Health and Climate Change 2

Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport

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Lancet 2009; 374: 1930–43

Published **Online** November 25, 2009 DOI:10.1016/S0140-6736(09)61714-1

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This is the second in a **Series** of six papers about health and climate change

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We used Comparative Risk Assessment methods to estimate the health effects of alternative urban land transport scenarios for two settings—London, UK, and Delhi, India. For each setting, we compared a business-as-usual 2030 projection (without policies for reduction of greenhouse gases) with alternative scenarios—lower-carbon-emission motor vehicles, increased active travel, and a combination of the two. We developed separate models that linked transport scenarios with physical activity, air pollution, and risk of road traffic injury. In both cities, we noted that reduction in carbon dioxide emissions through an increase in active travel and less use of motor vehicles had larger health benefits per million population (7332 disability-adjusted life-years [DALYs] in London, and 12 516 in Delhi in 1 year) than from the increased use of lower-emission motor vehicles (160 DALYs in London, and 1696 in Delhi). However, combination of active travel and lower-emission motor vehicles would give the largest benefits (7439 DALYs in London, 12 995 in Delhi), notably from a reduction in the number of years of life lost from ischaemic heart disease (10–19% in London, 11–25% in Delhi). Although uncertainties remain, climate change mitigation in transport should benefit public health substantially. Policies to increase the acceptability, appeal, and safety of active urban travel, and discourage travel in private motor vehicles would provide larger health benefits than would policies that focus solely on lower-emission motor vehicles.

Introduction

In 2004, transport accounted for almost a quarter of carbon dioxide (CO_2) emissions from global energy use.[1] Three-quarters of transport-related emissions are from road traffic.[1] Although large reductions in greenhouse-gas emissions are needed to prevent serious climate destabilisation,[2] emissions from transport are rising faster than from other energy-using sectors and are predicted to increase by 80% between 2007 and 2030.[1]

Reduction in transport-related greenhouse-gas emissions through less use of motor vehicles and increase in the distances walked and cycled could have important health benefits.[3] Reduction in the use of motor vehicles could reduce urban air pollution. Prevalence of physical inactivity and the associated burden of chronic disease could be lowered with increases in the distances walked and cycled.[4] Decrease in motor vehicle traffic also has the potential to reduce danger from road traffic, although exposure to the remaining danger might increase with the number of pedestrians and cyclists.[5] However, the extent of these effects is not known.

We modelled the effects of urban land transportation scenarios on CO_2 emissions and health. Motor vehicles are a source of several other climate-active pollutants, including black carbon, ozone (indirectly), nitrous oxide, and methane. In this Series, Smith and colleagues[6] discuss the climate and health implications of several of these pollutants. However, we have restricted our analysis to CO_2, and modelled emissions only from motor vehicle fuel combustion; full life-cycle modelling was beyond the scope of this analysis.

We focused on urban transport because more than half the world's population lives in cities and because we

Key messages

- Transport-related greenhouse-gas emissions are increasing, with a rapid growth projection in low-income and middle-income countries.
- Production of lower-emission motor vehicles (cars, motorcycles, and trucks) and reduction in travel by motor vehicles are needed to meet targets for reduction of greenhouse-gas emissions.
- Lower-emission motor vehicles would reduce the health burden from urban outdoor air pollution, but a reduction in the distance travelled by motor vehicles could have a greater effect.
- Increase in the distances walked and cycled would also lead to large health benefits. Largest health gains would be from reductions in the prevalence of ischaemic heart disease, cerebrovascular disease, depression, dementia, and diabetes.
- Although reducing motor vehicle use would decrease the injury risk for existing pedestrians and cyclists, if many more people walked and cycled there might be an increase in the number of pedestrian and cycle injuries, since more people would be exposed to the remaining risk.
- Creation of safe urban environments for mass active travel will require prioritisation of the needs of pedestrians and cyclists over those of motorists. Walking or cycling should become the most direct, convenient, and pleasant option for most urban trips.

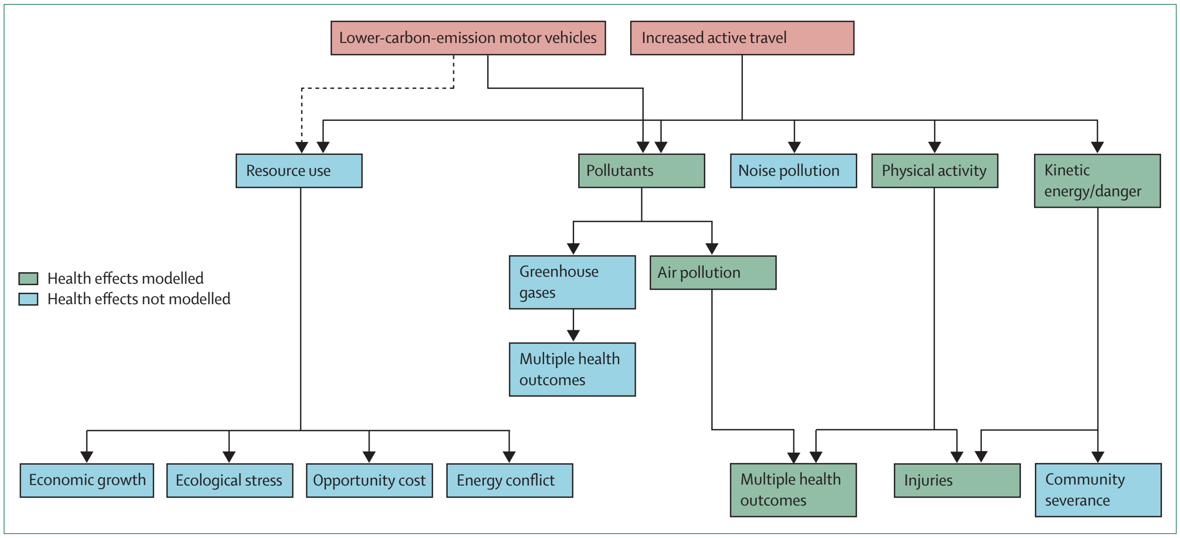

Figure 1: **Modelled and unmodelled pathways relating lower-carbon-emission motor vehicles and increased active travel scenarios with health**

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expected the potential for change and health effects to be greatest in cities. In low-income and middle-income countries, urbanisation is associated with an increased health burden from non-communicable diseases.[7] In the UK, transport in urban areas accounts for 20% of distance (km) travelled by vehicles,[8] but accounts for a disproportionate share of CO_2 emissions and air pollutants as a result of the driving conditions[9] and frequent vehicle cold starts.[10]

We assessed physical activity, outdoor air pollution, and risk of road traffic injury. Although transport can affect health in other ways, including noise pollution, community severance, and the opportunity cost of transportation resource use,[3] the three exposures were selected because the evidence linking them with health outcomes is strong. Figure 1 shows the pathways that were included and excluded.

