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Air Pollution in Cities

Part 1: Problems and solutions

Dr Audrey de Nazelle

Global Sustainability Summer School

Santa Fe Institute

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Learning outcomes

- Discuss state of air pollution problems around the world
- Identify solutions, but also trade-offs and co-benefits
- Get a sense of the complexity of air quality research and policy
- Propose and evaluate health promoting urban strategies

THE PROBLEM

Air Pollution in Cities

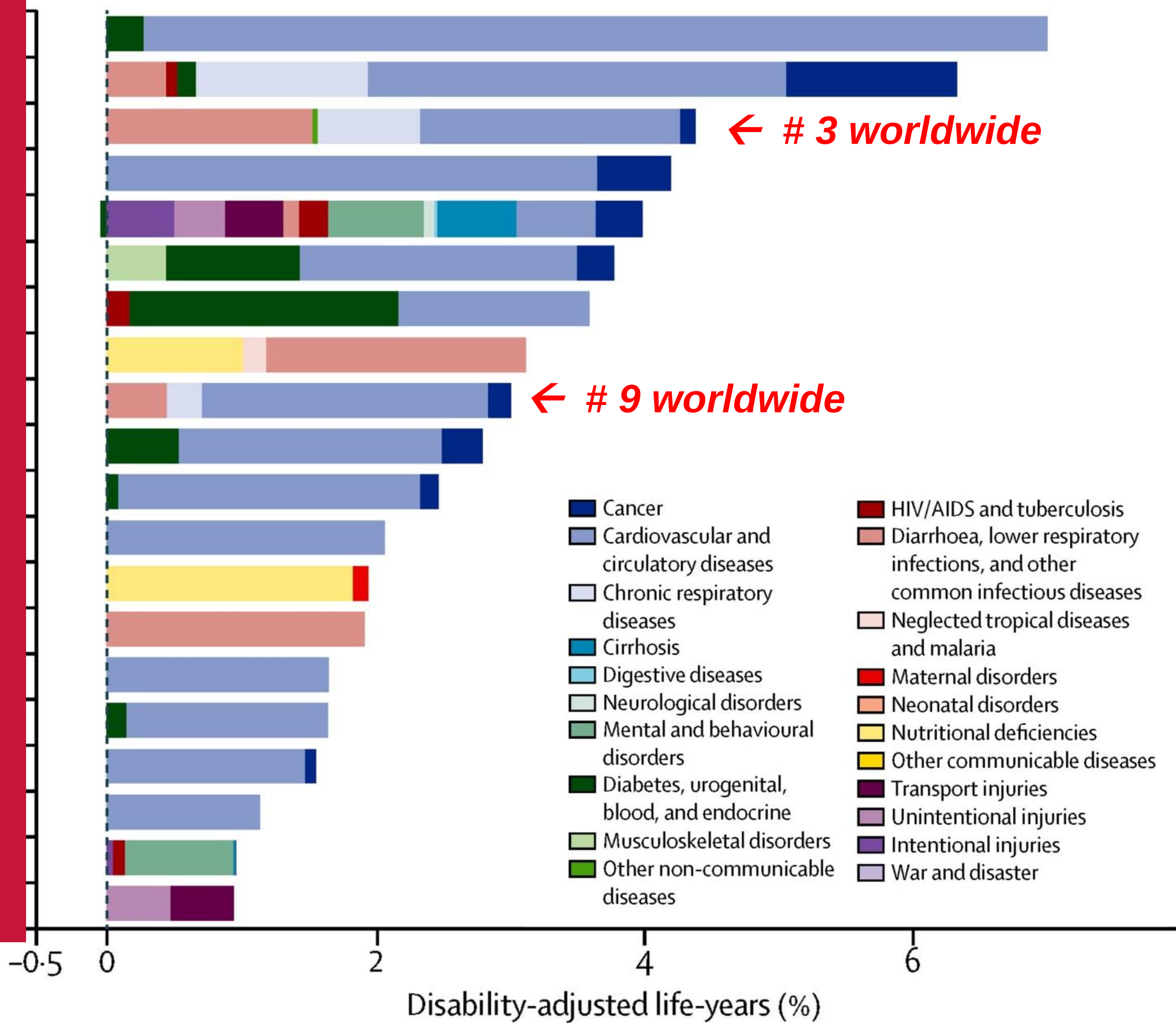
•Today, more than half the world’s population (**54%**) live in urban areas (UN, 2014).

- This number is expected to increase to 66% by 2050.

•More than **80%** of people living in urban areas are exposed to air quality levels that exceed WHO limits (WHO, 2016).

- Populations in low-income cities are the most impacted.
  - » 98% of cities* in low and middle-income countries do not meet WHO levels.
  - » This percentage decreases to 56% in high-income countries.

Global Burden of Disease 2010: top risk factors



Lim et al. The Lancet 2012

Risk factors ranked by attributable burden of disease, 2010

Ranking legend: 1–5 | 6–10 | 11–15 | 16–20 | 21–25 | 26–30 | 31–35 | 36–40 | >40

Risk factor	Global	High-income Asia Pacific	Western Europe	Australasia	High-income North America	Central Europe	Southern Latin America	Eastern Europe	East Asia	Tropical Latin America	Central Latin America	Southeast Asia	Central Asia	Andean Latin America	North Africa and Middle East	Caribbean	South Asia	Oceania	Southern sub-Saharan Africa	Eastern sub-Saharan Africa	Central sub-Saharan Africa	Western sub-Saharan Africa
High blood pressure	1	1	2	3	3	1	2	2	1	1	4	1	1	2	1	1	3	5	2	5	5	6
Tobacco smoking, including second-hand smoke	2	2	1	2	1	2	3	3	2	4	5	2	2	5	3	3	2	3	5	7	12	10
Household air pollution from solid fuels	3	42	..	..	..	14	23	20	5	18	11	3	12	7	25	8	1	4	7	2	2	2
Diet low in fruits	4	4	7	6	6	5	6	5	3	6	7	4	4	10	6	7	5	9	8	8	11	13
Alcohol use	5	5	6	9	7	4	4	1	8	2	2	6	5	1	18	9	10	7	1	6	10	5
High body-mass index	6	8	3	1	2	3	1	4	9	3	1	9	3	3	2	2	17	2	3	14	18	15
High fasting plasma glucose	7	7	5	5	4	7	5	10	7	5	3	5	7	6	4	4	7	1	6	10	13	11
Childhood underweight	8	39	38	37	39	38	38	38	38	32	23	13	25	18	20	14	4	8	9	1	1	1
Ambient particulate matter pollution	9	9	11	26	14	12	24	14	4	27	19	11	10	24	7	19	6	32	25	16	14	7
Physical inactivity and low physical activity	10	3	4	4	5	6	7	7	10	8	6	8	9	8	5	6	11	6	11	15	15	16
Diet high in sodium	11	6	10	11	11	9	11	9	6	9	13	7	6	13	8	15	14	16	13	21	17	18
Diet low in nuts and seeds	12	11	9	7	8	8	8	8	12	10	8	15	8	12	9	10	13	13	16	22	16	21
Iron deficiency	13	20	32	21	35	22	17	21	19	14	12	12	17	4	11	5	8	11	10	4	4	4
Suboptimal breastfeeding	14	..	..	..	..	..	27	..	24	22	15	14	16	9	13	13	9	10	4	3	3	3
High total cholesterol	15	12	8	8	9	10	9	6	13	11	10	16	14	16	10	16	20	14	19	28	27	30
Diet low in whole grains	16	10	16	16	17	11	12	11	11	12	14	26	13	17	12	12	15	15	32	24	19	24
Diet low in vegetables	17	14	13	12	13	13	10	12	15	16	20	10	11	14	16	11	16	12	15	23	23	20
Diet low in seafood omega-3 fatty acids	18	17	15	13	16	16	14	13	17	17	18	19	15	23	14	17	18	20	23	27	25	25
Drug use	19	13	14	10	10	20	13	17	18	13	16	18	20	11	17	18	22	19	12	19	24	22
Occupational risk factors for injuries	20	24	24	20	25	26	16	25	20	19	22	23	21	21	22	31	12	22	22	20	22	17
Occupational low back pain	21	15	17	15	23	18	20	24	14	15	24	17	24	22	19	26	23	17	24	17	21	19
Diet high in processed meat	22	22	12	14	12	15	18	15	29	7	9	27	19	15	27	24	25	27	28	31	28	28
Intimate partner violence	23	18	22	23	22	25	21	22	21	23	26	22	27	19	24	23	21	25	14	18	20	23
Diet low in fibre	24	16	18	18	18	19	15	16	16	25	28	20	18	28	21	22	33	21	33	36	34	36
Unimproved sanitation	25	38	39	39	41	42	40	40	40	40	38	30	37	31	32	28	19	18	18	9	7	9

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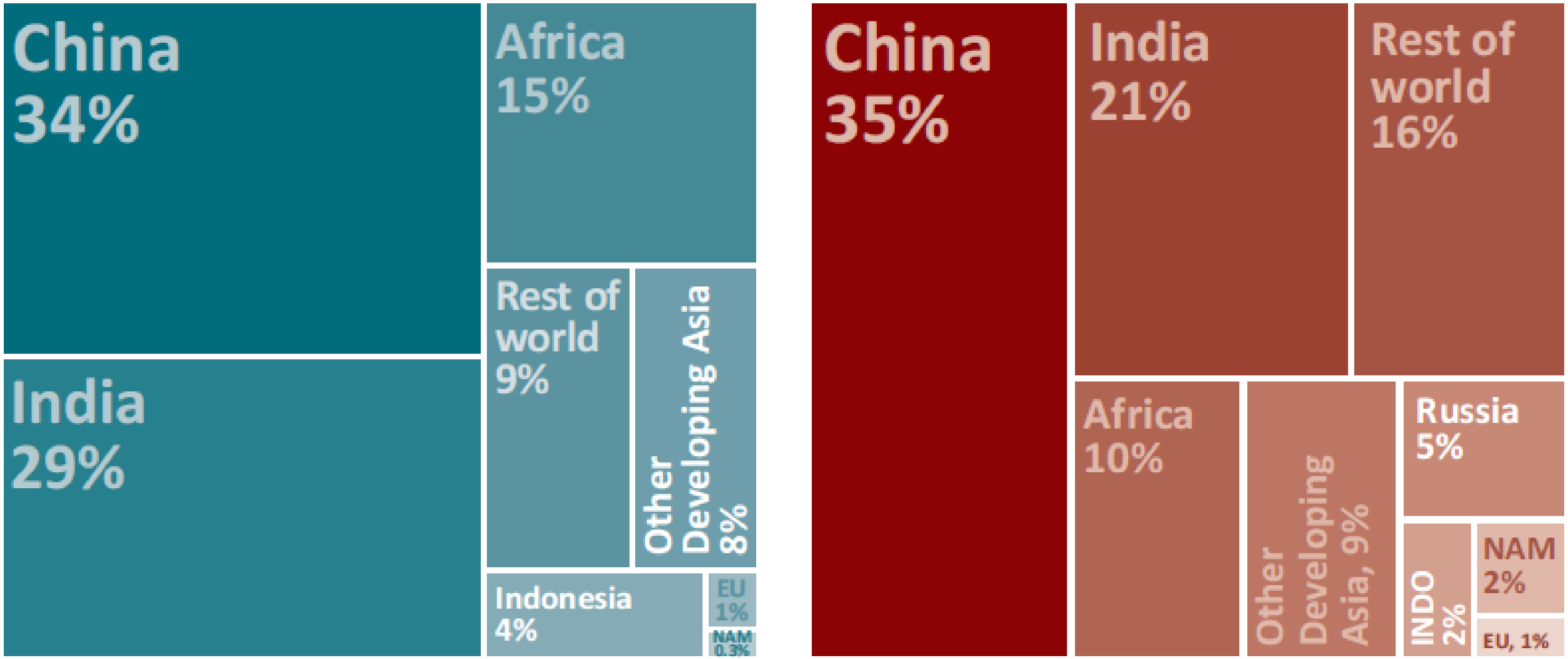
Air Pollution: the Greatest Environmental Risk

Figure 1.9 ▷ Deaths attributable to household and outdoor air pollution, 2012

Household: 4.3 million

Outdoor: 3.0 million



Notes: EU = European Union; NAM = North America; INDO = Indonesia.

Sources: WHO (2016d, forthcoming) and IEA analysis.

Source: WHO, 2016; IEA, 2016

Ambient air pollution health effects

- More than 3 million deaths/year (particulate matter and ozone)

40% Ischemic Heart disease

40% stroke

11% COPD

6% Lung cancer

3% Acute lower respiratory infection in children

- But also:
  - low birth weight and preterm birth
  - cognitive development
  - autism
  - diabetes
  - obesity

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What air pollutants?

