Published in final edited form as:
Lancet. 2016 December 10; 388(10062): 2925–2935. doi:10.1016/S0140-6736(16)30067-8.

Land-use, transport and population health: estimating the health benefits of compact cities

Prof Mark Stevenson,
University of Melbourne, Australia

Dr Jason Thompson,
Monash University, University of Melbourne, Australia

Dr Thiago Herick de Sa,
University of São Paulo, Brazil

Prof Reid Ewing,
University of Utah, USA

Prof Dinesh Mohan,
Indian Institute of Technology, Delhi, India

Prof Rod McClure,
Harvard School of Public Health, USA

Prof Ian Roberts,
London School of Hygiene and Tropical Medicine, UK

Prof Geetam Tiwari,
Indian Institute of Technology Delhi, India

Prof Billie Giles-Corti,
University of Melbourne, Australia

Prof Jim Sallis,
University of California, San Diego, USA

Prof Xiaoduan Sun,
Beijing University of Technology, China

Prof Mark Wallace, and
Monash University, Australia

Dr James Woodcock
University of Cambridge, UK

Abstract

Using a Health Impact Assessment Framework, we estimated the population health effects arising from alternative land-use and transport policy initiatives in six cities. Land-use changes were modelled to reflect a compact city in which land-use density and diversity were increased and distances to public transport were reduced to produce low motorised mobility, namely a modal shift from private motor vehicles to walking, cycling, and public transport. The modelled compact city scenario resulted in health gains for all cities (for diabetes, cardiovascular disease, and

Europe PMC Funders Author Manuscripts

respiratory disease) with the overall health gains ranging from 420 disability-adjusted life years (DALYs) per 100 000 population to 826 DALYs per 100 000 population. However, for moderate to highly motorised cities, such as Melbourne, London, and Boston, the compact city scenario predicted a small increase in road trauma for cyclists and pedestrians (health loss of between 34 to 41 DALYs per 100 000 population). The findings suggest that government policies need to actively pursue land-use elements (particularly a focus towards compact cities) that support a modal shift away from private motor vehicles towards walking, cycling, and low-emission public transport. At the same time, these policies need to ensure the provision of safe walking and cycling infrastructure. The findings highlight the opportunities for policymakers to positively influence the overall health of city populations.

Introduction

Cities around the world are dealing with the consequences of changing population demographics and policies that have failed to effectively manage the relationships between land-use, mobility, and population health. Urban growth and the pressure it places on urban infrastructure is now a major international challenge. By 2050, the populations of Australia's four largest cities will be similar to Australia's current total population,1 while the United States, China, and India will see increases in their larger cities of 33%, 38% and 96%, respectively.2

Associated with continued population growth are ever-increasing demands on transport systems. Governments are increasingly emphasising the need to integrate transport and land-use planning,3 acknowledging that land-use decisions significantly influence transport options and travel choices. Sprawling residential-only developments that dominate most suburban areas in North America, Australia, and New Zealand limit the ability of people to walk or cycle for their daily travel requirements.4 In these countries, low-density housing developments render public transport development costs prohibitive, producing a reliance on private motorised transport and increasing exposure to the risks associated with traffic speed, traffic volume, vehicle emissions, and physical inactivity.5 In response to economic growth, private car use is also dramatically increasing in many middle-income countries such as Brazil,6 China, and India.7 The resultant declines in physical activity and increases in air pollution, noise, and risk of motor vehicle crashes combine to produce increased rates of chronic disease and injury.8

For city planners and policy-makers with the power to influence the health of rapidly expanding cities and increasingly motorised populations, minimising health risk exposures while maintaining or enhancing the mobility of city residents needs to be a priority. Recent innovations in transportation have generated an expectation of a transportation revolution. With web connectivity, automated vehicles, and advanced software, a future is envisaged where road deaths, serious injury, and congestion are eliminated. Like an engineering fix for global warming, this vision is seductive and will eventually play some part in solving current transportation challenges. However, serious obstacles including software viruses, security risks, and fall-back options in the case of major connected system failures mean that technological solutions will be achieved, but only over the ensuing decades. Additionally,

Europe PMC Funders Author Manuscripts

these solutions will not address the broader health and environmental consequences associated with land-use, the transport system and rapid motorisation identified in the first paper in this series,[9] namely increased cardiovascular disease, diabetes,[10] and respiratory disease[11, 12] coupled with escalating road traffic injury[13] and the ongoing challenges associated with infectious diseases in highly urbanised areas.[14]

Globally, deaths from road traffic injury have increased by 46% over the 20 years to 2012, making it the eighth leading cause of death.[15] The United Nations General Assembly resolution on global road safety acknowledges the emerging challenges associated with reducing road injury,[16] as do initiatives such as Sustainable Safety[17] and Vision Zero.[18] These efforts are consistent with the United Nations Post-2015 Sustainable Development Agenda, which emphasises the risks associated with global trends towards urbanisation and disaster risk reduction and mitigation. However, these efforts have rarely acknowledged the impact of land-use issues (such as urban sprawl) on travel mode choice or travel distance, and the consequent effects on population and environmental health.