Modelling the scenarios

We designed scenarios with reference to a large city in a highly motorised country (London, UK), and a large city in a country that is becoming rapidly motorised (Delhi, India).

For London, we developed four scenarios and compared them with a business-as-usual 2030 projection (panel 1; webappendix p 9). In the lower-carbon-emission motor vehicles scenario, we focused on reducing the emission factors from motor vehicles. The increased active travel scenario represented a large increase in cycling, a doubling in the distance walked, and a reduction in car use with a small reduction in road freight. The towards sustainable transport scenario combined the lower-emission motor vehicles from the lower-carbon-emission motor vehicles scenario, and the low car use and longer distances walked and cycled from the increased active travel scenario. The short-distance active travel scenario included the same low-car use as in the increased active travel scenario but with half the rise in distances walked and cycled because of shorter distances and reduced travel times.

The Greater London Authority has adopted a target of 60% cross-sector reduction in emissions by 2025,[11] and the mitigation scenarios draw on the work done to quantify and model this target, including the study for Visioning and Backcasting for Transport (VIBAT)[12] in London and the related Transport and Carbon Simulation model.[13] Table 1 shows the total distance travelled per person and CO_2 emitted from vehicles according to the different scenarios (webappendix pp 10–11).

We developed four equivalent transport scenarios and a business-as-usual projection for Delhi (panel 2; webappendix p 9). Projections for Delhi are based on few data for vehicle and passenger flows. With a lower baseline than London and a rising population, the predicted scenarios focused on prevention of the rise in emissions. No specific targets for reductions have been set by the city authorities. The basis for the Delhi transportation scenarios were the VIBAT in India and Delhi scoping studies,[15,16] and the work done by Wilbur Smith Associates.[17] Table 2 shows the total distance travelled per person and CO_2 emissions for the Delhi transportation scenarios.

See **Online** for webappendix

Modelling health effects

For all scenarios, we estimated the distributions of physical activity and exposure to air pollution. We then used the methods of Comparative Risk Assessment (webappendix pp 6–8) to estimate the change in disease burden. A modified approach was used for road traffic injury in which we calculated absolute numbers of deaths. Although we started with projected data for disease burden for 2010, we compared each mitigation

Panel 1: **London, UK, scenarios**

Business-as-usual 2030

- Ground transport emissions (road and rail) of carbon dioxide (CO_2) in London are projected to increase from 9·6 megatonnes in 2006 to 10·3 megatonnes by 2030.
- 4% increase in total transport CO_2 emissions from 1990 levels.
- Per person transport CO_2 emissions are 1·17 tonnes.
- Basically a projection of present trends in the next 20 years, including some actions to reduce growth in the use of cars and increased investment in public transport. There is little change in the efficiency of the car stock and in use of alternative fuels, and no coherent strategy for change.

Lower-carbon-emission motor vehicles

- Focus is on reduction of the emission of CO_2 from motor vehicles through more efficient engines and fuel switching.
- 35% reduction in transport CO_2 emissions from 1990 levels.
- Per person CO_2 emissions are 0·73 tonnes.
- This scenario relies on an ambitious implementation of technologies, mainly lower-emission motor vehicles and other fuels, with some use of information and communication technologies to reduce the emissions from motorised travel. In this scenario, we assume an average of 95 g/km CO_2 for cars compared with 177 g/km CO_2 at the moment.
- Policy change would require government legislation for mandatory lower-emission motor vehicles and acceptance and use of alternative fuels, motor manufacturers to produce lower-emission vehicles for the mass market, and consumer behaviour change in purchasing these vehicles.

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Increased active travel

- Focus is on replacement of some car travel with active travel. Also includes a small reduction in distance (km) travelled by road freight and a large reduction in the number of motorcycles (from a low baseline).
- 38% reduction in transport CO_2 emissions from 1990 levels.
- Per person CO_2 emissions are 0·69 tonnes.
- High levels of walking and cycling are assumed, similar to the practice in some cities in continental Europe (eg, Copenhagen [Denmark], Delft [Netherlands], Amsterdam [Netherlands], Freiburg [Germany]).
- Assumptions made for this scenario are that the distance walked is more than doubled and distance cycled is increased eight-fold (but from a low baseline).
- Policy change implies a reprioritisation designed to restrict car use and ensure active travel is the most convenient, pleasant, and quickest way to reach destinations.
- Specific policies would include substantial investment in the design of infrastructure for pedestrians and cyclists to reshape the streetscape and public realm, carbon rationing, geographically expanded road pricing, traffic demand management, restrictions on car parking and access, reduced speed limits, and behavioural change approaches (eg, raised awareness, travel planning).

Towards sustainable transport

- Represents progress towards a sustainable transport system that includes complete implementation of the lower-carbon-emission motor vehicles and increased active transport scenarios.
- 60% reduction in transport CO_2 emissions from 1990 levels.
- Per person CO_2 emissions are 0·45 tonnes.
- Policy change would require high-intensity implementation and effectiveness of all measures.
- Transport emissions in London and Delhi are converging and moving towards sustainable levels. Further reduction in emissions would still be needed to achieve truly sustainable transport.
- Further reductions could occur through use of electric vehicles with energy from low-carbon sources; reduction of trip distances; and continued modal shift from car use to walking or cycling.

Short-distances active travel (sensitivity analysis)

- In this scenario, we envisaged the same motor vehicle distances as in the sustainable transport scenario but only half the increase in distances walked and cycled. This scenario represents less travel and shorter travel distances than in the other scenarios.

scenario against the 2030 business-as-usual transport scenario—ie, if 1000 individuals died in 2010, we estimated the number of deaths for 2030 business as usual and every mitigation scenario. We then calculated the difference in the number of deaths for each mitigation scenario compared with 2030 business-as-usual scenario to estimate the effect of the mitigation strategy. We used this approach because the effects of other changes on disease burdens were difficult to predict. Estimates of the effect of the relevant risk factor on health outcomes, including exposure-response associations, were obtained mostly from systematic reviews. Baseline estimates of disease burden were obtained from Mathers and Loncar[18] and from STATS19[19] and data provided by the Delhi police.[20]

We estimated the health effects of the changes in active travel that would arise with the different transportation scenarios (full details of the methods are provided in the webappendix pp 12–19). The scenarios were used to provide estimates of mean distances walked and cycled per year, which we used to estimate mean time spent walking and cycling per week. We then created travel-time distributions by fitting log-normal distributions. Because we modelled disease burdens by age and sex, we needed age-specific and sex-specific travel-time distributions. Estimates of how travel times and speeds varied by age and sex were obtained from a travel survey of London, UK.[21] Table 3 provides the walking and cycling speeds. The London travel time and speed ratios were used for Delhi because of the absence of high-quality data for Delhi. For the two scenarios with high levels of cycling, the estimated age and sex distributions were based on data from the Netherlands where levels of cycling are similar to those in these scenarios.[22] In London and Delhi, men are more likely to cycle than are women, whereas the proportions are similar in the Netherlands. Intensity of physical activity is usually measured with metabolic equivalents (METs); one MET is the typical energy expenditure of an individual at rest (1 kcal/kg/h). The distributions of the times for walking and cycling were converted into distributions of METs with tabulated data for different activities and speeds.[23] Median MET times (h) were taken as the best summary statistic of active travel for all age–sex groups. To estimate total physical activity, we added these estimates to those of non-travel-related physical activity derived from surveys[24,25] (webappendix p 13).