"Criteria air pollutants"

- Nitrogen dioxide (NO2) – NOx, NO and NO2 stem form high temperature combustion
- Particulate matter – PM10 and PM2.5, primary (incomplete combustion; dust) or secondary (reactions between SO2, NH3, and NOx)
- Ozone – formed from NOx and VOCs in the presence of sunlight
- Sulfur dioxide (SO2) – combustion i

PM2.5

Secondary PM formation:

SO2 emitted -> SO4 sulfate

NH3 emitted -> NH4 Amonium

NOx emitted -> NO3 nitrate

NH4NO3

$(NH_4)_2SO_4$

Secondary Particles (PM10, PM2.5)

NO + VOCs → NO_2

NO_2 + UV → NO + O

O + O2 → O_3

NO_2 + VOCs → PAN, etc

NO + O3 --> NO2 + O2

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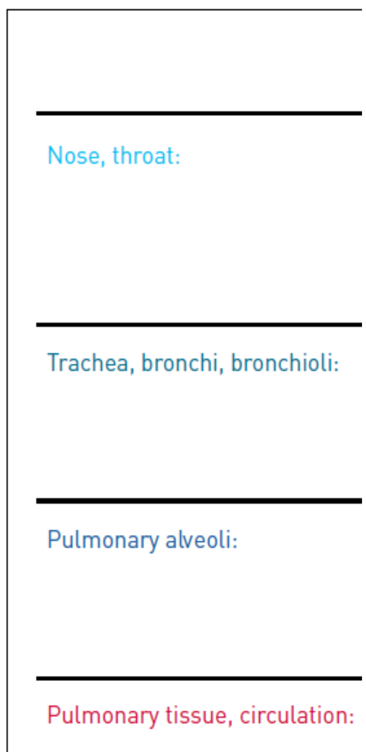
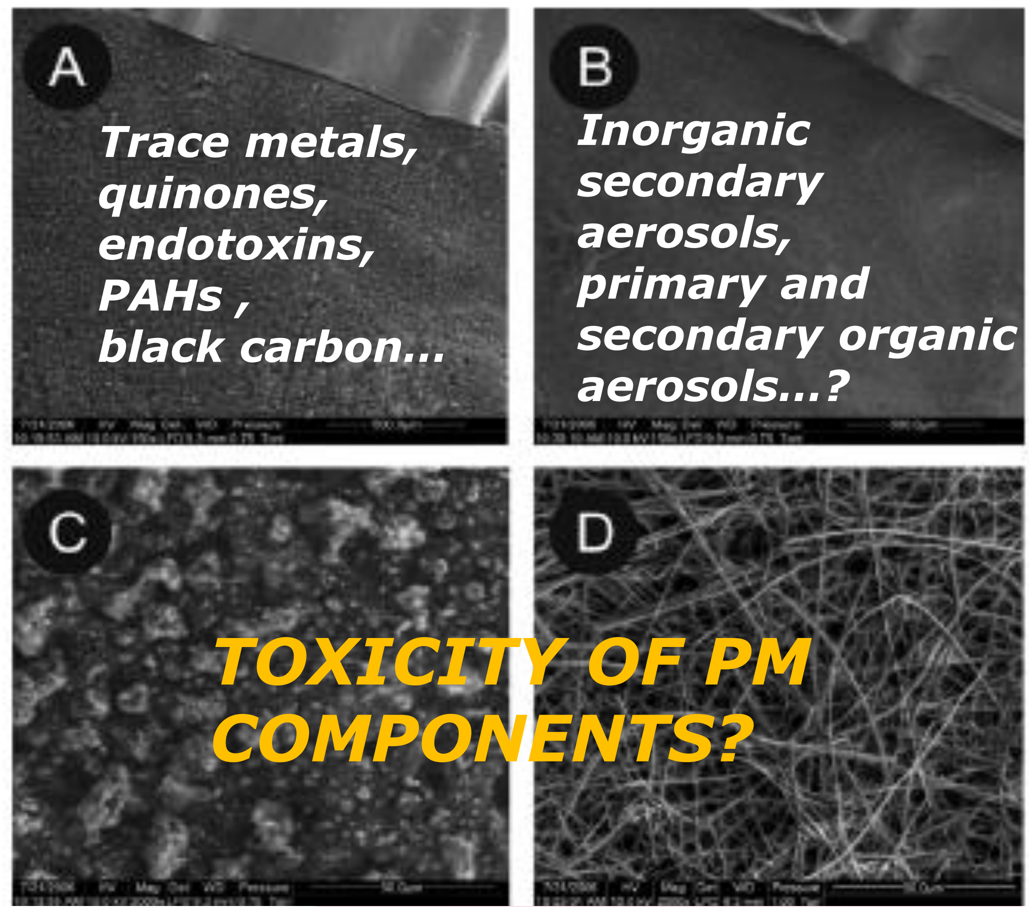
Air pollutants

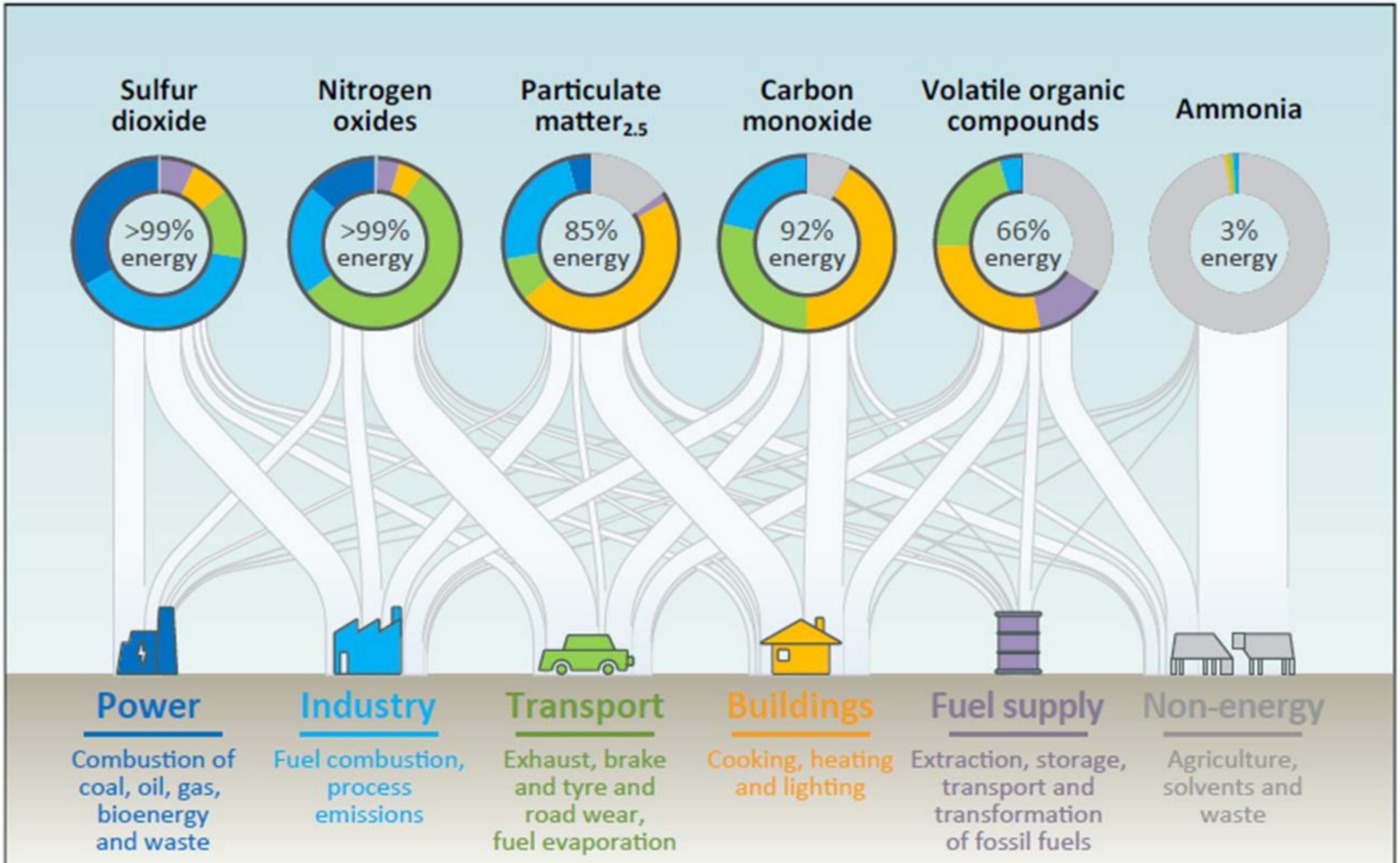
Also (not criteria pollutants):

- Ammonia (NH_3)
- VOCs (including benzene)
- Ultrafine particles
- Black carbc components





Sources of Air Pollutants: primary pollutants



Source: IEA, 2016

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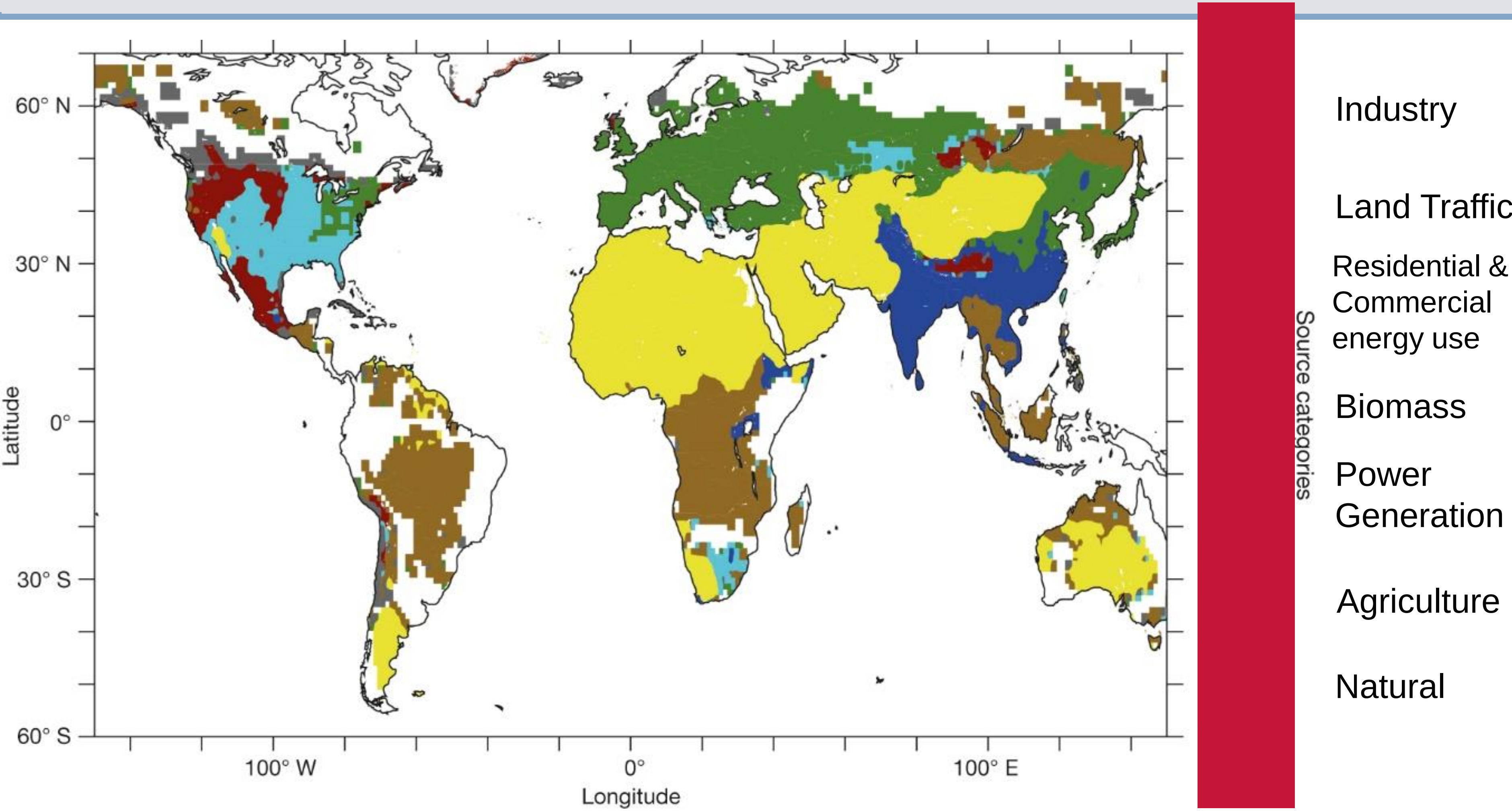
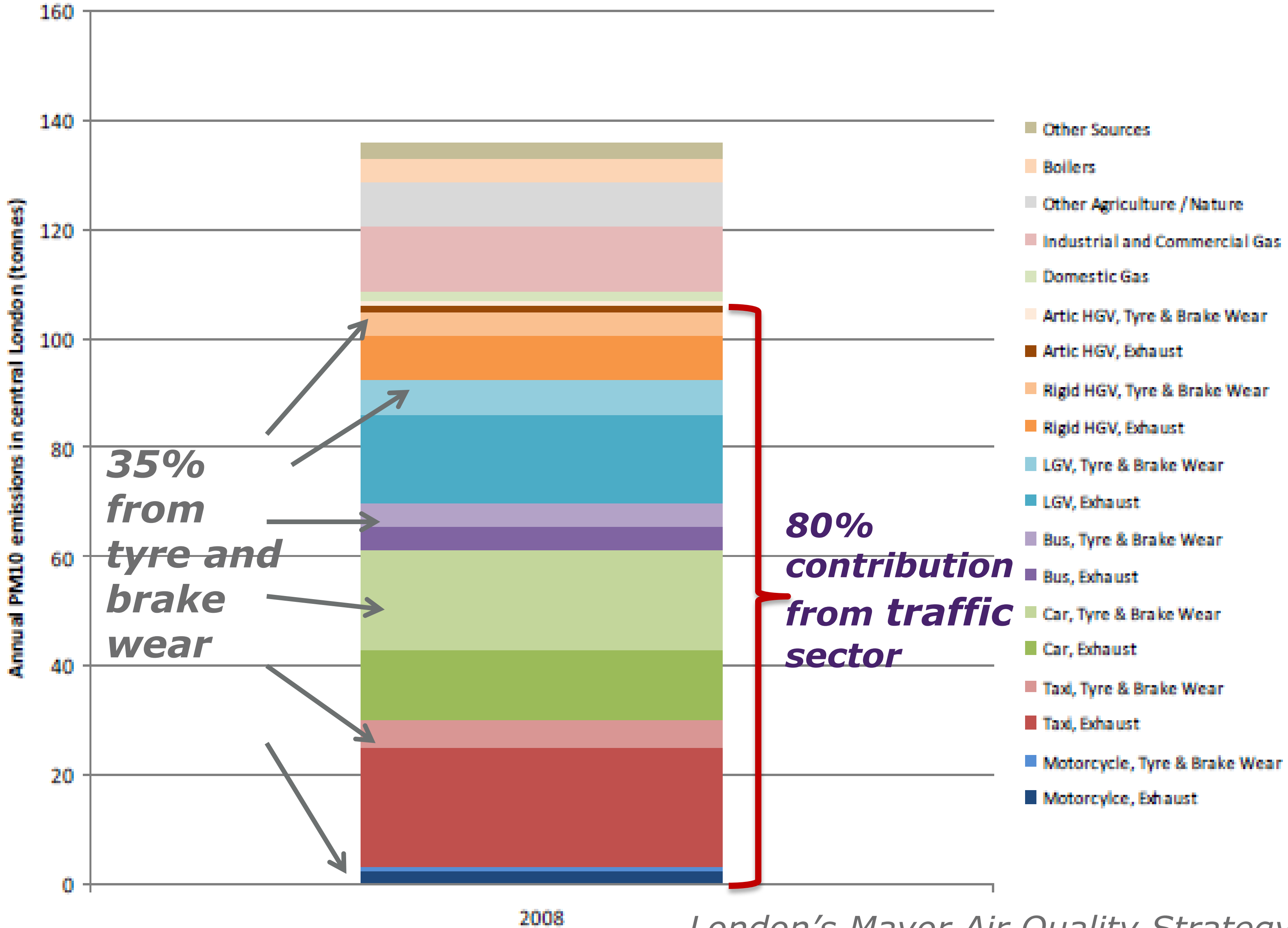
Source categories responsible for the largest impact on mortality linked to outdoor air pollution in 2010



