents along HTRs are also in a high SEP area, while only 14% are in a low SEP area. There were no differences between baseline concentrations in different socioeconomic groups, and the average NO\textsubscript{2} exposure decreased from 2001 to 2005 by 5−6 μg/m\textsuperscript{3} in all groups. However, considering the policy, the highest NO\textsubscript{2} difference was observed in the highest socioeconomic group (−1.21 μg/m\textsuperscript{3} vs −0.29 μg/m\textsuperscript{3} in the lowest socioeconomic group under the optimistic scenario).

All residents along HTRs were predicted to gain 2456 years, that is, 921 years of life per 100 000 (average gain per person: 3.4 days) from the optimistic scenario reduction in NO\textsubscript{2}, and 1812 years, that is, 685 years per 100 000 (average gain per person: 2.5 days) were gained from the pessimistic scenario. This gain was seen in the railway ring and LTZ areas (with 15 and 19 days per person, respectively). The highest socioeconomic group benefited most from the policy (1587 YLG vs 340 YLG per 100 000 in the optimistic scenario due to the reduction in NO\textsubscript{2} exposure). For subjects living along an HTR, the optimistic and pessimistic reductions in PM\textsubscript{10} exposure resulted in 153 YLG and 130 YLG per 100 000, respectively, substantially less than estimated for NO\textsubscript{2}, but consistently four times greater for the highest compared to the lowest socioeconomic group.

Table 3 shows the impacts of PM\textsubscript{10} air pollution on YLG in Rome on the population living along an HTR by SEP using SEP-specific CRFs. The difference in the health gains seen in high and low SEP groups is smaller than that shown in table 2. The greatest gain was obtained by the two highest socioeconomic groups, but the social gradient of the effect was attenuated compared to the results we obtained using a single CRF.

Table 4 shows the population-weighted exposure to traffic-related NO\textsubscript{2} and PM\textsubscript{10} for those living at a distance ≤150 m of HTRs. This illustrates the potential for additional health gains for a larger population living near (n=1077 460) but not necessarily on an HTR (n=264 522). The gain in life expectancy was due to the reduction in the average population-weighted annual

| Table 1: Modelled average traffic contribution along HTRs (>10 000 vehicles circulating per day) to the annual average of NO\textsubscript{2} and PM\textsubscript{10} concentrations (in micrograms per cubic metre) by circular zone in Rome |

<table>
<thead>
<tr>
<th>Circular zone</th>
<th>Number of segments with traffic data</th>
<th>Length of segments (m)</th>
<th>Number of HTR segments</th>
<th>Length of HTR segments (m)</th>
<th>2001 NO\textsubscript{2}</th>
<th>2001 PM\textsubscript{10}</th>
<th>2005 without policy scenario NO\textsubscript{2}</th>
<th>2005 without policy scenario PM\textsubscript{10}</th>
<th>2005 with optimistic policy scenario NO\textsubscript{2}</th>
<th>2005 with optimistic policy scenario PM\textsubscript{10}</th>
<th>2005 with pessimistic policy scenario NO\textsubscript{2}</th>
<th>2005 with pessimistic policy scenario PM\textsubscript{10}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside main ring</td>
<td>2004</td>
<td>1 323 052</td>
<td>543</td>
<td>463 192</td>
<td>21.3</td>
<td>6.8</td>
<td>16.2</td>
<td>5.5</td>
<td>16.2</td>
<td>5.5</td>
<td>16.2</td>
<td>5.5</td>
</tr>
<tr>
<td>Main ring</td>
<td>1147</td>
<td>541 428</td>
<td>459</td>
<td>214 046</td>
<td>22.9</td>
<td>7.6</td>
<td>17.4</td>
<td>6.1</td>
<td>17.4</td>
<td>6.1</td>
<td>17.4</td>
<td>6.1</td>
</tr>
<tr>
<td>Green strip</td>
<td>1584</td>
<td>472 273</td>
<td>710</td>
<td>202 360</td>
<td>26.3</td>
<td>9.7</td>
<td>20.2</td>
<td>7.6</td>
<td>20.2</td>
<td>7.6</td>
<td>20.2</td>
<td>7.6</td>
</tr>
<tr>
<td>Railway ring</td>
<td>1653</td>
<td>292 502</td>
<td>501</td>
<td>96 913</td>
<td>23.3</td>
<td>9.3</td>
<td>17.7</td>
<td>7.2</td>
<td>13.6</td>
<td>6.5</td>
<td>14.7</td>
<td>6.6</td>
</tr>
<tr>
<td>Limited traffic zone</td>
<td>201</td>
<td>35 771</td>
<td>15</td>
<td>2938</td>
<td>19.7</td>
<td>6.5</td>
<td>14.8</td>
<td>5.1</td>
<td>13.6</td>
<td>4.6</td>
<td>12.5</td>
<td>4.7</td>
</tr>
<tr>
<td>Total</td>
<td>6589</td>
<td>2 665 026</td>
<td>2228</td>
<td>978 447</td>
<td>22.9</td>
<td>7.8</td>
<td>17.4</td>
<td>6.2</td>
<td>17.0</td>
<td>6.1</td>
<td>17.1</td>
<td>6.1</td>
</tr>
</tbody>
</table>