We did systematic searches until March, 2009, for studies of the association between moderate-intensity physical activity and the incidence (fatal and non-fatal) of prespecified conditions included in the assessment of global burden of disease (webappendix pp 13–18). We selected the most recent high-quality systematic reviews for every condition (except depression) to assess the evidence for a causal association. For depression, we did a broad search and assessed the main studies. When the association between physical activity and disease outcome is modelled, the shape of the exposure-response function is important, but this association has been assessed in only a few systematic reviews.

If the systematic review provided an exposure-response function, we used that. If not, then we used three exposure-response functions with different shapes. These were a square-root linear model (webappendix pp 18–19), a linear model, and a linear model with a threshold (with an assumption of no further benefit beyond a particular exposure). We used the relative risk from the systematic review, estimated the corresponding exposure in METs, and then applied each of the three different shapes to generate exposure-response functions between MET time (h per week) and the relevant disease outcome. When we modelled the health effects of the different scenarios, we selected the median overall change in disability-adjusted life-years (DALYs) from physical activity as our main estimate, with the range representing the uncertainty bounds (webappendix p 18).

We showed the potential effect on the population distribution of body-mass index by modelling the effect of the scenario with increased active travel on the prevalence of obesity and overweight for men aged 45–59 years in London, assuming a constant energy intake.[26]

Figure 2: New bicycle facilities in Delhi, India

	Car	Bus	Rail	HGV	Walking	Bicycle	Motorcycle	Total (km)	CO_2 emissions (tonnes)*
2010	5599	1110	2630	244	262	151	70	10 065	1·27
2030 BAU	5053	1044	2776	217	233	137	69	9528	1·17
Lower-carbon-emission motor vehicles	5053	1044	2776	217	233	137	69	9528	0·73
Increased active travel	3698	1044	2776	173	573	1239	25	9528	0·69
Towards sustainable transport	3698	1044	2776	173	573	1239	25	9528	0·45
Short-distances active travel	3698	1044	2776	173	403	688	25	8807	0·45

HGV=heavy goods vehicle. CO_2=carbon dioxide. BAU=business as usual. *London scenarios included the effects of a range of policy packages that were not included in the Delhi scenarios.

Table 1: Distance travelled and CO_2 emissions per person per year in London, UK, for each scenario

Although traffic generates various pollutants, we modelled only the health effects of fine particulate matter (particulate matter with aerodynamic diameter 2·5 μm or less [$PM_{2·5}$]) for which the strongest evidence of health effects exists.[27] The basis for our method is WHO's Comparative Risk Assessment exercise for urban air pollution.[27] The methods are summarised here and further details are provided in the webappendix (pp 20–22).

Because few data exist about emissions and ambient concentrations of $PM_{2·5}$ in London, we modelled the PM_{10} concentrations for our transportation scenarios and then assumed that the changes in concentrations between our mitigation scenarios and 2030 business-as-

Panel 2: **Delhi, India, scenarios**

Business as usual 2030

- Projected population increase accounts for some of the projected increase in emissions.
- We estimated that ground transport emissions for Delhi, starting with a lower baseline than in London, UK, would increase from 6·1 million tonnes of carbon dioxide (CO_2) in 2004 to 19·6 million tonnes in 2030.
- 526% rise in CO_2 emissions from 1990 values.
- Per person CO_2 emissions are 0·75 tonnes.
- Projection of existing trends and no coherent strategy to reduce the increase in the use of cars, but includes an anticipated increase in rail use.
- Most vehicles in the UK are expected to achieve Euro 6 emission[14] standards by 2020. In the primary analyses, we assumed that vehicles in Delhi will have achieved this standard, which is considerably lower than present levels, by 2030. If emission factors remained unchanged, CO_2 and particulate-matter emissions would be much higher than 0·75 tonnes per person.

Lower-carbon-emission motor vehicles

- 447% rise in transport CO_2 emissions from 1990.
- Per person CO_2 emissions are 0·66 tonnes.
- This scenario relies on an ambitious implementation of vehicle technologies, and represents an anticipated increase in rail use.
- The policy trajectory would require government legislation on mandatory lower-emission motor vehicles and acceptance and use of alternative fuels, motor manufacturers to produce lower-emission motor vehicles for the mass market, and consumer behaviour change in purchasing such vehicles.

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Increased active travel

- 235% rise in transport CO_2 emissions from 1990.
- Per person CO_2 emissions are 0·40 tonnes.
- In this scenario, a reversal of present trends is assumed with a small increase in the distance walked and more than double increase in distance cycled. It represents a large increase in rail use and small increase in bus use. Other assumptions made are a slower increase in distance (km) travelled in freight vehicles than in the business-as-usual scenario, substantial reductions in motorcycle use, and similar car use to 2010.
- Policy change would require prioritisation for people who walk and cycle, and restriction of car travel to ensure active travel is the safest and most convenient, pleasant, and quickest way to reach destinations. The reallocation of space to provide a high-quality streetscape that is designed to meet the needs of pedestrians and cyclists is of particular importance. Rather than active travel being the mode of necessity for those unable to afford motor vehicles it would become the mode of choice.
- Specific policies would perhaps include substantial investment in infrastructure designed for pedestrians and cyclists rather than for cars, carbon rationing, road pricing, traffic demand management, restrictions for car parking and access, reduced speed limits, and behavioural change approaches (eg, raised awareness, travel planning).

Towards sustainable transport

- This scenario represents progress towards a sustainable transport system that includes complete implementation of the lower-carbon-emission motor vehicles and increased active transport scenarios.
- 199% increase in CO_2 emissions from 1990.
- Per person CO_2 emissions are 0·36 tonnes.
- Emissions per person are higher than in 1990 but lower than in 2010.
- Policy change would require high-intensity implementation and effectiveness of all measures.
- Transport emissions in Delhi and London are converging and moving towards sustainable levels. Further reduction in emissions would still be needed to achieve truly sustainable transport.
- Further reduction could occur through use of electric vehicles with energy from low-carbon sources; shorter-distance trips; and continued shift from car use to walking or cycling.