*J Lelieveld et al. Nature **525**, 367-371 (2015) doi:10.1038/nature15371*

Emission sources in cities

Figure 2.11: PM_{10} emissions from all sources[8] in central London in 2008



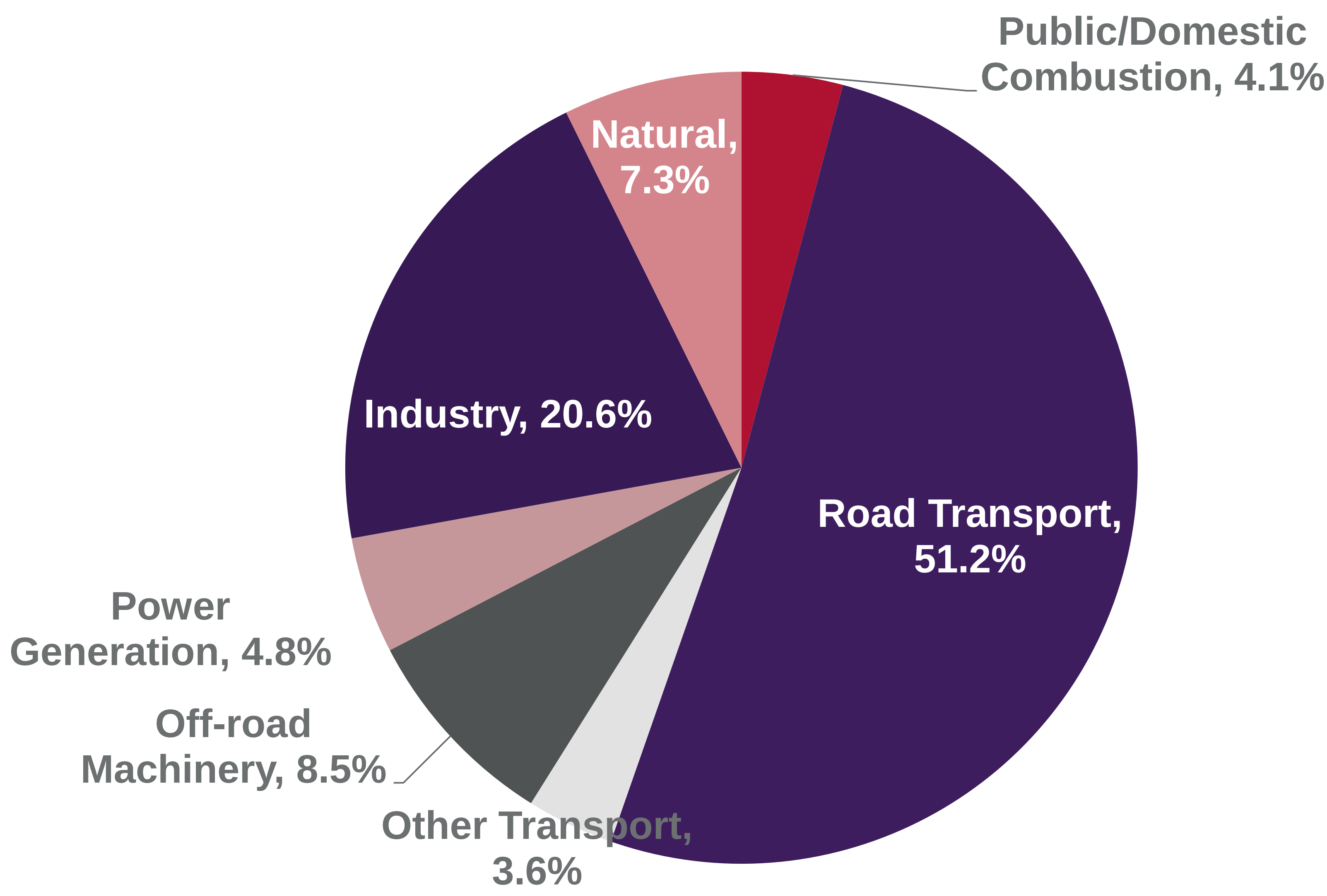
London's Mayor Air Quality Strategy 2010

BUT concentrations ≠ emissions

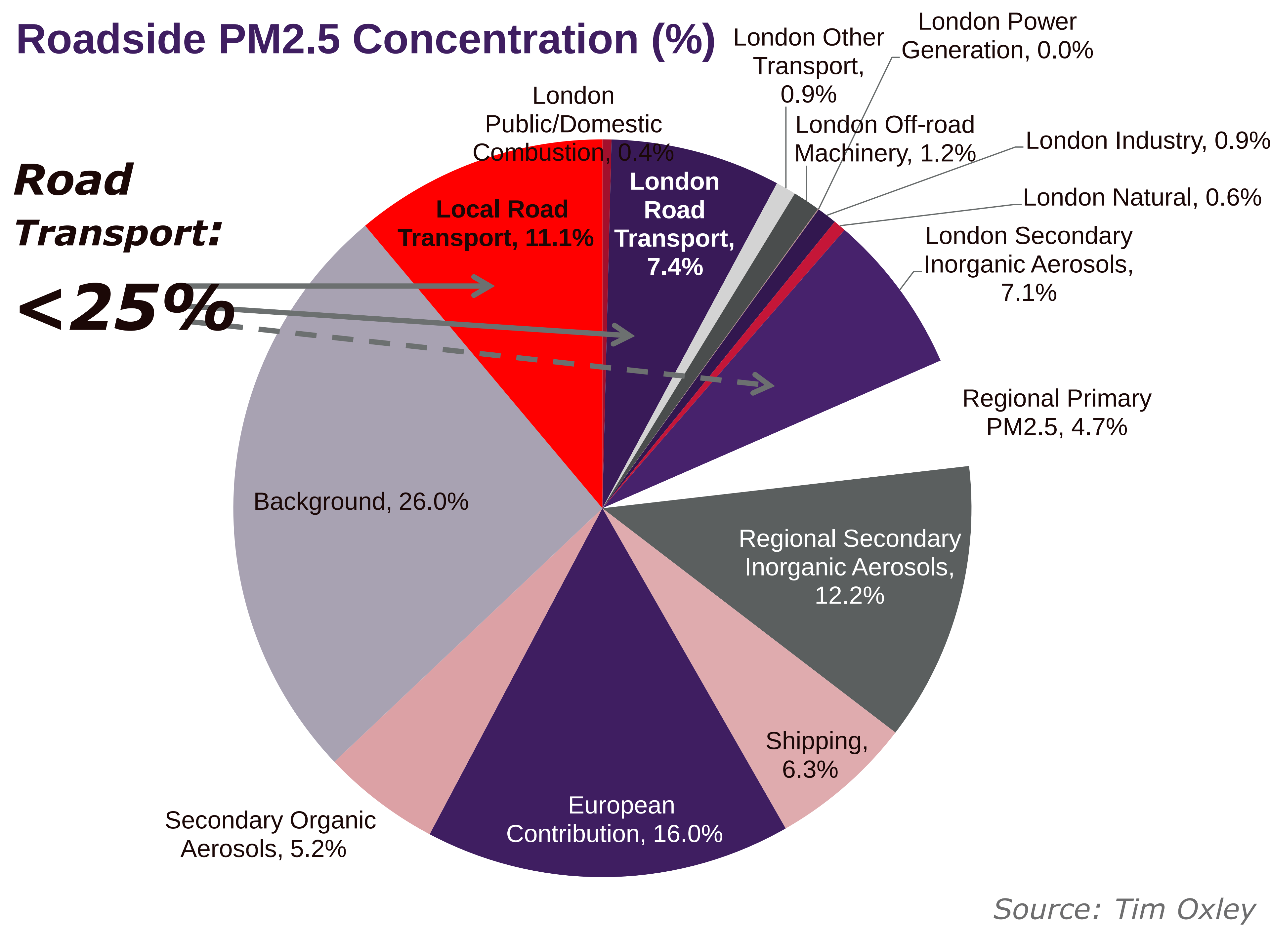
Example:
Contributions to PM2.5 in Greater London

Compare % emissions from the transport sector in Greater London to % contribution to concentration on the roadside in London

Greater London PM2.5
Emissions contributions from different sectors (%)



Source: Tim Oxley



Roadside PM2.5 Concentration (%)
Road Transport: <25%
London Public/Domestic Combustion, 0.4%
London Other Transport, 0.9%
London Power Generation, 0.0%
London Off-road Machinery, 1.2%
London Industry, 0.9%
London Natural, 0.6%
London Secondary Inorganic Aerosols, 7.1%
Local Road Transport, 11.1%
London Road Transport, 7.4%
Regional Primary PM2.5, 4.7%
Background, 26.0%
Regional Secondary Inorganic Aerosols, 12.2%
Shipping, 6.3%
European Contribution, 16.0%
Secondary Organic Aerosols, 5.2%
Source: Tim Oxley

SOLUTIONS

Air pollution control options

- Pollution dispersion
- More efficient processes
- Cleaner processes
- End-of-pipe (tail pipe): physical and/or chemical removal
- Regulatory schemes
- Consumer demand management

London Congestion Charging Scheme

- Introduced in February 2003 (22km^2)
- Study measured air pollution 2001-2004 in affected and control sites, at background sites:
  - 12% decrease in PM10
  - 10 to 25 % decrease in NO,
  - 2 to 20% increase in NO2

(Kelly et al. 2011 HEI 155)

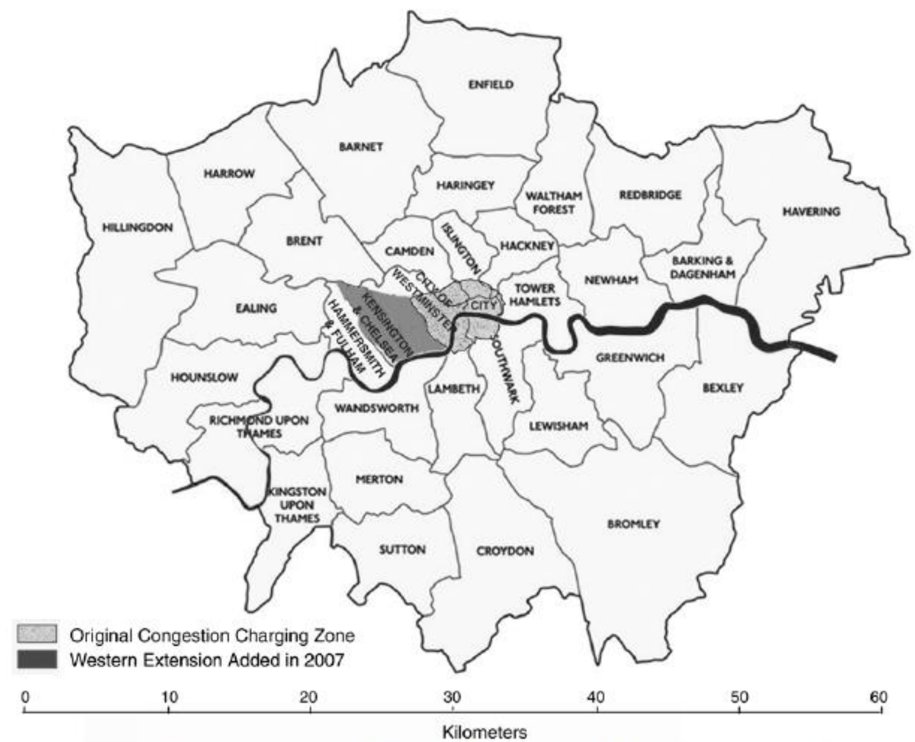


Figure 2. Relationship of the CCZ to Greater London. (Map includes the Western Extension, which was introduced in 2007.) Adapted with permission from Transport for London 2006.

Congestion charge

However:

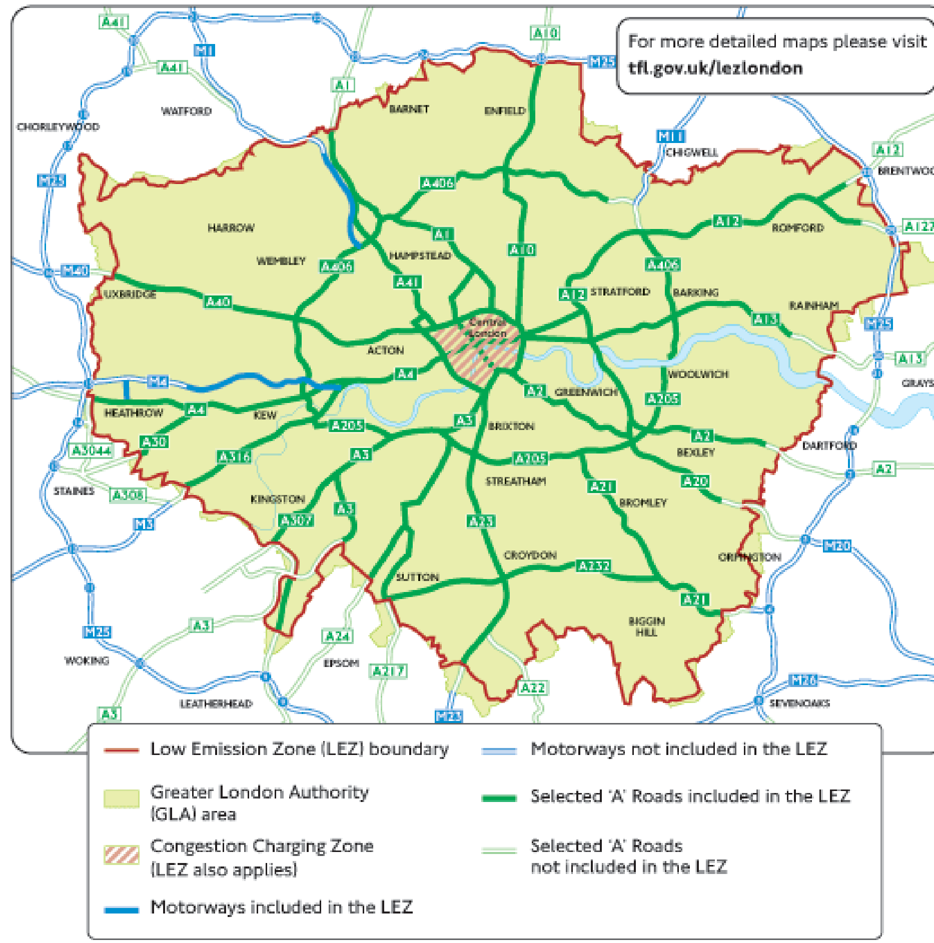
- Difficulties in attributing changes in air pollution:
  - Weather
  - Construction
  - Increase in diesel-powered buses and taxis
  - Other trends and changes
  - Number and location of air quality monitors
  - Expected reductions from local level schemes necessarily relatively small.
- Impact may erode: In London, congestion back at pre-2002 levels since 2012 (after initial 18% reduction)
- Beware of toll plazas! Introduction of electronic collection (E-Zpass) reduced prematurity and low birth weight among mothers living nearby (Currie et al 2011 *American Economic Journal: Applied Economics*, 3(1): 65-90.