Indeed, the effects of land-use and transport modal choice on population health are not well described. In part, this is because they occur against a backdrop of complex, interacting, and dynamic environmental, technological, and population conditions that evolve over years. Building on elements of the first paper in this series,[9] this paper investigates the population health outcomes associated with land-use policies that influence a city's transport modal choice. We model urban design interventions to create a compact city and quantify the potential health gains that residents of compact cities would obtain by adopting low motorised mobility.

A model of land-use, transport mode choice, and population health

To assess the relationship between land-use, transport, and population health, we selected the key elements presented in the preceding paper (and highlighted in blue in figure 1) for which information and relationships have been demonstrated.[19] We also conducted a review of the literature to identify measures of association for the key elements identified in the preceding paper. Having obtained estimates of the relationship between land-use and transport modal choice, we applied a Health Impact Assessment Framework[20] to produce a model for which estimates of population health outcomes were derived.

To model the city-specific effect of land-use and urban design interventions on transport modal choice and population health, we took characteristics from six cities. We selected the cities based on a combination of the country's stage of development, level of motorisation, geographic disparity, and the availability of reliable transport and health data. These cities were: Melbourne, Australia (a high-income and highly motorised city); Boston, United States (a high-income and moderately motorised city); London, United Kingdom (a high-income and moderately motorised city); Copenhagen, Denmark (a high-income and moderately motorised city); São Paulo, Brazil (an upper- to middle-income and moderately motorised city); and Delhi, India (a low- to middle-income and rapidly motorising city).[21] We applied weighted average associations between urban design (density, distance, and diversity) and transport mode choice for each city that were derived from a meta-analysis undertaken by Ewing and Cervero.[19] The associations ranged from 0·02 to 0·29 per unit

Europe PMC Funders Author Manuscripts

change in the relationship between density, distance, and land-use diversity and the respective transport mode choice. Density refers to population density, residential unit or intersection density, distance refers to the average distance to public transport, and diversity refers to the land-use mix within a given precinct (eg, mix of commercial and residential land-use). These urban design elements are further illustrated in figure 2.

It is important to note that the estimates derived from the meta-analytic approach included studies with small samples that were predominantly from North American cities and included uncontrolled confounding factors. Therefore, an element of uncertainty is associated with these estimates.[19]

For each city, we assessed the influence of land-use, urban design interventions, and transport mode choices on population health outcomes, namely road trauma (road deaths and serious injury; ICD-AM V00-V89), cardiovascular disease (ICD-AM I00-I99), diabetes (ICD-AM E10-E14), and respiratory disease (ICD-AM J30-J98). For comparative purposes, road trauma and chronic disease health outcomes (cardiovascular disease, diabetes, and respiratory disease) were reported as disability-adjusted life years (DALYs), which are a combination of the sum of the years of potential life lost due to premature mortality and years of productive life lost due to a disability.[22]

The key determinants of population health associated with transport mode choice as identified in the literature and applied within the model were:

- risk of death or injury per kilometre travelled by mode[23–25]
- level of physical activity (measured by metabolic equivalents (METS)[26, 27]) expended by mode choice per hour[28–31] and its effect on cardiovascular disease and type 2 diabetes
- chronic exposure (via inhalation) to fine particulate matter (PM_{10} and $PM_{2\cdot5}$) associated with exhaust emissions and raised dust from transport.[32]

Baseline population, transport mode share, road trauma, levels of physical inactivity, and air quality data were input for each city using the most recent data sources available.

Modelled changes in road trauma—Travel-mode, road deaths and serious injury data were available from recent travel surveys and government agencies in Melbourne,[33, 34] Delhi,[35] São Paulo,[36] London,[37] Boston,[38] and Copenhagen.[39, 40] These data included distance travelled per mode and per day and road fatalities and injuries by mode per year (injury data for Delhi were adjusted to account for historical under-reporting[41]). To estimate differences in road trauma as a result of changing mode share, we applied an approach that combined the probability of a crash between different road users given the changing proportions of transport modes within the transport system.[23, 24, 42, 43] We based estimates of chronic disease burden associated with road trauma on country-level data from the Global Burden of Disease Study 2013[44] converted to city-specific DALY estimates scaled to city population size.

Europe PMC Funders Author Manuscripts

Modelled changes in chronic disease—Levels of transport-related physical inactivity and vehicle emissions were modelled for each city. Changes in physical activity were estimated by calculating changes in the average estimated distance travelled per person, per mode and per day. We then applied consistent average METS per hour associated with each form of travel for each city.26 Average time spent in each travel mode was calculated using a combination of average speed by mode and daily distance travelled for each city.