Short-distance active travel (sensitivity analysis)

- In this scenario, we envisaged the same motor vehicle distances travelled as in the sustainable transport scenario but only half the increase in distances walked and cycled. This scenario represents less travel and shorter travel distances than in the other scenarios.

usual scenario were in the $PM_{2\cdot5}$ size range. This assumption seems reasonable since the transportation scenarios would mainly affect the $PM_{2\cdot5}$ subset of PM_{10}. For London, population-weighted yearly average PM_{10} concentrations for every scenario were estimated with an emission-dispersion model (webappendix pp 20–21).[28] To account for changes in the contribution of traffic outside London to the concentrations of PM in London because of the long-range transport of pollutants, we assumed that the same changes occurred in other European cities. We assumed that the non-traffic sources of PM did not change. For Delhi we used a simpler model because of few available data. $PM_{2\cdot5}$ concentrations were estimated for each scenario from source-specific emissions data with the simple interactive models for better air quality (SIM-AIR, version 1.3).[29]

Further information about the model inputs and assumptions are provided in the webappendix (p 22). We considered the effects of PM on mortality from cardiorespiratory disease and lung cancer in adults, and

	Car	Bus	Rail	HGV	Walking	Bicycle	Two-wheel motorcycle	Three-wheel motorcycle	Total (km)	CO_2 emissions (tonnes)*
2010	1118	2860	582	36	536	650	1716	312	9820	0·47
2030 BAU	2995	2860	1456	104	463	390	2860	260	11 388	0·75
Lower-carbon-emission motor vehicles	2995	2860	1456	104	463	390	2860	260	11 388	0·66
Increased active travel	1186	3245	1950	68	616	1716	1258	260	10 299	0·40
Towards sustainable transport	1186	3245	1950	68	616	1716	1258	260	10 299	0·36
Short-distance active	1186	3245	1950	68	540	1053	1258	260	9559	0·36

HGV=heavy goods vehicle. CO_2=carbon dioxide. BAU=business as usual. *London, UK, scenarios included the effects of a range of policy packages that were not included in the Delhi scenarios.

Table 2: **Distance travelled and CO_2 emissions per person per year in Delhi, India, for each scenario**

from acute respiratory infections in children. In the main analysis, we used a linear model for London where present and projected yearly average $PM_{2·5}$ concentrations are much lower than 40 μg/m³, and a log-linear model for Delhi where the concentrations are greater than 40 μg/m³. Table 4 shows the concentrations for each of the scenarios. In the sensitivity analysis, we also estimated health effects using a log-linear model for London and a linear model for Delhi.

Changes in the amount of motor vehicle traffic and in the numbers of pedestrians and cyclists in the transportation scenarios could affect the numbers of individuals injured as a result of road traffic. We used a different approach for injury from that used for physical activity and air pollution. We developed a model to generate absolute numbers, rather than relative risks, of deaths from road traffic collisions. Therefore, we used these data in preference to those available at the national level from the global burden of disease project.

We constructed an injury matrix for road traffic that described the injury risk per unit of travel for each type of road user. For London, numerator data were obtained from STATS19,[19] and for Delhi, they were obtained from the Delhi police.[20] Denominator data for the number of vehicles and average distance (km) travelled were based on the scenarios with additional data from Transport for London (webappendix p 23).

Because injury risk for each group of road users also depends on the distance travelled by other road users, we estimated the injury risk per unit of travel from the vehicles that could cause injury. For example, the risk of a pedestrian being injured by a car was expressed as a linear function of both the distance walked and the distance travelled by cars. This method is an elaboration of the injury model described by Bhalla and colleagues (webappendix pp 23–26).[30] For London, we adapted this method to take into account variations in injury risks over different parts of the road network; data for Delhi were insufficient. For all scenarios we estimated the expected number of deaths and serious injuries after changes to the distance travelled by all the included road users. These were then used to estimate the changes in years of life lost (YLL) and years of healthy life lost as a result of disability (YLD). To calculate YLLs and YLDs, we assumed that their ratios to deaths were the same as those from the global burden of disease national data for road traffic injuries in both countries.

	Walking		Cycling	
	Men	Women	Men	Women
15–29 years	4·6	4·0	14·8	12·0
30–44 years	4·3	3·7	17·7	14·4
45–59 years	4·0	3·4	14·0	11·3
60–69 years	3·4	2·9	10·6	8·6
70–79 years	2·8	2·4	9·8	7·9
≥80 years	2·4	2·1	8·9	7·2

Table 3: **Walking and cycling speeds (km/h) by age group**

	2010	BAU	Lower-carbon-emission vehicles	Increased active travel	Towards sustainable transport
London, UK	10·1	8·2	7·8	7·7	7·4
Delhi, India	88·7	90·4	79·0	75·5	72·3
Sensitivity analysis					
Delhi (high)*	88·7	134·0	108·4	82·7	78·4

BAU=business as usual. *Fewer improvements in vehicle emission factors than in the main Delhi analysis.

Table 4: **Estimates of air pollution (particulate matter with aerodynamic diameter of 2·5 μm or less) concentrations (μg/m³)**

Sensitivity analyses were done to take into account possible reductions in injury risk for pedestrians and cyclists from measures to increase their safety. Such measures (eg, reduced speed limits, increased enforcement of driving rules, and improved infrastructure) could be expected as part of the scenarios for increased active travel. We therefore used the injury rates per 100 million km walked and cycled for the Netherlands, a country in which people do a lot of walking and cycling with low injury rates.

Findings

Evidence from systematic reviews showed that increased physical activity reduced the risk of cardiovascular disease, depression, dementia, diabetes, breast cancer, and colon cancer. Table 5 shows the results of our overview, strength of the association between the

	Systematic review/ study, year	Studies included	RR (95% CI) and corresponding exposure	Age group (years)	RR reduction from 2·5 h per week of moderate intensity physical activity		Maximum exposure per week for linear threshold
					Square-root model	Linear model	
Dementia (U087)	Hamer et al, 2009 (search year 2007)[31]	16 cohort studies (163 797 people, 3219 cases)	0·72 (0·60–0·86); 33 METs per week (>1657 kcal per week)[32]	≥45	–0·18	–0·11	21 METs (>2 miles walked per day)[33]
Cardiovascular diseases (ischaemic heart disease [U106], hypertensive heart disease [U107], cerebrovascular disease [U108])	Hamer et al, 2008 (search year 2007)[34]	18 cohort studies (459 833 people, 192 49 cases)	0·84 (0·79–0·90); 7·5 METs per week (3 h walking per week)	≥30	–0·19	–0·23	52·5 METs (>10·5 MET h per day from walking)[35]
Diabetes (U079)	Jeon et al, 2006 (search year 2006)[36]	10 cohort studies (301 211 people, 9367 cases)	0·83 (0·75–0·91); 10 METs per week	≥30	–0·18	–0·19	22·5 METs (>4 h per week moderate activity)[37]
Breast cancer (U069)	Monninkhof et al, 2007 (search year 2006)[38]	19 cohort studies, 29 case control studies	0·94 (0·92–0·97) for each additional h per week	≥15 (women only)	Not used	–0·13	57·8 METs[39]
Colon cancer (U064)	Harriss et al, 2009 (search year 2007)[40]	15 cohorts (7873 cases)	Men 0·80 (0·67–0·96); women 0·86 (0·76 to 0·98); METs per week: 30·1 for men and 30·9 for women	≥15	–0·13 for men, –0·09 for women	–0·08 for men, –0·05 for women	47 METs[41]
Depression (U082)	Paffenbarger et al, 1994[42]	Cohort study (10 201 men, 387 first episodes of physician-diagnosed depression)	1·0*, 6·9 METs per week (<1000 kcal per week); 0·83*, 24·2 METs per week (1000–2499 kcal per week); 0·72*, 63·7 METs per week (≥2500 kcal per week)	≥30 (15–29: smaller effect assumed)	–0·14 (–0·07†)	–0·07 (–0·03†)	34·6 METs (>2511 kcal per week)[42]

RR=relative risk. METs=metabolic equivalents. *95% CIs not available. †Effect used in age group 15–29 years.