Low Emission Zones (LEZ)

Areas where the most polluting vehicles are regulated.

- 220 cities in 14 countries around Europe operate or are preparing LEZ
- UK, Germany, Sweden, Netherlands, Denmark, Italy, Hong Kong, Japan, Singapore

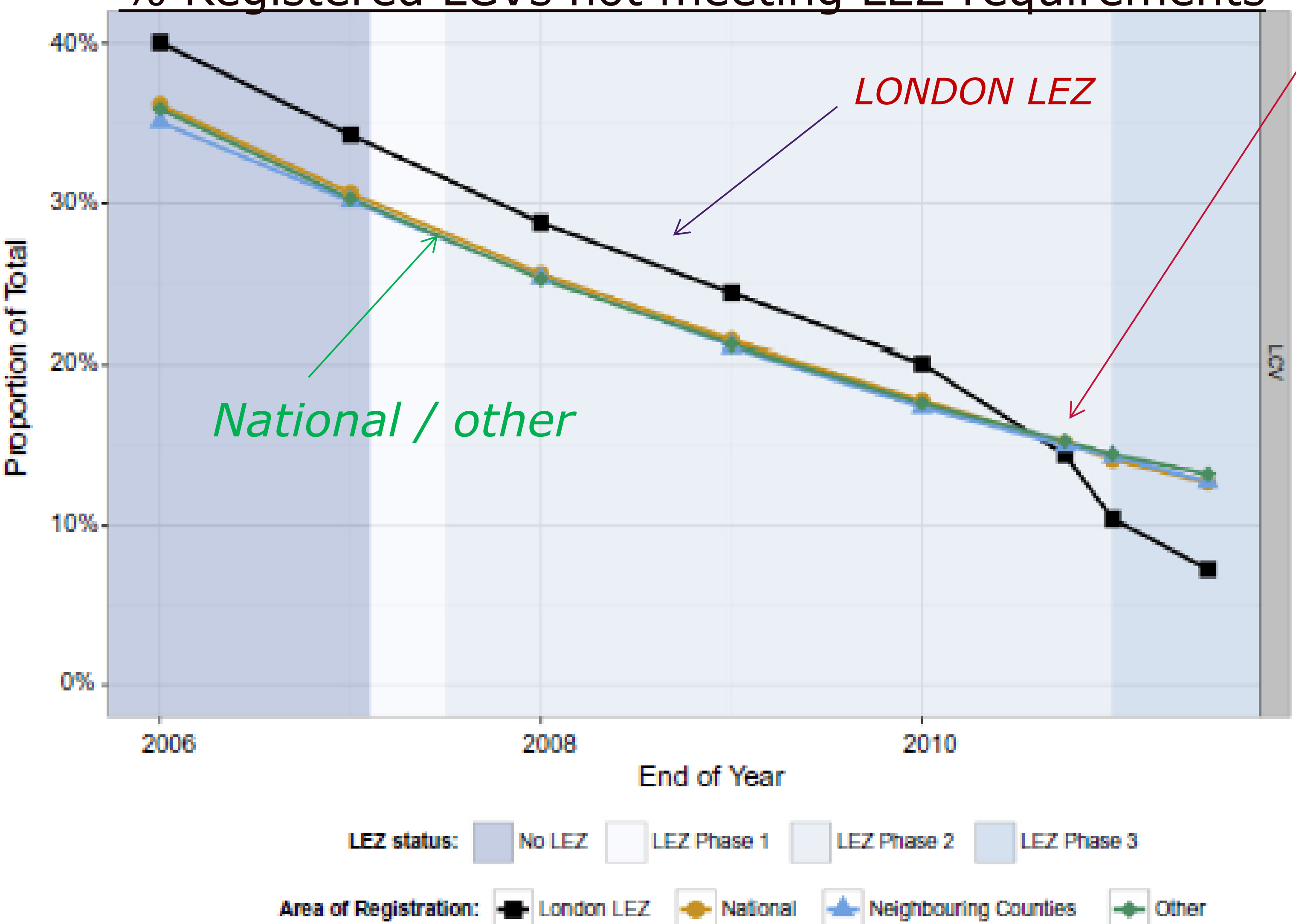
Typically targets commercial vehicles, but London has a proposal to include private vehicles



London's LEZ

Light commercial vehicles (LCVs - 60% of freight in London LEZ) became subject to LEZ requirements for the first time in 2012

% Registered LCVs not meeting LEZ requirements



Mean PM10 concentration decreased by 13% in LEZ vs 7% decrease outside the LEZ

Ellison et al./ Transportation Research Part D (2013) 25-33

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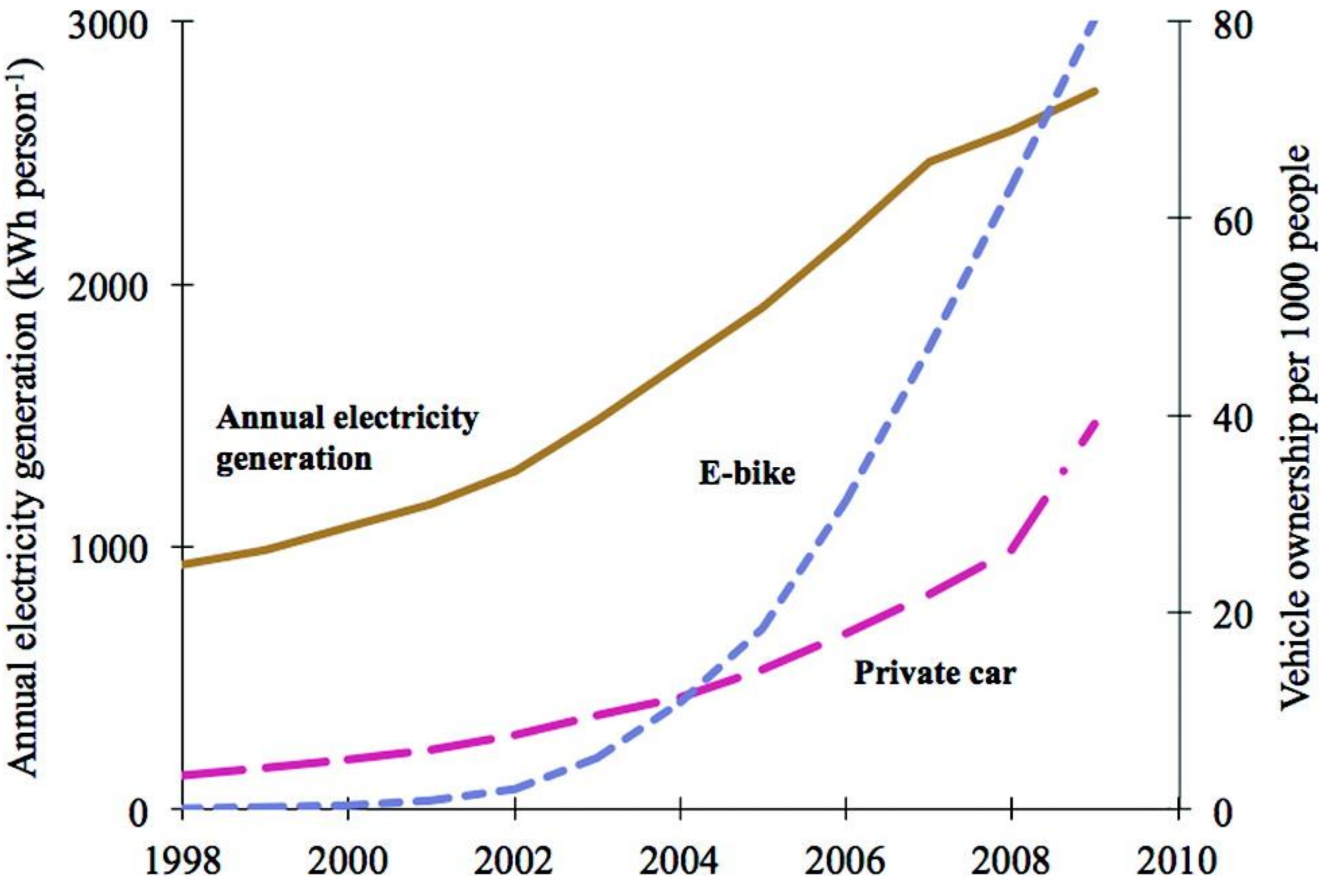
Electric vehicles: example China



- 300,000 deaths/year from ambient AP
- Auto ownership: 3 cars/1000 people in 1998, at least 39 cars/1000 people in 2009
- Energy sources: 75% coal

Ji et al. Environ. Sci. Technol. ***2012,*** *46, 2018-2024.*

Electric vehicles: example China

Comparison of emissions and environmental health impacts from the use of conventional vehicles and electric vehicles in 34 majors cities in China

- Station-to-wheel emission estimates
  - emission factors from **conventional vehicles (CV)** and **electricity generation units (EGU)** varying along 15 regional electricity grids
- Intake fraction and mortality impacts

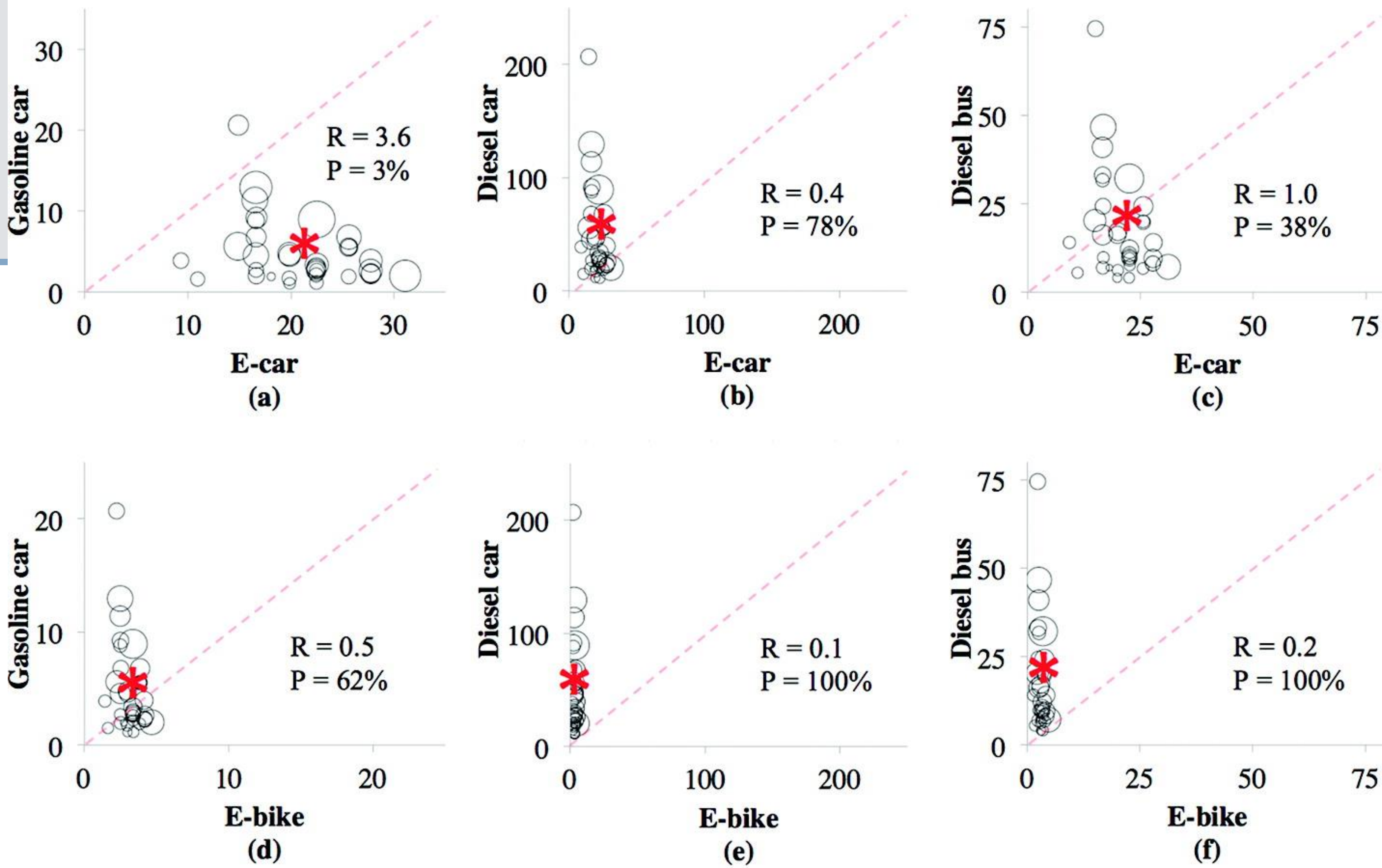
Ji et al. Environ. Sci. Technol. ***2012,*** *46, 2018-2024.*