*We assumed that traffic composition only changed in the Railway ring and in the limited traffic zone, HTR, high-traffic roads.*

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exposure in the LTZ and in the railway ring areas. These resulted in 686 YLG per 100 000 for NO2 reduction and 116 YLG per 100 000 for PM10 reduction in the population living at a distance of ≥150 m of an HTR. Considering the city as a whole, the gain was greater in the highest than in the lowest SEP group. Patterns observed with respect to zone and SEP were as observed for the HTR population.

DISCUSSION

The policy resulted in 53% and 58% lower PM10 and NO2 emissions from passenger cars in the intervention area. Changes in concentrations of NO2 and PM10 were modest city-wide (<1 μg/m3), but larger reductions were estimated in the intervention area. Predicted changes were larger for NO2 than for PM10, consistent with the known impact of traffic on this pollutant.13 14

Consistent with the modest change in air pollution concentrations, the policy resulted in small gains in life expectancy at the city level (3.4 days on average per person living at a distance of ≤50 m from HTR). Life expectancy gains were substantially larger when they were calculated for the population in the intervention area (19 and 15 days gained per resident in the LTZ and in the railway ring areas, respectively). Because of the geographical distribution of SEP within the city, the decrease in annual air pollution exposure was larger in the highest socioeconomic group. Despite higher baseline mortality rates in the lowest socioeconomic group, the gain in life expectancy was more substantial in the high socioeconomic groups. Socioeconomic differences were less marked in life expectancy gains when we used SEP-specific CRFs for PM10.

The small gain at the city level is very likely an underestimation of the true impact of the policy change. In fact with the modelling tools available, we only evaluated impacts of the policy on HTRs, assuming that there was no impact on urban background levels. Even though the impact on background conditions was probably very small, there are many people who are affected by background levels. Moreover, due to constraints in emission data, air pollution dispersion models and CRFs, we limited the assessment to NO2 and PM10. These pollutants are not the most specific indicators of the complex mixture of emissions from motorised traffic. The impact of the intervention on concentrations of ultrafine particles, soot and possible polycyclic aromatic hydrocarbons may have been more substantial. Furthermore, we only assessed impacts on residents and ignored

### Table 2
Changes in average population-weighted annual exposure to air pollution (NO2 and PM10, in micrograms per cubic metre) and associated impacts as YLG according to circular zone and SEP in subjects living along HTRs