Table 5: **Studies used to generate exposure-response functions by condition (global burden of disease code)**

	2010		Business as usual		Increased active travel		Short-distance active travel	
	Men	Women	Men	Women	Men	Women	Men	Women
15–29 years	95 (51–174)	107 (58 –196)	84 (45–154)	95 (51–174)	329 (179–604)	371 (202–680)	198 (107–363)	223 (121–409)
30–44 years	86 (47–158)	97 (53–178	77 (17–140)	86 (47–158)	299 (163–549)	337 (183–613)	180 (98–330)	203 (110–372)
45–59 years	70 (38–128)	79 (42–144)	62 (33–113)	70 (38–128)	243 (132–445)	273 (148–501)	146 (79–267)	164 (89–301)
60–69 years	77 (42–141)	87 (47–159)	68 (37–125)	77 (42–141)	267 (145–490)	301 (164–552)	161 (87–295)	181 (98–332)
70–79 years	69 (37–125)	77 (41–141)	61 (33–111)	69 (37–125)	214 (116–392)	241 (131–442)	143 (77–261)	161 (87–294)
≥80 years	50 (27–92)	57 (30–104)	45 (24–82)	50 (27–92)	155 (84–284)	174 (95–320)	105 (57–192)	118 (64–216)

Table 6: **Median active travel times per week (min; 25th to 75th percentiles) by age group in London, UK**

exposure and outcome, and estimates used in the modelling (webappendix pp 27–31).

All these conditions, except for depression and dementia, were included in the earlier Comparative Risk Assessment study of physical activity (search date 2001).[43] Physical activity seems to reduce the duration and severity of existing depression, and also the incidence.[44–46] Of particular relevance to this project were longitudinal studies in which new episodes of doctor-diagnosed depression arose less frequently in individuals who undertook regular physical activity, including walking and cycling, than in those who did not.[42] Evidence from randomised trials of individuals with memory loss and decline in cognitive function lend support to the observational epidemiological evidence for physical activity and dementia.[47,48] The changes in the distances walked and cycled in the scenarios were converted into changes in the time spent in active travel and MET time (h) for all age groups in London and Delhi. Table 6 and table 7 show the median times spent in active travel, and median MET times for travel and other activities are presented in the webappendix (pp 32–33). Figure 3 shows the distributions of the active travel times for men in one age group for the mitigation scenarios.

Table 8 shows the estimated changes in health burden with the different transport scenarios. For London, with the lower-carbon-emission motor vehicles scenario, the total number of premature deaths and DALYs were reduced through reductions in the rate of mortality caused by air pollution. For the increased active travel and sustainable transport scenarios, substantial reductions were noted in premature deaths and DALYs as a result of increased physical activity and reductions in the rates of mortality caused by air pollution. These

	2010		Business as usual		Increased active travel		Short-distance active travel	
	Men	Women	Men	Women	Men	Women	Men	Women
15–29 years	203 (92–446)	229 (104–502)	153 (69–335)	172 (78–377)	410 (186–900)	462 (210–1014)	269 (122–590)	303 (137–665)
30–44 years	185 (84–405)	208 (94–457)	139 (63–304)	156 (71–343)	373 (169–818)	420 (191–922)	245 (111–537)	275 (125–604)
45–59 years	150 (68–328)	169 (76–370)	112 (51–246)	127 (57–278)	302 (137–663)	340 (154–747)	198 (90–434)	223 (101–490)
60–69 years	165 (75–362)	186 (84–408)	124 (56–272)	140 (63–306)	333 (151–731)	375 (170–823)	218 (99–479)	246 (112–540)
70–79 years	147 (66–321)	165 (75–362)	110 (50–241)	124 (56–272)	246 (112–540)	277 (126–608)	161 (73–354)	182 (82–399)
≥80 years	108 (49–236)	122 (55–267)	81 (36–175)	91 (42–200)	164 (74–360)	185 (84–405)	108 (49–236)	121 (55–266)

Table 7: **Median active travel times per week (min; 25th to 75th percentiles) by age group in Delhi, India**

gains more than compensated for the increase in the burden from road traffic injuries. In 1 year, compared with business as usual, the lower-carbon-emission motor vehicles scenario saved 160 DALYs and 17 premature deaths per million population, increased active travel saved 7332 DALYs and 530 premature deaths per million population, and the towards sustainable transport scenario saved 7439 DALYs and 541 premature deaths per million population. Disease-specific estimates for each of the different exposure-response functions are provided in the webappendix (pp 34–36). For London, the largest gains were from reductions in ischaemic heart disease (10–19% of total ischaemic heart disease burden), cerebrovascular disease (10–18% of cerebrovascular disease burden), dementia (7–8% of dementia disease burden), depression (4–6% of total depression disease burden), and breast cancer (12–13% of total breast cancer disease burden). Although walking and cycling became safer per km travelled the large increase in the total distance walked and cycled led to the road traffic injury disease burden rising by 39%.

For Delhi, the lower-carbon-emission motor vehicles and increased active travel scenarios resulted in a greater health gain from reduced air pollution than for London. Unlike for London, we noted that in Delhi the increased active travel scenario substantially reduced the burden of road traffic injury compared with business as usual. However, the estimated burden of road traffic injury with increased active travel was still higher than for 2010. For 1 year, compared with business as usual, the lower-carbon-emission motor vehicles scenario saved a total of 1696 DALYs and 74 premature deaths per million population, increased active travel scenario saved 12 516 DALYs and 511 premature deaths per million population, and the towards sustainable transport scenario saved 12 995 DALYs and 532 premature deaths per million population. The largest health gains were from reductions in ischaemic heart disease (11–25% of total ischaemic heart disease burden), cerebrovascular disease (11–25% of total cerebrovascular disease burden), and diabetes (6–17% of total diabetes disease burden); the reduction in road traffic injuries was 27%.