Table 1. Example Calculation: Health Effects of $PM_{2.5}$ in Shanghai[a]

	gasoline car	diesel car	bus	e-car	e-bike
emission factor (mg [person-km]$^{-1}$)	3	30	12	58	9
kilometers traveled (km y^{-1})	10^{10}	10^{10}	10^{10}	10^{10}	10^{10}
intake fraction (ppm)	51	51	51	8.2	8.2
unit dose (g death^{-1})	188	188	188	188	188
total excess deaths per year	9	90	32	26	3
	(8, 10)	(70, 111)	(15, 67)	(11, 38)	(2, 5)

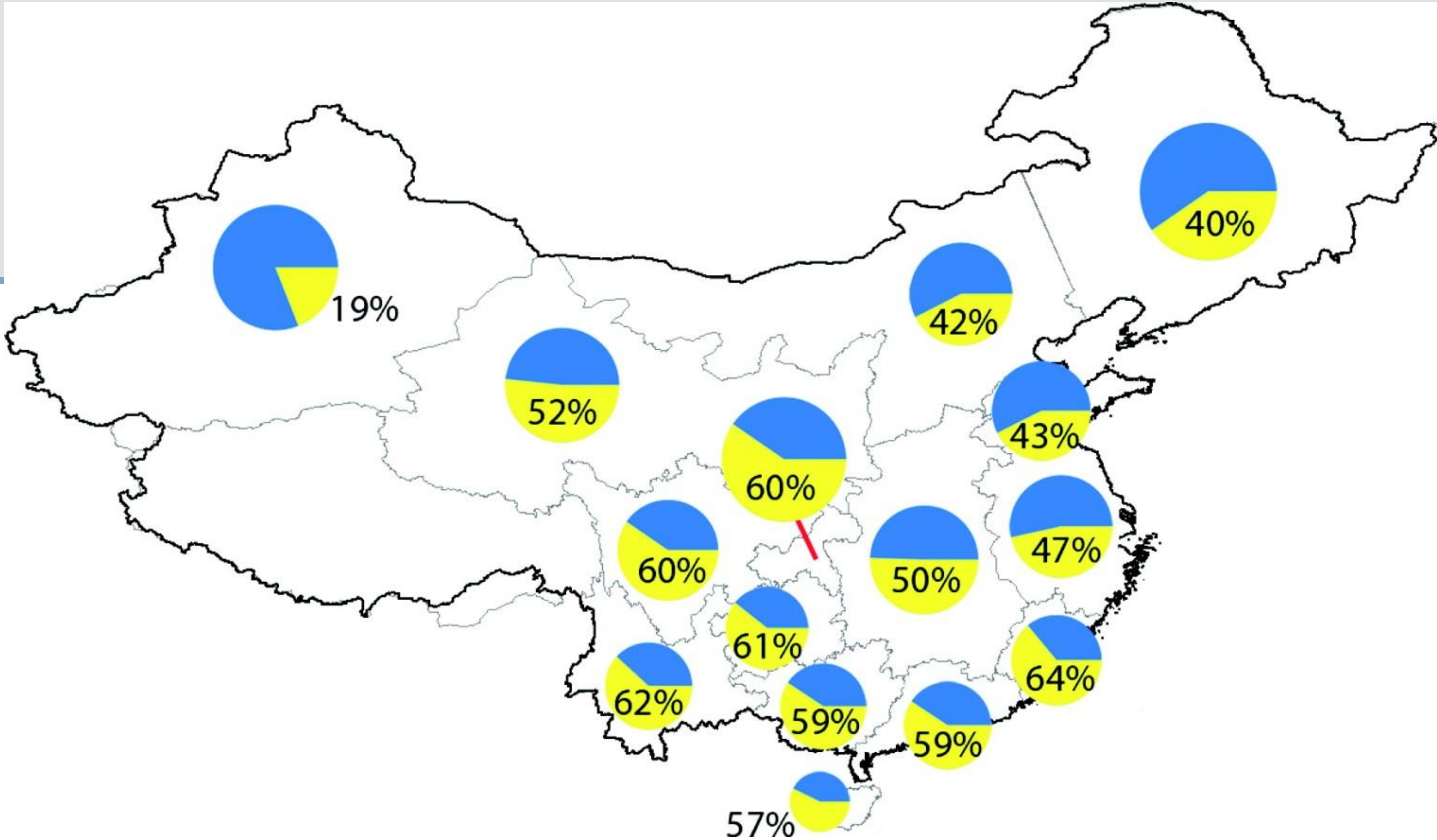
[a]Load factors are listed in the caption for Figure 3. The values in parentheses are the 5th and 95th percentiles of Monte Carlo simulation results.

Ji et al. Environ. Sci. Technol. ***2012,*** *46, 2018-2024.*



***PM2.5 mortality risk** per 10^{10} passenger-km, for the 34 cities considered. Icon size is proportional to city population. In each plot, "R" is the population-weighted average ratio between x- and y-axes, "P" is the proportion of the population (among the 34 cities) for which the mortality risk is lower for EVs than for CVs. For reference, dashed lines are 1:1 lines. The population-weighted average value is indicated with an asterisk.*

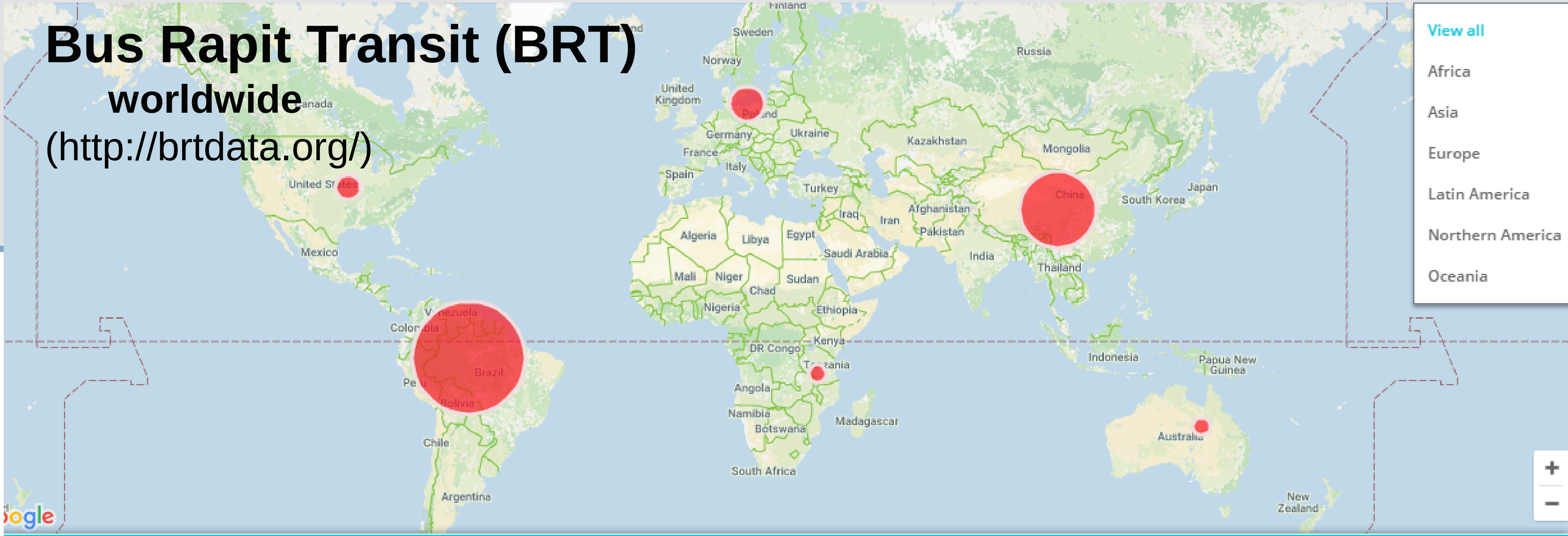
Ji et al. Environ. Sci. Technol. ***2012,*** *46, 2018-2024.*



***Portion of primary PM2.5 health impacts from EGUs experienced by rural versus urban populations**. Icon area is proportional to PM2.5 emission factor (g km–1) for an EV in that power grid. Numbers identify nonurban mortality impact proportions, i.e., of the total mortality impacts attributable to primary PM2.5 from electricity generation – here, owing to urban use of EVs. Urban use of EVs rather than CVs typically moves the emissions (and, exposures and health impacts) to more rural locations. In general, a substantial proportion – on average, about half – of the emissions from urban use of EVs are inhaled by nonurban populations.*

Ji et al. Environ. Sci. Technol. ***2012,*** *46, 2018-2024.*

Bus Rapit Transit (BRT)
worldwide
(http://brtdata.org/)



VIEWING NOW
WORLDWIDE

Find your City or Indicator...

? EN ES PT

33,302,692 PASSENGERS PER DAY	206 CITIES	5,347 km TOTAL LENGTH

› KEY INDICATORS per Region

Filter

Regions	Passengers per Day	Number of Cities	Length (km)
Africa	262,000 (0.78%)	3 (1.45%)	83 (1.54%)
Asia	9,293,372 (27.9%)	42 (20.38%)	1,490 (27.85%)
Europe	2,022,347 (6.07%)	59 (28.64%)	951 (17.77%)
Latin America	20,274,549 (60.87%)	67 (32.52%)	1,795 (33.57%)
Northern America	1,020,383 (3.06%)	29 (14.07%)	933 (17.45%)
Oceania	430,041 (1.29%)	6 (2.91%)	96 (1.78%)

Bus Rapid Transit: Example Mexico City

- Fourth largest urban agglomeration in the world
- Population ~21 million
- Elevation: 2,240 m
- Surrounded by mountains and volcanoes (4,000-5,00m)
  - Frequent thermal inversions, trapping pollutants
  - high altitude and intense sunlight contribute to create O_3

- **5 million vehicles** that consume around **25 million litres** of fuel per day.
- The transport sector is the largest source of emissions in the city. It accounts for:
  - 98% of CO total emissions
  - 88% of NOx total emissions
  - 79%of Black Carbon total emissions
  - 49% of CO_2eq total emissions

Source: UN, 2015; Molina J., 2004

BRT Systems: Example Mexico City (Metrobus)

Metrobus BRT system has:

•Segregated bus lanes; enclosed stations; large articulated and bi-articulated buses; and automatic fare system with a smart card.

Metrobus is an alternative to the costly implementation of Metro:

•Constructing one kilometre of Metro is as expensive as building one entire 22-km BRT corridor.

Source: MB, 2016

Mexico City's Bus Rapid Transit (BRT) System

Metrobus: Mexico City's Bus Rapid Transit (BRT) System

•Metrobus started operations in June **2005** with a **20 km corridor** along one of the main streets in the city (Insurgentes Avenue).

•Today, 125 Km total, serving over **1,000,000** passengers / day

Source: MB, 2016

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Metrobus: Insurgentes Avenue before and after

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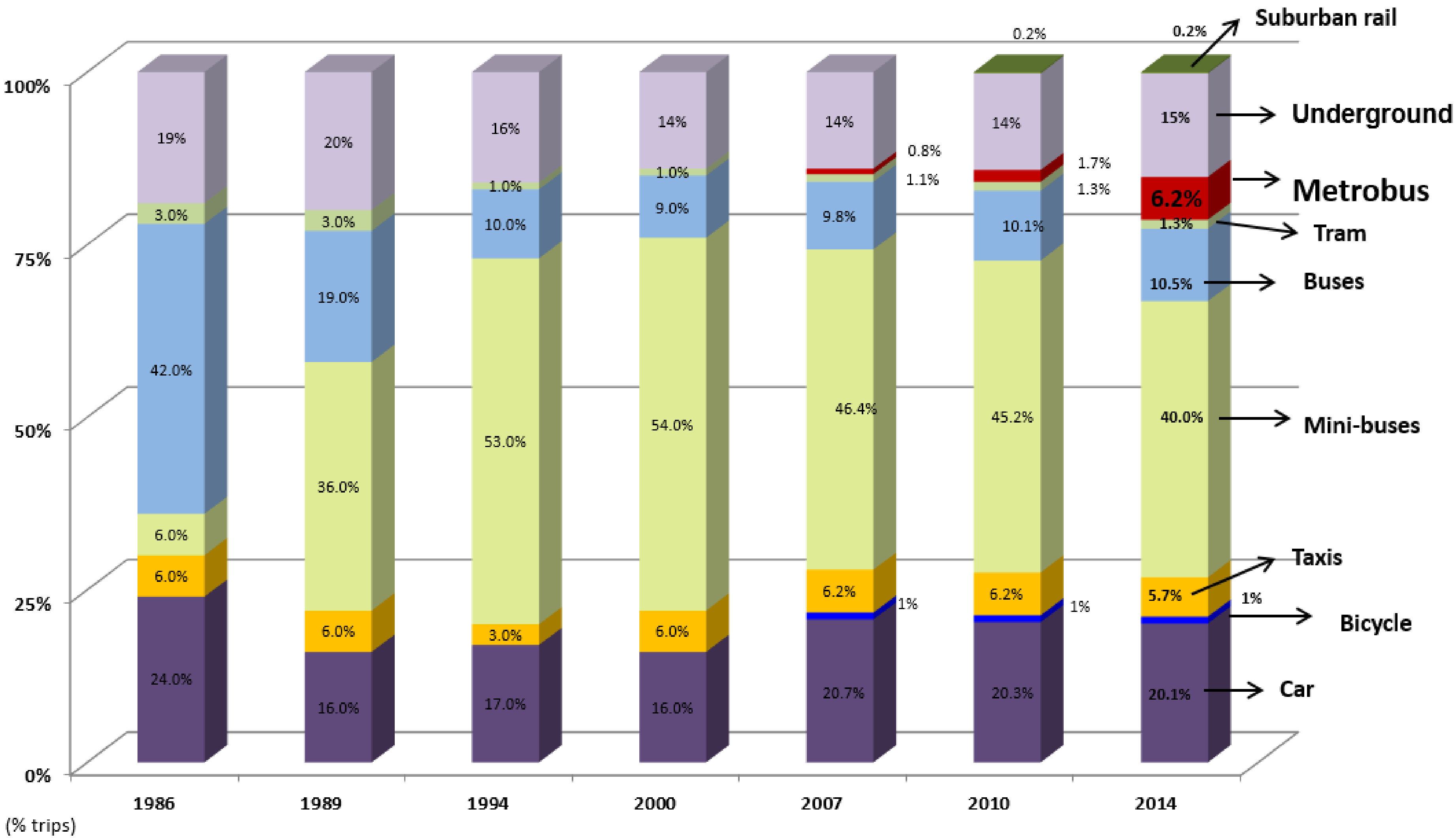
Modal Distribution in Mexico City



Source: MB, 2016

Metrobus: Breaking the Mobility Paradigm

- With the BRT system, Mexico City changed from **an unregulated, inefficient, disorganized operation framework for buses to a modern, efficient, and reliable transport system** (Francke, E, 2012).