<table>
<thead>
<tr>
<th></th>
<th>NO2 2001</th>
<th>PM10 2001</th>
<th>Difference with/without policy 2005 optimistic scenario</th>
<th>Difference with/without policy 2005 pessimistic scenario</th>
<th>Residents 2005 along HTR</th>
<th>Mortality rates per 100 000 population</th>
<th>YLG per 100 000 during 15 years optimistic scenario</th>
<th>YLG per 100 000 during 15 years pessimistic scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NO2</td>
<td>PM10</td>
<td>NO2</td>
<td>PM10</td>
<td>NO2</td>
<td>PM10</td>
<td>NO2</td>
<td>PM10</td>
</tr>
<tr>
<td>Outside main ring</td>
<td>12.86</td>
<td>3.47</td>
<td>9.69</td>
<td>2.85</td>
<td>0</td>
<td>0</td>
<td>19.661</td>
<td>924</td>
</tr>
<tr>
<td>Main ring</td>
<td>22.76</td>
<td>7.51</td>
<td>17.3</td>
<td>6.07</td>
<td>0</td>
<td>0</td>
<td>59.230</td>
<td>924</td>
</tr>
<tr>
<td>Green strip</td>
<td>28.76</td>
<td>8.85</td>
<td>20.8</td>
<td>7.89</td>
<td>0</td>
<td>0</td>
<td>123.401</td>
<td>924</td>
</tr>
<tr>
<td>Railway ring</td>
<td>23.49</td>
<td>9.07</td>
<td>17.84</td>
<td>7.01</td>
<td>−3.27</td>
<td>−0.54</td>
<td>−2.42</td>
<td>−0.45</td>
</tr>
<tr>
<td>Limited traffic zone</td>
<td>23.52</td>
<td>9.13</td>
<td>17.9</td>
<td>7.12</td>
<td>−4.02</td>
<td>−0.68</td>
<td>−2.97</td>
<td>−0.57</td>
</tr>
</tbody>
</table>

By SEP

1 (high) 23.92 8.69 18.22 6.76 −1.21 −0.20 −0.90 −0.17 57.733 854 1387 229 1031 194
2 25.33 9.25 19.36 7.23 −1.00 −0.17 −0.74 −0.14 61.174 933 1167 198 863 163
3 24.53 8.77 18.79 6.89 −0.62 −0.10 −0.46 −0.08 63.325 901 733 118 543 95
4 23.70 8.56 18.01 6.67 −0.57 −0.10 −0.42 −0.08 45.180 896 665 115 483 91
5 (low) 22.22 7.83 16.91 6.21 −0.29 −0.05 −0.21 −0.04 37.110 1029 340 59 245 46
Total 24.12 8.70 18.4 6.81 −0.78 −0.13 −0.58 −0.11 264.522 924 921 135 685 130

Baseline mortality rates standardised for age using the total Rome population of 2005. Pre—post differences of 2005 based on population-weighted average concentrations of address data of 264 522 subjects. We have assumed that the difference results in a reduction in hazards for the years 2005 till 2019 based on the CRF of 1.06 per 10 μg/m3 in NO2 or PM10. These CRFs were applied for people aged ≥30 years. HTR: >10 000 vehicles circulating per day. CRF, concentration—response function; HTR, high-traffic road; SEP, socioeconomic position; YLG, years of life gained.

### Table 3
Changes in average population-weighted annual exposure to air pollution (PM10) and associated impacts as YLG according to SEP in subjects living along HTR using SEP-specific CRFs

<table>
<thead>
<tr>
<th></th>
<th>Population</th>
<th>Mortality rates per 100 000 population</th>
<th>Pre—post difference optimistic scenario (PM10)</th>
<th>Pre—post difference pessimistic scenario (PM10)</th>
<th>YLG per 100 000 during 15 years optimistic scenario</th>
<th>YLG per 100 000 during 15 years pessimistic scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>By SEP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 (high)</td>
<td>57 733</td>
<td>854</td>
<td>−0.20</td>
<td>−0.17</td>
<td>191</td>
<td>163</td>
</tr>
<tr>
<td>2</td>
<td>61 174</td>
<td>933</td>
<td>−0.17</td>
<td>−0.14</td>
<td>262</td>
<td>216</td>
</tr>
<tr>
<td>3</td>
<td>63 325</td>
<td>901</td>
<td>−0.10</td>
<td>−0.08</td>
<td>156</td>
<td>125</td>
</tr>
<tr>
<td>4</td>
<td>45 180</td>
<td>896</td>
<td>−0.10</td>
<td>−0.08</td>
<td>151</td>
<td>122</td>
</tr>
<tr>
<td>5 (low)</td>
<td>37 110</td>
<td>1029</td>
<td>−0.05</td>
<td>−0.04</td>
<td>94</td>
<td>75</td>
</tr>
</tbody>
</table>

Baseline mortality rates standardised for age using the total Rome population of 2005. Pre—post differences of 2005 based on population-weighted average concentrations of address data of 264 522 subjects. We have assumed that the difference results in a reduction in hazards for the years 2005 till 2019 based on different CRFs for the different SEP groups. These CRFs were applied for people aged ≥30 years. CRF of 1.05 for the highest SEP group, 1.08 for the three middle groups, and a CRF of 1.10 for the lowest group. HTR: >10 000 vehicles circulating per day. CRF, concentration—response function; HTR, high-traffic road; SEP, socioeconomic position; YLG, years of life gained.
Total 1 077 460 924
change in NO2 concentration was 0.73 in the CCZ versus was also largely restricted to the city centres: in London, the pricing in Stockholm were 206 YLG per 100 000 over 10 years.20

they are exposed more than disadvantaged groups of the popu-
wealthy residents are more likely to live in the city centre, and

5.3% in Greater Stockholm.