In both cities, we noted that the risk to pedestrians, and especially cyclists, was higher from heavy goods vehicles (HGVs) than from cars. On A-type roads (ie, main roads but not motorways or freeways) in London, the risk of an injury for a cyclist was 23 times higher per km from HGVs than from cars. For pedestrians, the risk from HGVs was four-fold greater than that from cars. For cyclists in Delhi, risk of injury from HGVs was 30 times greater than that from cars, whereas for pedestrians the difference was 15-fold. Indicating the effect on obesity, the proportion of men (aged 45–59 years) who were obese decreased by about 5% when compared with the increased active travel scenario against the 2010 baseline for London (table 9).

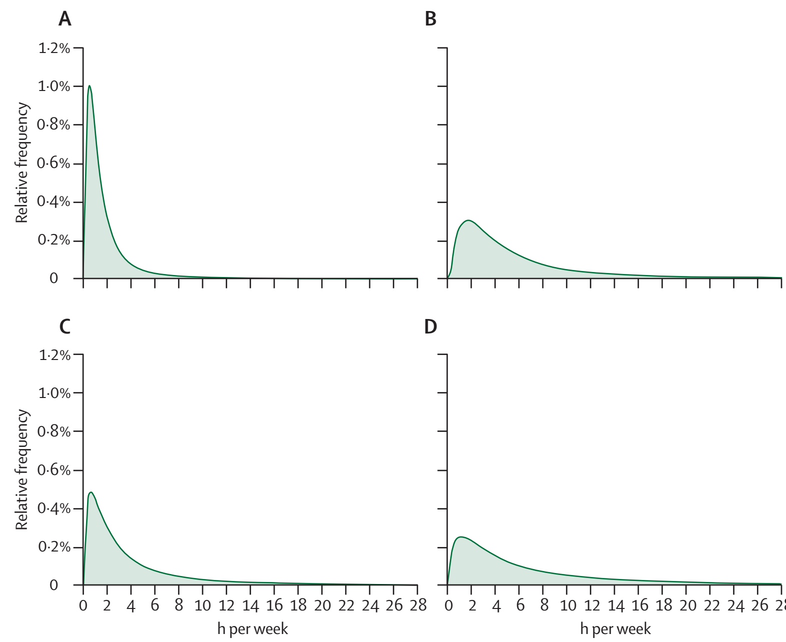

Figure 3: **Distribution of active travel times for men aged 45–59 years in London, UK, and Delhi, India**
(A) London 2010. (B) London: increased active travel. (C) Delhi 2010. (D) Delhi: increased active travel.

Although there were many sources of uncertainty in the development and modelling of the scenarios, we assessed the effect of a few sources of uncertainty one at a time. We focused on the exposure-response relation for air pollution and physical activity, PM emissions from vehicles in Delhi for 2030 business as usual, achievement of best safety practice for pedestrians and cyclists to avoid

	Delhi			London		
	Lower-carbon-emission motor vehicles	Increased active travel	Towards sustainable transport	Lower-carbon-emission motor vehicles	Increased active travel	Towards sustainable transport
Physical activity						
Premature deaths	0	–352	–352	0	–528	–528
YLL	0	–6040	–6040	0	–5496	–5496
YLD	0	–816	–816	0	–2245	–2245
DALYs	0	–6857	–6857	0	–7742	–7742
Air pollution						
Premature deaths	–74	–99	–122	–17	–21	–33
YLL	–1696	–2240	–2749	–160	–200	–319
YLD	0	0	0	0	0	0
DALYs	–1696	–2240	–2749	–160	–200	–319
Road traffic crashes*						
Premature deaths	0	–67	–67	0	11	11
YLL	0	–2809	–2809	0	418	418
YLD	0	–730	–730	0	101	101
DALYs	0	–3540	–3540	0	519	519
Total†						
Premature deaths	–74	–511	–532	–17	–530	–541
YLL	–1696	–10 969	–11 448	–160	–5188	–5295
YLD	0	–1547	–1547	0	–2144	–2144
DALYs	–1696	–12 516	–12 995	–160	–7332	–7439

Negative numbers indicate reduction in disease burden. YLL=years of life lost. YLD=years of healthy life lost as a result of disability. DALYs=disability-adjusted life-years. *Injuries were calculated directly and then transformed into YLLs and YLDs rather than with a Comparative Risk Assessment approach. †Data were adjusted for double counting for the effect on cardiovascular disease.

Table 8: **Health effects (per million population) in 1 year in Delhi, India, and London, UK, compared with business as usual**

	2010	2030 more active travel
Walking (min per day)	7·5	22
Cycling (min per day)	2·5	14
Driving (min per day)	50	25
Energy intake (MJ per day)	11·06	11·06
Obesity (%)	25·7	20·6
Overweight (%)	77·1	71·7

Table 9: **Prevalence of obesity and overweight in men (aged 45–59 years) in London, UK**

injuries, and uptake of active travel for physical activity and risk of injury (webappendix pp 37–38 for full results of the sensitivity analyses).

When we applied a linear model for air pollution in Delhi and a log-linear model for London we noted greater health benefits than in the main analysis. We also noted increased health effects in the mitigation scenarios when we assumed a less optimistic 2030 business as usual for Delhi, in which PM emissions per km from vehicles stayed at present levels rather than achieving Euro 6 standards (webappendix p 37).[14] In this analysis, 7590 DALYS as a result of reduced air pollution were saved with the towards sustainable transport scenario compared with 2749 DALYs in the main analysis.

When we applied injury rates per km walked and cycled from the Netherlands to our respective distances in the increased active travel scenarios, the injury rates were reduced by 14% in London and by 58% in Delhi (webappendix p 38).

In the short-distances active travel scenario, we noted smaller benefits from increased physical activity combined with a smaller increase in road traffic injuries for London, and a substantial reduction in injuries in Delhi compared with the increased active travel scenarios. In both cities, this led to smaller overall health gains per million population (4817 DALYs in London and 11 704 DALYs in Delhi).

For London and Delhi, the increased active travel scenarios saved more DALYs than did the lower-carbon-emission motor vehicle scenarios. For London, the effects from physical activity were greater than were those from air pollution or injuries in the towards sustainable transport scenario for all sensitivity analyses. For Delhi, ranking of the effects was sensitive to the model used.

Strengths and weaknesses

We noted that a scenario that represented a move towards sustainable transport could provide substantial reductions in chronic diseases, including ischaemic heart disease, stroke, depression, and dementia. The health gains were larger from increases in active travel and reductions in use of motor vehicles than from use of lower-carbon-emission motor vehicles.

Panel 3 shows the key assumptions used to model the scenarios. Our estimates of health effects depend crucially on the structure and parameters of the model. With respect to structure, several important transport-related exposure-outcome associations were not included—eg, the effect of traffic noise on health or effect of biofuels for transport on food availability. Additionally, we did not assess the wide economic or social effects.

To avoid double counting, we did not consider the health effect of the reductions in body-mass index that we might expect with increased active travel in our physical activity model. We also did not include the effect of physical activity on nicotine cravings and on smoking cessation. Moderate exercise, such as walking and cycling, reduces cigarette cravings.[49] In a Cochrane review[49] of physical activity interventions for smoking cessation, the odds of success of smoking cessation were 1·24-times higher than in control groups. With the small sample sizes of studies, this difference was not significant but if the point estimate is accurate, then applying this to the UK the increase in distances walked and cycled in the population as a whole could lead to an increase in tens of thousands of smokers stopping every year.