- Metrobus has also had an important impact on public health;
  - Wöhrnschimmel H. et al. found that “the implementation of the BRT system resulted in **reductions in commuters’ exposure to CO**, benzene and $PM_{2.5}$ ranging between **20%** and **70%**.”

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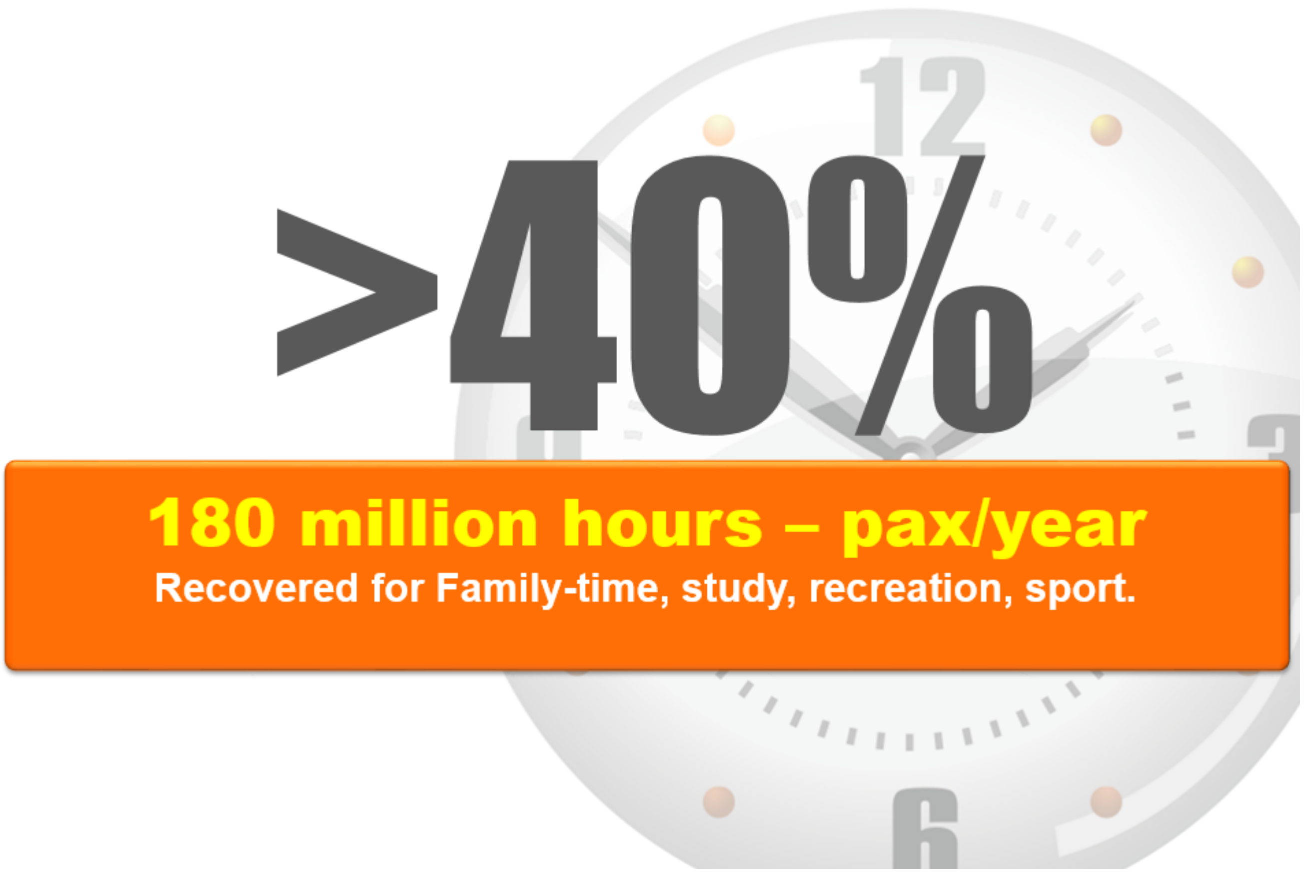
Reduction in Travel Time

Metrobus has promoted a significant **reduction in travel time**

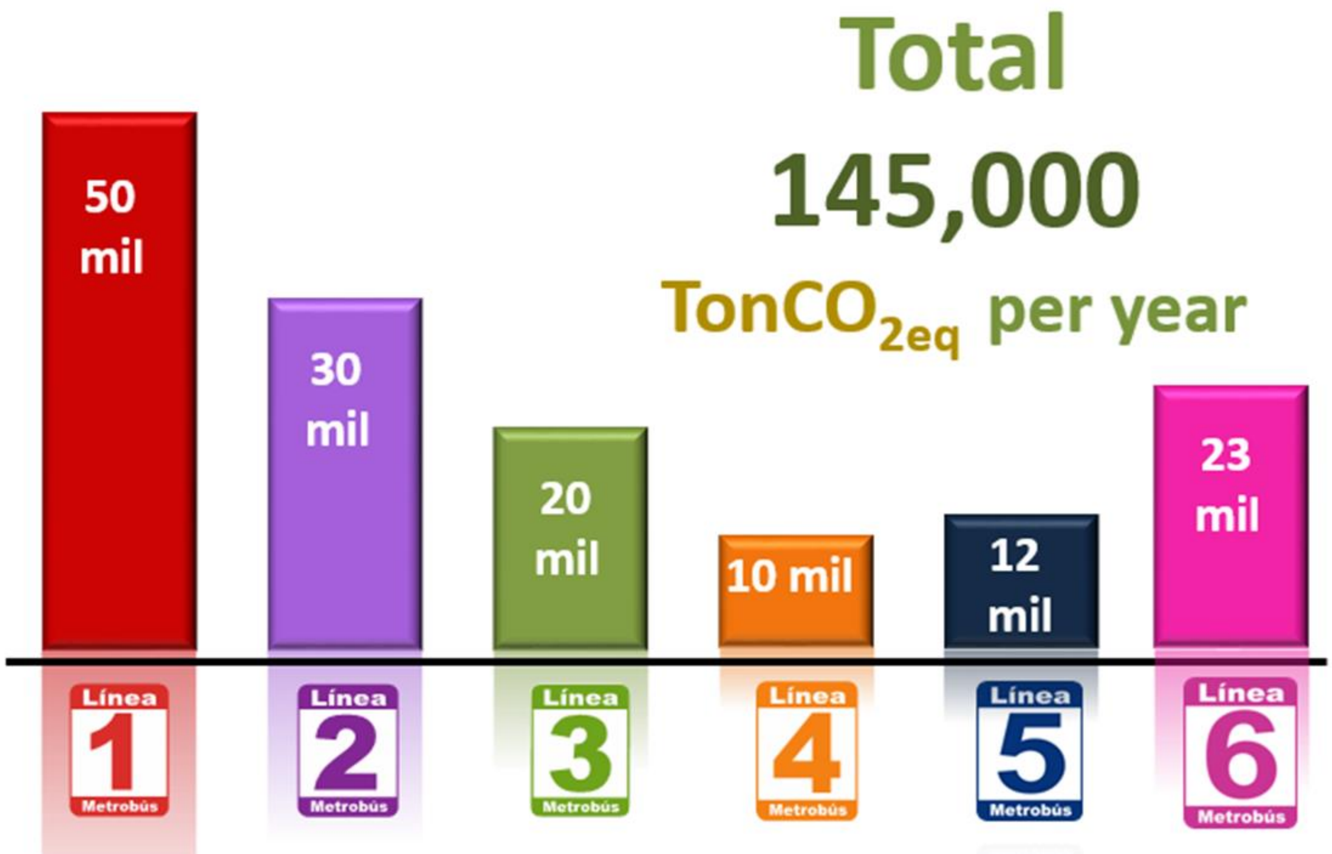


Source: MB, 2016

Metrobus and Climate Change Mitigation

Metrobus was the **first transport system in the world** to commercialize carbon credits.

•During its operation, Metrobus has reduced **874,304 ton CO_2eq**



Source: MB, 2016

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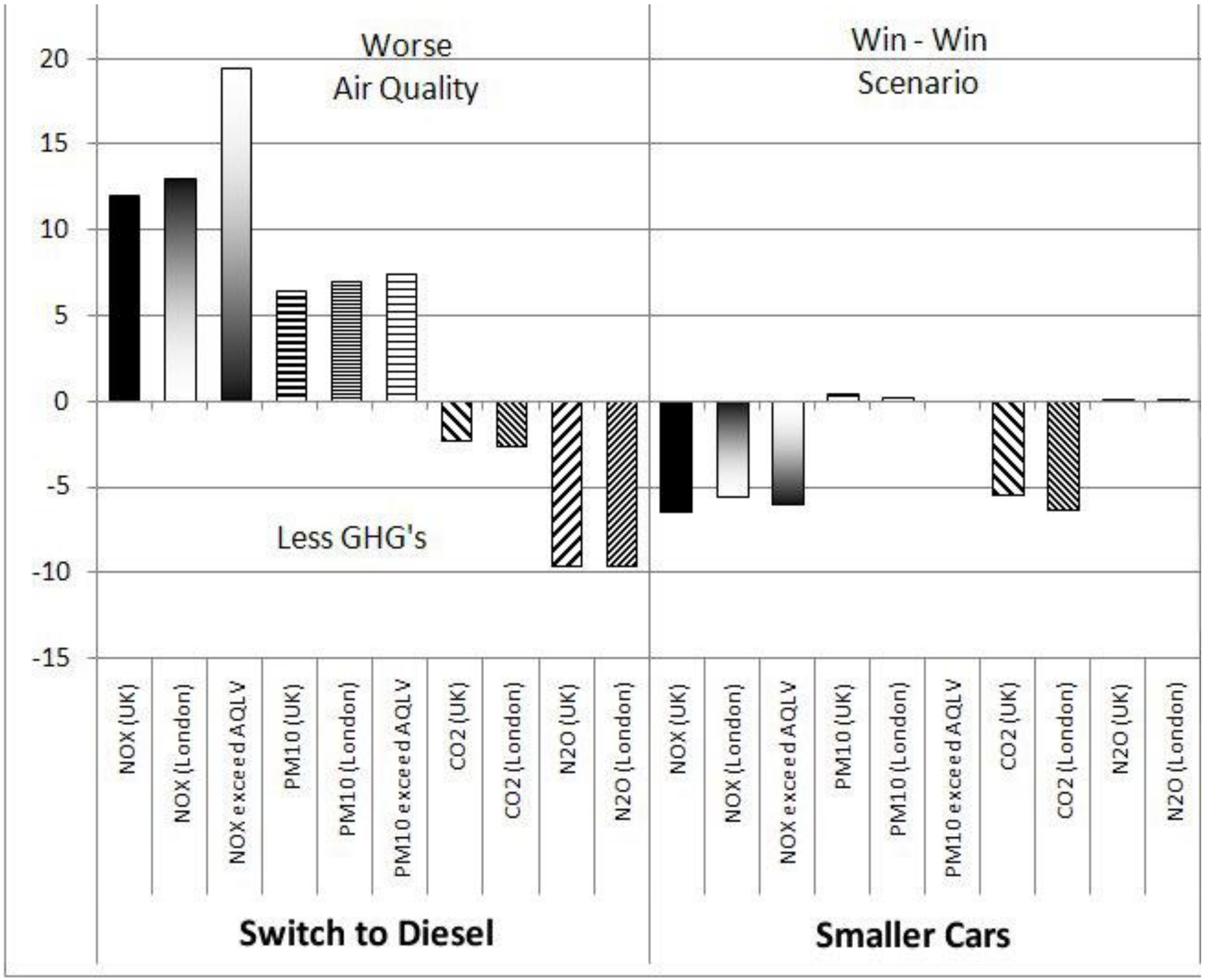
Climate change and air pollution: Synergies and trade-offs

- Black carbon has high radiative forcing potential
- Sulfates have a cooling effect
- Diesel vehicles are more efficient than petrol but pollute more
- Climate change likely to increase ozone concentrations globally (increased energy demand + higher temperatures and sunlight)
- Complex interactions between heat stress, air pollution exposure, social vulnerability

Illustrative scenarios: benefits air quality v greenhouse gases

Oxley, T., Elshkaki, A., Kwiatkowski, L., Castillo, A., Scarbrough, T., ApSimon, H., 2012. Pollution abatement from road transport: cross-sectoral implications, climate co-benefits and behavioural change. Environmental Science & Policy 19–20, 16-32.