In other European studies also the highest air pollution
levels are reported for persons with the highest SEP.28 38

wealthy. In other European studies also the highest air pollution

CONCLUSIONS
This study provides evidence that policies aimed at reducing
traffic-related air pollution have beneficial effects: a decrease of
emissions, of concentrations, of population exposure, and health
gains. The socioeconomic distribution of these effects is not
readily apparent and requires a thorough assessment in view of
current concerns related to environmental justice.

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Competing interests None.

Contributors Each author has contributed to the conception and design of the work, the acquisition of data or the analysis of the data in a manner substantial enough to take public responsibility for it; each believes that the manuscript represents valid work; and each has reviewed the final version of the manuscript and approves it for publication.

Potential benefits to commuters/traffic participants and people who work in the city.

This area are based on PM, given the sensitivity of NOx to

changes in traffic we would recommend using NOx together
with PM for traffic-based evaluations (provided that double
counting is excluded).

Table 4 Changes in average population weighted annual exposure to air pollution (NO2 and PM10, in micrograms per cubic metre) and associated impacts as YLG according to circular zone and SEP in residents within 150 m from HTRs

By circular zone

<table>
<thead>
<tr>
<th>Population</th>
<th>NO2</th>
<th>Mortality rates per 100 000</th>
<th>Pre—post difference optimal scenario (NO2)</th>
<th>Pre—post difference pessimistic scenario (NO2)</th>
<th>YLG per 100 000 during 15 years optimistic scenario</th>
<th>YLG per 100 000 during 15 years pessimistic scenario</th>
<th>PM10</th>
<th>Pre—post difference optimal scenario (PM10)</th>
<th>Pre—post difference pessimistic scenario (PM10)</th>
<th>YLG per 100 000 during 15 years optimistic scenario</th>
<th>YLG per 100 000 during 15 years pessimistic scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside main ring</td>
<td>98 896</td>
<td>924</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Main ring</td>
<td>235 964</td>
<td>924</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Green strip</td>
<td>495 713</td>
<td>924</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Railway ring</td>
<td>225 839</td>
<td>924</td>
<td>−2.50</td>
<td>−1.85</td>
<td>3117</td>
<td>2300</td>
<td>−0.41</td>
<td>−0.34</td>
<td>506</td>
<td>420</td>
<td></td>
</tr>
<tr>
<td>Traffic limited zone</td>
<td>21 048</td>
<td>924</td>
<td>−3.13</td>
<td>−2.32</td>
<td>3362</td>
<td>2483</td>
<td>−0.53</td>
<td>−0.44</td>
<td>563</td>
<td>467</td>
<td></td>
</tr>
</tbody>
</table>

Baseline mortality rates standardised for age using the total Rome population of 2005. Pre—post differences of 2005 based on population-weighted average concentrations of address data of 1 077 460 subjects. We have assumed that the difference results in a reduction in hazards for the years 2005 till 2019 (15 years) based on the CRF of 1.06 per 1 000 000 residents of London.14 Similarly, the benefits for the most deprived, a result of the above-mentioned studies.

This study provides evidence that policies aimed at reducing traffic-related air pollution have beneficial effects: a decrease of emissions, of concentrations, of population exposure, and health gains. The socioeconomic distribution of these effects is not readily apparent and requires a thorough assessment in view of current concerns related to environmental justice.
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Health benefits of traffic-related air pollution reduction in different socioeconomic groups: the effect of low-emission zoning in Rome

Giulia Cesaroni, Hanna Boogaard, Sander Jonkers, Daniela Porta, Chiara Badaloni, Giorgio Cattani, Francesco Forastiere and Gerard Hoek

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