We used projected disease burden data for 2010. Changes with time in health status other than those directly linked to transport were not included. Thus we

Panel 3: **Key assumptions**

Baseline

- Population and health status based on WHO projections (global burden of disease and Comparative Risk Assessment) for 2010, and present emissions sources and air pollution levels.
- Our use of data from the whole of India to estimate disease burden in Delhi might have resulted in an underestimation of the incidence of coronary heart disease and related risk factors.

Business as usual (2030)

London, UK

- Population assumed to increase by 13% compared with 2010, and vehicle-km (excluding walking and cycling) to increase by 2%.
- Vehicle technology (emissions per vehicle-km) based on model of change achieved by 2025.
- Non-road transport sources of pollution as for 2010.

Delhi, India

- Population assumed to increase by 49% compared with 2010, vehicle-km (excluding walking and cycling) to increase by 187%.
- Main analysis assumes achievement of Euro 6 emission standards by 2030 entailing substantial improvements in carbon dioxide (CO_2) and particulate matter emissions per vehicle-km, compared with 2010 and phasing out of two-stroke two-wheeled vehicles. In the sensitivity analysis, no change in vehicle technology (CO_2 or particulate matter emissions per vehicle-km) from 2010 except for phasing out of two-stroke two-wheeled vehicles.
- Decrease in sulphur content of fuel from 350 parts per million to 50 parts per million; industrial emissions at 2010 values.

Mitigation scenarios

- Main comparison: 2030 scenarios with 2030 business as usual. The effect per million population in 2010 based on such comparisons is not affected by differences in population size (except by affecting local pollutant emissions) or changes with time in exposures (except by affecting the 2030 baseline for business as usual).
- For London, the assumption was that reduction in emissions from transport in London was matched elsewhere in Europe (effect on regional air masses).
- We modelled the health effects of the different transport scenarios as if they had been implemented instantaneously. In reality, background changes and other changes that might accompany the scenarios would affect the health effects.

(Continues in next column)

(Continued from previous column)

Health effects

- Derived from attributable burdens calculated with adaptation of the method for Comparative Risk Assessment: assumes health effects of a scenario are represented by the difference in modelled exposures compared with the baseline, from which attributable burdens are computed with relevant relative risks and 2010 mortality and disease rates. Ignores time lags even for chronic disease and lung cancer, and any irreversibility of the effect of past exposures.
- Years of life lost (YLL) computed as a difference between age at death and the theoretical optimum life expectancy at that age which, to be normative across populations, is always calculated with reference to Japanese life tables.
- No time discounting or age-weighting of health effects.
- No inclusion of indirect health effects (eg, operating through economic pathways) or those that arise from success in restricting climate change.
- Model used for direct calculation of death from road traffic crashes and, for London, injury rates. Data converted to YLLs and years of healthy life lost as a result of disability using ratios from the 2010 global burden of disease study.
- Use of population median as best representative of physical activity. Assumption of no changes in non-travel physical activity.

did not consider other changes in road safety, emissions of PM from other sources, changes in background physical activity, or population age structure.

We noted that there was greater uncertainty for the variables for Delhi than for London—in particular, for estimates of the level and distribution of non-travel physical activity for Delhi. Confidence in future estimates for Delhi could be improved if primary data are gathered.

Our estimates of the health effects of physical activity are susceptible to measurement error and confounding. In a systematic review,[50] physical activity, when measured objectively, had a stronger association with mortality than did self-reported physical activity, which might suggest that we underestimated the effect. However, the effect of residual confounding is not as clear. With the large contribution of changes in ischaemic heart disease to the overall effect, the exposure-response function that we selected is especially important. Evidence for a large effect of walking on cardiovascular disease accords with data from a systematic review done after our search, in which the association between weekly walking METs and coronary heart disease was near linear.[51]

The plausibility of our scenarios can be questioned. In the increased active travel and the sustainable transport scenarios, we envisage large increases in the distances walked and cycled, and a 37% reduction in car use in London (after exclusion of light-goods vehicles). In the dataset from the London area travel survey,[21] 55% of distance travelled in cars was accounted for by trips shorter than 8 km (ie, within cycling distance), including

11% by trips shorter than 2 km (ie, within walking distance), suggesting that large reductions in car use are possible. Another assumption is that changes to total distances walked and cycled lead to changes in the respective median times, and that there is no change in the amount of other physical activity.

The main uncertainties in modelling the health effects of PM exposure are the functional form of the PM exposure response at low and high concentrations and modelled concentrations of PM in Delhi.

For London, our emission-dispersion air pollution model was well suited for modelling the effects of modal shifts and changes in the vehicle fleet on air pollution. We could not use the same model for Delhi because of insufficient data. For Delhi, several factors contribute to uncertainty in the changes in $PM_{2\cdot5}$ concentration between the scenarios. These include uncertainties in the increase of motor vehicle use, composition of and emission factors for the projected 2030 vehicle numbers, and the extent of paved roads that affect the resuspension of PM. If PM emissions per km in Delhi do not improve in accordance with Euro 6 emission standards, the health burden from PM exposure in 2030 under the business-as-usual scenario will be much greater than we estimate (webappendix p 37).

Achievement of reductions in particulate and CO_2 emissions through technology is associated with more uncertainties than through reductions in distances travelled in motor vehicles. For example, diesel engines generally emit less CO_2 than do petrol engines, but currently emit more particles, including black carbon, which also causes climate warming.[6,52] Similarly, diesel particle traps, although effective at reducing particle emissions, increase emissions of CO_2 and nitrogen dioxide.[52,53] Although further improvements could be achieved with vehicles that use batteries powered from renewable sources, PM emissions could persist from brake and tyre wear and resuspension of road dust.

Our injury model, an elaboration of the model described by Bhalla and colleagues,[30] is also based on assumptions—in particular, a linear association between distance travelled and risk of injury from road traffic. In other words, we assumed that if the distance walked is doubled then the risk of injury to the pedestrian is also doubled; and if the distance driven in motor vehicles is halved then the risk of injury to the pedestrian is also halved. Although the direction of these associations is supported by empirical evidence,[54,55] the quantitative association is uncertain. Research has shown that increased levels of walking or cycling are associated with safer walking or cycling.[56] Although this outcome might be due to the lower motor vehicle volumes, it could indicate a non-linear safety-in-numbers effect. Furthermore, finding different directions of effect on injuries from the increased active travel scenarios for London and Delhi suggest greater uncertainty than with those for physical activity or air pollution.