% effect of emissions and air quality



Active travel

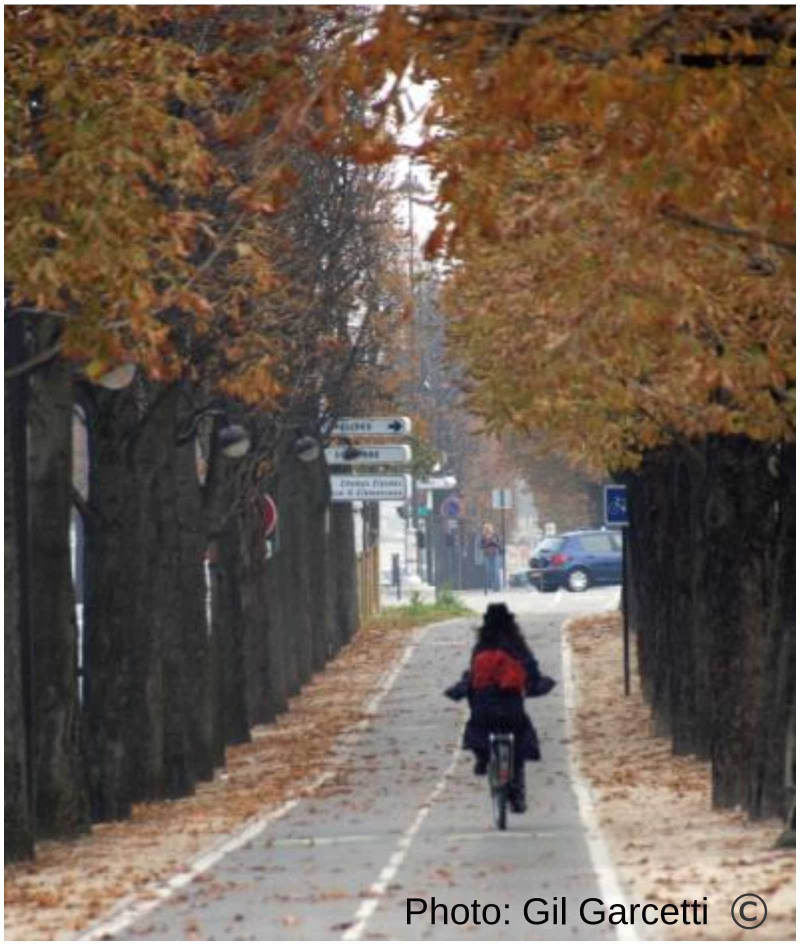


Photo: Gil Garcetti ©

Changes in air pollution and deaths/year for transport scenarios in Barcelona

scenario	PM2.5 concentration % reduction
20% in-city car trip reduction, all replaced by biking	0.32
20% in-out city car trip reduction, 20% replaced by biking	0.58

Rojas-Rueda et al. Environment International 49 (2012) 100-10

Health impact assessments (HIA)

- Main message so far from all of 20 published studies: Benefits of active travel in terms of physical activity outweigh adverse effects associated with air pollution and/or traffic injuries

Mueller et al. 2015. Health impact assessmei transportation: A systematic review. Preventi 114.

Can air pollution negate the health benefits of cycling and walking?

Preventive Medicine 87 (2016) 233–236

Contents lists available at ScienceDirect

Preventive Medicine

journal homepage: www.elsevier.com/locate/ypmed

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Brief Original Report

Can air pollution negate the health benefits of cycling and walking?

CrossMark

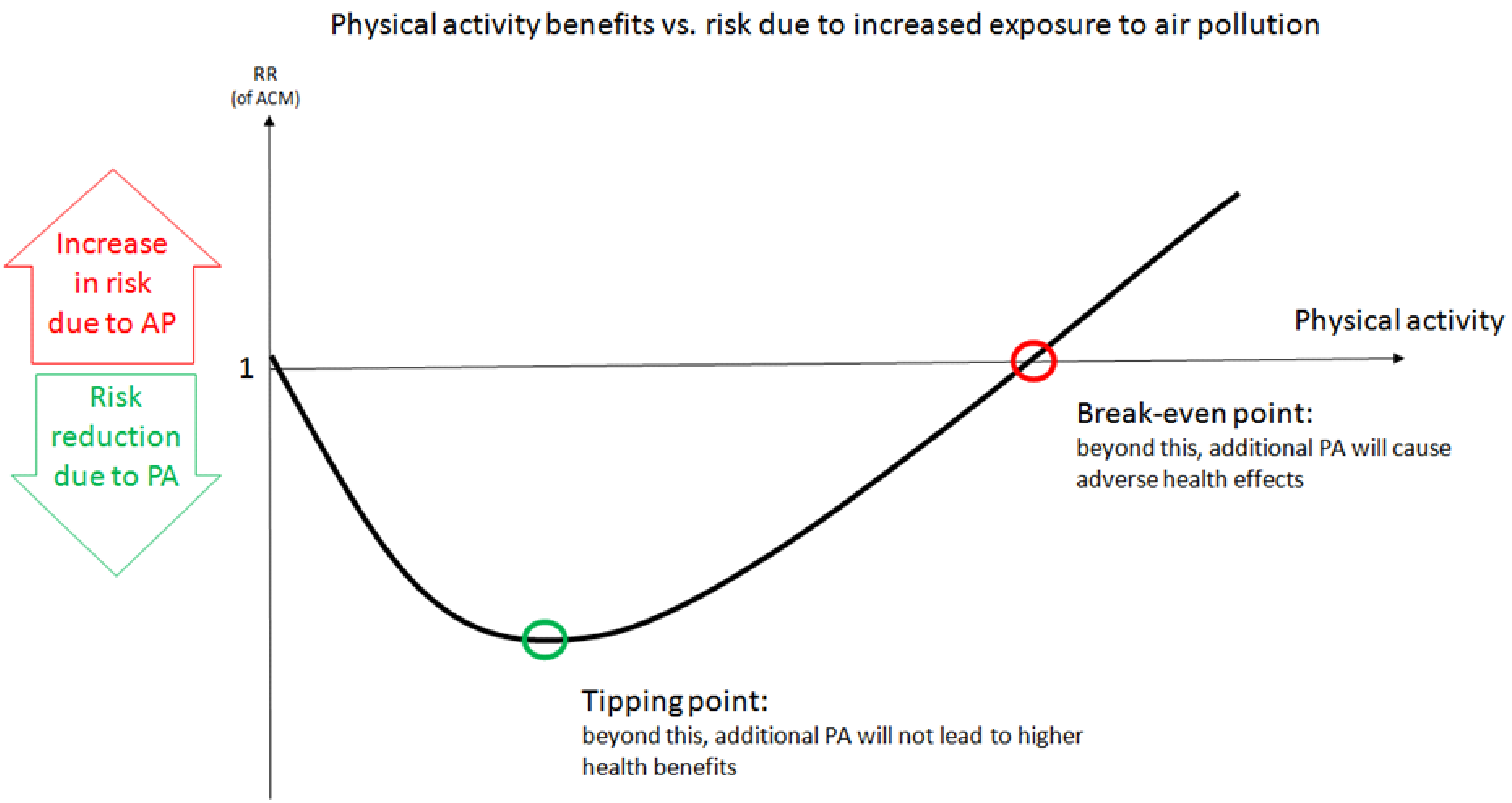
Marko Tainio [a,*], Audrey J. de Nazelle [b], Thomas Götschi [c], Sonja Kahlmeier [c], David Rojas-Rueda [d,e,f], Mark J. Nieuwenhuijsen [d,e,f], Thiago Hérick de Sá [g], Paul Kelly [h], James Woodcock [a]

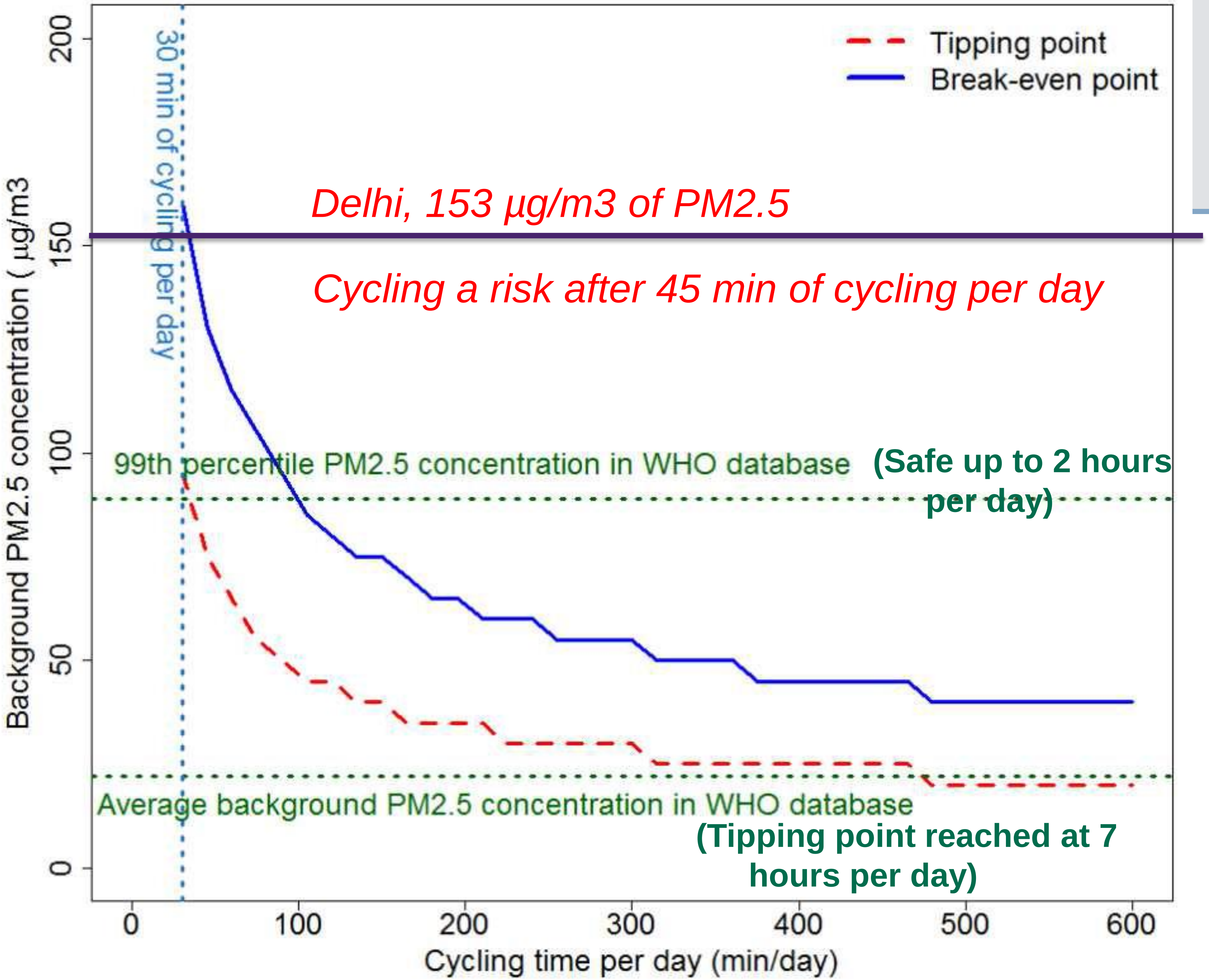
[a] UKCRC Centre for Diet and Activity Research, MRC Epidemiology Unit, University of Cambridge School of Clinical Medicine, Institute of Metabolic Science, Cambridge, UK
[b] Centre for Environmental Policy, Imperial College London, London, UK
[c] Physical Activity and Health Unit, Epidemiology, Biostatistics and Prevention Institute, University of Zurich, Zurich, Switzerland
[d] Center for Research in Environmental Epidemiology (CREAL), Barcelona, Spain
[e] Universitat Pompeu Fabra (UPF), Barcelona, Spain
[f] Centro de Investigación Biomédica en Red de Epidemiología y Salud Pública (CIBERESP), Madrid, Spain
[g] Centre for Epidemiological Research in Nutrition and Health, School of Public Health, University of São Paulo, São Paulo, Brazil
[h] Physical Activity for Health Research Centre (PAHRC), University of Edinburgh, UK

- Current Altmetric score 942: best score over all articles ever published in Preventive Medicine
- In "the top 5% of all research outputs ever tracked by Altmetric"

942

For a given level of air pollution, is there a tipping beyond which additional physical activity does not bring additional benefits, and a "break-even" point beyond which additional physical activity brings greater risks?





Tipping point
Break-even point
Delhi, 153 µg/m3 of PM2.5
Cycling a risk after 45 min of cycling per day
30 min of cycling per day
99th percentile PM2.5 concentration in WHO database
(Safe up to 2 hours per day)
Average background PM2.5 concentration in WHO database
(Tipping point reached at 7 hours per day)
Background PM2.5 concentration (µg/m3
Cycling time per day (min/day)
0
50
100
150
200
0
100
200
300
400
500
600

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Purely technological solutions vs demand management

Woodcock et al. (2009) Comparison of GHG emission policy scenarios in London: ***death per million people***

scenario	physical activity	Air pollution	Traffic mortality	TOTAL
increased active travel	**-528**	**-21**	**+11**	**-538**
lower carbon emission vehicles	**0**	**-17**	**0**	**-17**

Woodcock et al. 2009 The Lancet , v3674, 9705: 1930-1943

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Tech vs behaviour: HIA of London scenarios

Scenario	Technological and behavioural changes
Tech 1	All double-deck buses to hybrid; all single deck buses to zero emission; all taxis to Euro 6 (diesel black cabs)
Tech 2	Tech 1 + Ultra Low Emission Zone (ULEZ) implemented
Tech 3	Tech 2 + ban diesel cars completely from London
Behaviour 1	Cycle superhighway (all reduced car traffic to bicycles) – reduce traffic flow 10%
Behaviour 2	Increased active travel (5% car trips to cycling; 5% car trips to walking) and public transport (10% car trips to bus) = 20% of car trips replaced
Behaviour 3	Most increased active travel (25% car trips to cycling; 15% car trips to walking) and public transport (10% car trips to bus) = 50% of car trips replaced
Combined ideal	No private cars in London (30% car trips to bus, all of which are zero emission; 50% car trips to cycle; 20% car trips to walking) and all black cabs zero emission, including London wide ULEZ standards for remaining vehicles