We did not model changes in vehicle speeds, which could arise in at least four ways in our scenarios. First, with a reduction in the number of vehicles, congestion might fall with consequent increases in speeds. Second, policies that reallocate space from motor vehicles to other road users could reduce speeds. Third, legislation and enforcement might reduce vehicle speeds. Fourth, changes to the traffic mix—eg, bicycles and cars, could also affect speeds.

With our assumptions about model structure and the uncertainties in the model variables, the results of this study should be regarded as provisional and should be revised when more accurate estimates become available. One real-world indication that decarbonisation can produce positive health effects, even under difficult circumstances, is provided by Cuba. In the early 1990s after the collapse of the Soviet Union and with the US embargo, transport and agriculture were largely decarbonised, with substantial reductions in calorie intake and increases in the distance cycled and overall physical activity. In this period the average body-mass index fell by 1·5 units from 24·83 kg/m² in 1991 to 23·34 kg/m² in 1995, with the prevalence of obesity halved (from 14% to 7%). Results from epidemiological studies show that during this period the numbers of deaths from diabetes decreased by 51%, from heart disease by 35%, and from stroke by 20%.[57]

The extent to which our results can be generalised to other cities is open to question. For example, London and Delhi are megacities with high levels of public transport use, which suggests that they are likely to have more walking and lower carbon emissions per person than cities with lower levels of public transport use. In cities with higher car use, the emission cuts needed would be increased but the health benefits could be even greater.

We did not consider the socioeconomic distribution of effect although evidence suggests inequalities in the adverse health effects of motorised transport.[58,59] Since traffic-related air pollution is unevenly distributed within cities, reduction in the amount of traffic is likely to have large health benefits in some areas. For example, from the results of a study of the socioeconomic distribution of mortality benefits from reduced air pollution as a result of the London congestion charge, health benefits were estimated to be the largest in the most deprived areas of London.[60] In this city, differences between high-income and low-income groups in distances walked are small, but high-income groups are more likely to cycle and participate in recreational physical activity than are those in low-income groups. In Delhi, individuals living in low-income groups walk and cycle more than do those in high-income groups (39·0% *vs* 3·6% and 20% *vs* 5%, respectively).[61] Therefore, high-income groups in Delhi could be expected to increase their activity more than would the low-income groups, whereas the low-income groups might benefit more from the reduced risk of road injury than would high-income groups.

Because we have estimated the health effects of scenarios rather than specific interventions we cannot assess cost effectiveness. However, the infrastructure for individuals to walk or cycle might be less resource-intensive than that for cars. Additionally there are likely to be direct and indirect economic and social effects that cannot be adequately addressed here. A key consideration is whether such cities could, with low resource use, achieve social goals.

Implications for policy

Effective policies to increase the distances walked and cycled and reduce use of motor vehicles are needed to achieve the health benefits we have discussed. Policies that encourage people to walk and cycle would be expected to increase the safety of active travel, as shown in our sensitivity analysis of injury risks in the Netherlands.[22] Substantial increases in the distances cycled in cities, including Copenhagen (Denmark), London, and New York (USA), are associated with a decrease in the numbers of cyclists killed or seriously injured (webappendix p 38).[19,62–66] Without strong policies to increase the acceptability, appeal, and safety of walking and cycling, the vicious circle of increased motorisation and road danger will continue in Delhi, and the large potential health and environmental gains will not be achieved.

Creation of safe urban environments for mass active travel will mean prioritisation of the needs of pedestrians and cyclists compared with those of motorists. Walking or cycling should be the most direct, convenient, and pleasant options for most urban trips. Policy makers should divert investment from roads for motorists towards provision of infrastructure for pedestrians and cyclists.[67] Compared with cars and trucks, pedestrians and cyclists should have direct routes with priority at junctions. Strict controls for HGVs in urban areas are key safety prerequisites for cyclists. Properly enforced reductions in speed limits or zones can reduce injuries.[5,68] With such policies, achievement of low levels of risk from road injury for active travel, at least as low as the best practice in the Netherlands, should be possible. Enhanced streetscape design can make active travel pleasant.[69] With short distances, active travel becomes convenient; planned mixed-use developments would reduce distances to employment, education, services, and retail. Urban form matters since the incidence of road traffic injuries and urban crime are related to street design and land-use patterns.[70,71] Hence effective urban design can enable high modes shares for walking and cycling.

Conclusions

Important health gains and reductions in CO_2 emissions can be achieved through replacement of urban trips in private motor vehicles with active travel in high-income and middle-income countries. Technological measures to reduce vehicle pollutants might reduce emissions, but the health effect would be smaller. The combination of reduced reliance on motorised travel and substantial increases in active travel with vigorous implementation of low-emission technology offers the best outcomes in terms of climate change mitigation and public health. In many cities, the increase in use of cars, motorcycles, and HGVs, with the resulting increase in road danger has meant that many individuals who can afford to are changing to private motorised transport. An increase in the safety, convenience, and comfort of walking and cycling, and a reduction in the attractiveness of private motor vehicle use (speed, convenience, and cost) are essential to achieve the modal shifts envisaged here. Although the model assumptions can be questioned and further research will undoubtedly provide more robust estimates, large health benefits associated with active travel are highly likely and these benefits should be taken into account in the development and implementation of policy.

Contributors

IR, JW, AH, BGA, PE, CT, and ZCha led the conceptual development of the report. RH, JW, DM, OA, GT, and DB led the development of the scenarios. CT, BGA, SB, ZCho, and AC led the air pollution and health impact modelling. JW, PE, ZCha, OHF, AW, and GL led the physical activity and health impact modelling, and literature reviews. JW, PE, and IM led the injury modelling with contribution from ZCha and IR.
The text was mainly drafted by JW, CT, PE, IR, and AH with contribution from all authors.

Conflicts of interest

We declare that we have no conflicts of interest.

Acknowledgments

The project that led to this Series was funded by the Wellcome Trust (coordinating funder); Department of Health, National Institute for Health Research; the Royal College of Physicians; the Academy of Medical Sciences; the Economic and Social Research Council; the US National Institute of Environmental Health Sciences; and WHO. The Royal College of Physicians was supported by an unrestricted educational grant from Pfizer. The funders had no role in the design, analysis, or interpretation of the study. The views expressed are those of the authors and do not necessarily reflect the position of the funding bodies or the Health Effects Institute or its sponsors. We thank K Blackhall and L Felix (both London School of Hygiene and Tropical Medicine, London, UK) for help with the searches; J Dowie (London School of Hygiene and Tropical Medicine) and M Joffe (Imperial College, London, UK) for commenting on drafts of the report; P Wilkinson (London School of Hygiene and Tropical Medicine) for methodological advice; C Mathers (WHO, Geneva, Switzerland) for provision of data; G Fuller (Environmental Research Group, School of Biomedical and Health Sciences, King's College London, London, UK) for help with the air pollution modelling; and R West (University College London, London, UK) for advice about physical activity and smoking cessation. Slides for teaching are available for download.

For **the slides** see http://www.lshtm.ac.uk/nphiru/research/transportandhealthgroup/

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