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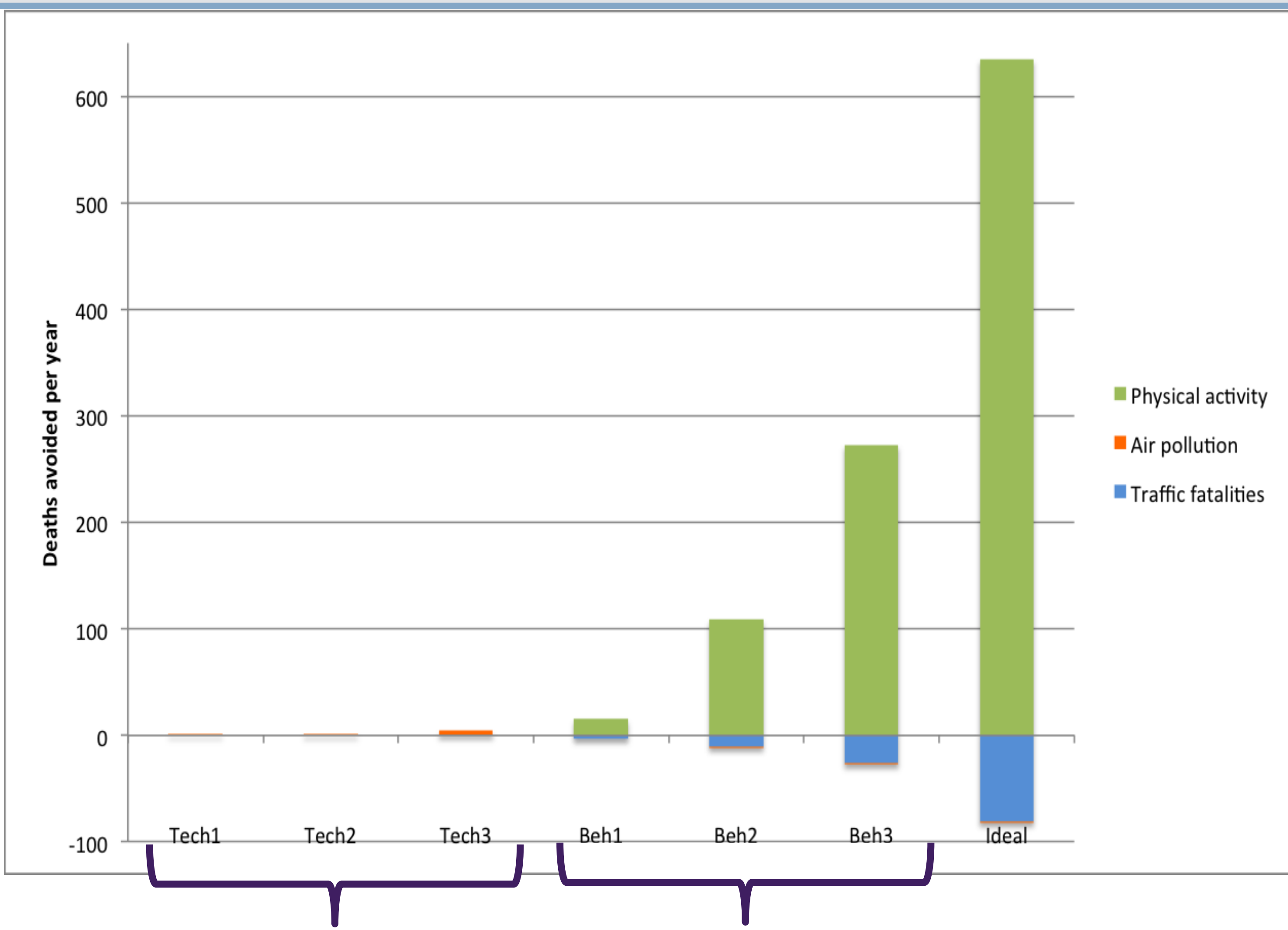
Tech vs behaviour

Deaths avoided/year



Tech scenarios

Behavioural scenarios

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Air pollution strategies:

Co-benefits?

- Climate change
- Greenspace
- Biodiversity
- Noise
- Physical activity
- Traffic injuries
- Diet
- Etc

Trade-offs?

- Reduction in efficiency
- Cooling agents
- Air pollution inhalation
- Traffic injuries
- etc

Audrey de Nazelle
anazelle@imperial.ac.uk

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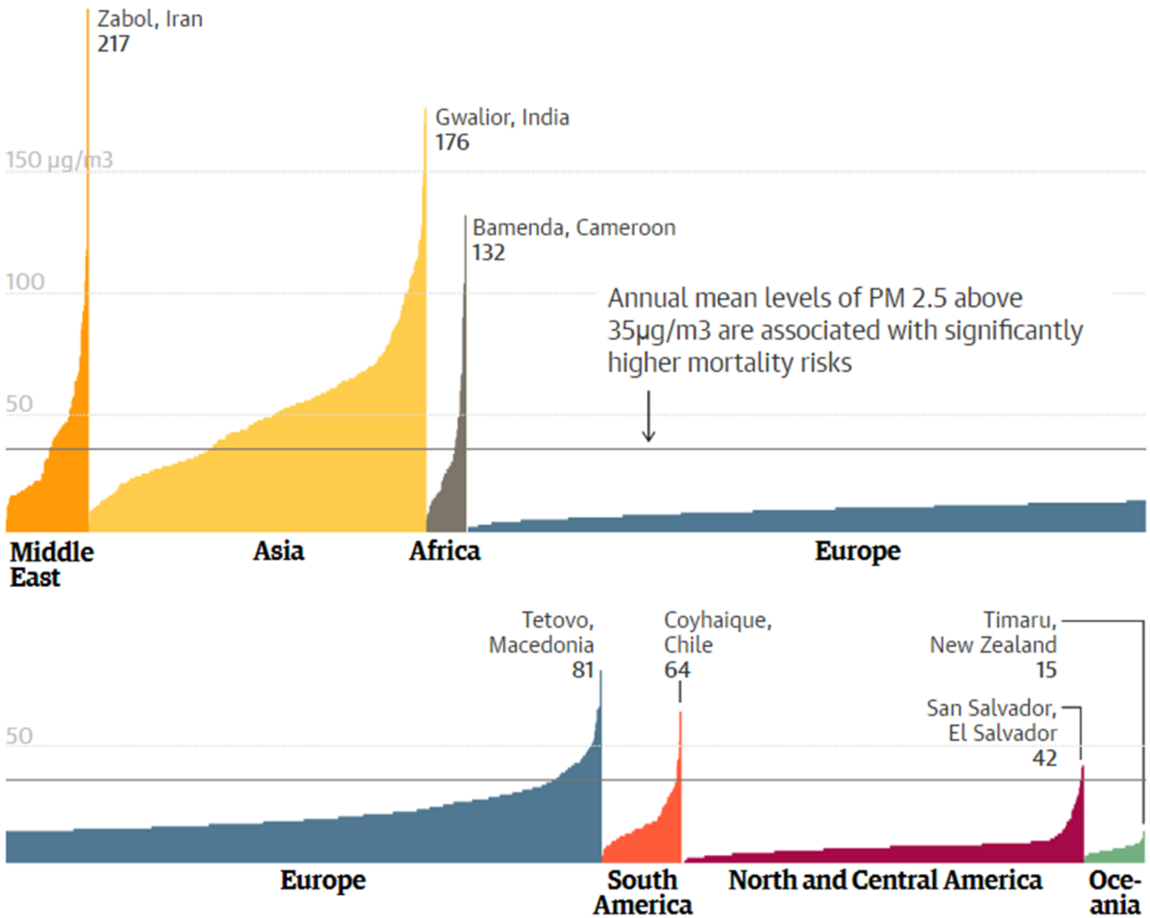
Air Pollution in Cities in Regions of the World

Annual mean of $PM_{2.5}$ in levels for cities by region



Source: WHO, 2016; TG, 2016

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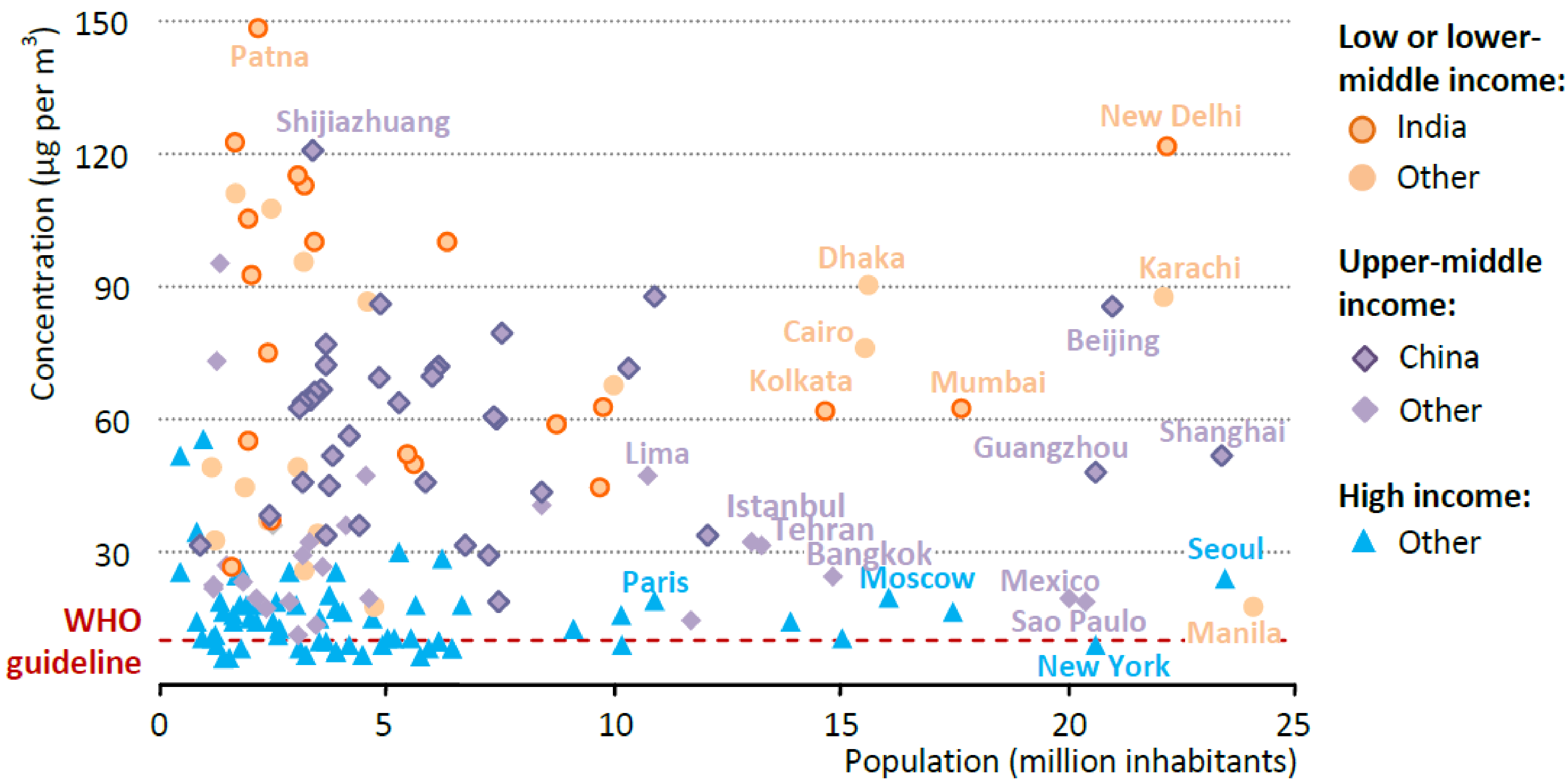
Air Pollution in Cities

Average annual outdoor $PM_{2.5}$ concentrations and population in cities



Source: IEA, 2016

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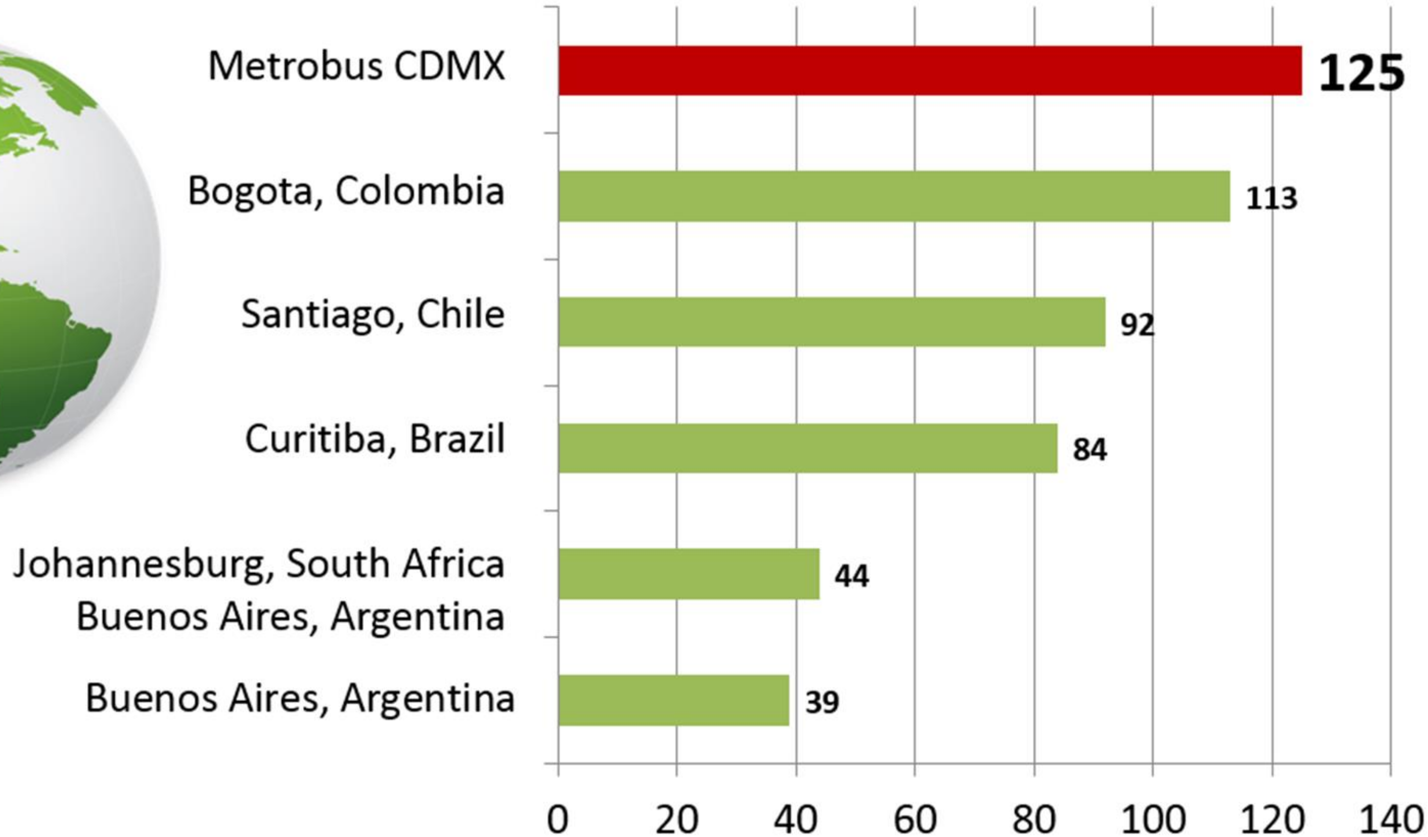
Bus Rapid Transit (BRT) Systems Around the World



Source: Metrobus. (2016). Metrobús: Transporte Sustentable. Mexico City, Mexico