The effect of increased physical activity (in METS per week) on cardiovascular disease and diabetes was estimated using linear associations established in the literature of 0·25 and 0·20 per 1000 kcal per week, respectively,45–50 with a benefit threshold restricted to activity in excess of 2·5 METS per hour.51 We considered this method to be appropriate for the small variations in overall physical activity that we modelled. However, it should be noted that associations between non-vigorous physical activity and disease risk has previously been shown to be non-linear in a meta-analysis of studies that incorporated greater proportional changes.52 As well, the modelling of physical activity did not take into account demographic differences (eg, age profiles and gender) in the likelihood of a modal shift between passive and active transport modes, the effects of exercise compensation,53, 54 or differences in average speeds or METS associated with different demographic groups. Although these differences have been explored elsewhere,55 we considered the levels of uncertainty associated with the estimates to be too great to be reliable at anything other than population levels.

To estimate total vehicle emissions in each city, we obtained the most recently available city-specific particulate emissions (PM_{10} and $PM_{2·5}$) data and estimates of the proportion of particulate matter generated by motor vehicles through combustion and suspended road dust in Melbourne, Delhi, São Paulo, and London.56–64 Data on the proportion of PM_{10} produced by vehicles for Boston and Copenhagen were unavailable so an estimate of 30% was used, which approximated the median of the other cities. To reflect the clean fuel technology bus fleets implemented in Delhi64 and the urban bus renewal program in São Paulo,65 additional vehicle kilometres travelled (VKT) by bus was assumed to be undertaken in fleets powered by compressed natural gas, which emits negligible additional fine particle emissions.66

We modelled DALYs attributable to respiratory disease and cardiovascular disease associated with coarse ($<PM_{10}$) and fine ($<PM_{2·5}$) particulate emissions. Particulate emissions associated with vehicles were assumed to change proportionately with kilometres travelled. The effect of $PM_{2·5}$ reduction on long-term cardiovascular disease risk and the effect of PM_{10} reduction on respiratory disease risk were then estimated using associations gathered from a systematic search of the literature. The search identified an approximate 20% increase in cardiovascular disease mortality risk per 10 μg/m^3 increase in $PM_{2·5}$67–71 and an approximate 2·5% increase in respiratory disease risk per 10 μg/m^3 increase in PM_{10}72–77 (although estimates for this effect vary widely between studies). We assumed that air pollution affected mortality and incidence to the same degree,78 and we assumed that levels of PM_{10} and $PM_{2·5}$ were closely correlated79, 80 and their effects on cardiovascular disease were not additive. Particulate emissions from private motorised transport modes per person and per kilometre travelled81, 82 were assumed to be equivalent.

Applying this model involved co-ordination and linkage of multiple studies and effects across a wide variety of disciplines, each with their own inherent sources of error. We acknowledge these uncertainties and undertook Monte Carlo simulation using Analytica 4.4 software83 for each of the city-specific models. The simulation provided confidence interval boundaries for the estimated DALYs associated with population health outcomes as well as sensitivity analyses to identify factors that were most influential in contributing to chronic disease and road trauma outcomes (see the Web Appendix for details). To reflect the uncertainty associated with both land-use changes on transport mode choice and transport mode choice on the risk of road death or injury, we allowed the estimates associated with these variables to vary according to normal distributions with standard deviations equal to 20% of the mean.84 For example, the effect of land-use density change on VKT was allowed to vary according to a normal distribution, as was the effect of VKT change on the risk of exposure to death or injury per kilometre travelled. Other variables for each city that were allowed to vary due to acknowledged real-world uncertainty72 and likely skewed distributions were the proportion of active transport transferred from vehicles distributed between cycling and walking, total kilometres travelled per year (negatively skewed log-normal distribution),51 METS associated with transport modes,85 average speed by mode, and total particulate matter. The relationship between levels of physical activity and chronic disease and between exposure to particulate matter and chronic disease reflected a normal distribution, as described above. Nonetheless, the breadth of findings for many effects of land-use on transport mode choice, or the effects of transport mode choice on the key outcomes (both road trauma and chronic disease) are likely to vary beyond the conservative estimates made here. The model and underlying assumptions are available in the Web Appendix.

City comparisons by land-use, transport and population health

The burden of disease and injury (with respect to road trauma, cardiovascular disease, diabetes, and respiratory disease) associated with land-use and transport were estimated for each city. The proportion of VKT by travel mode and the risk of road death and serious injury per VKT for each city are reported in figure 3 and tables 1a and 1b, respectively. There are considerable differences between cities in relation to the proportion of VKT travelled using private motor vehicles compared with public transport, cycling, and walking. In part, differences in VKT by travel mode reflect cities with significant population size but low population densities.

Consequently, these cities have typically invested in road infrastructure and have high levels of private motorised transport (eg, Melbourne and Boston). Despite the contrast in transport modal choice within and between cities (see box 1), it is also important to highlight the considerable between-city differences in estimated risk of death or injury for similar transport modes. For example the estimated per kilometre risk of death if travelling as a driver in a private motorised vehicle in Delhi is 3·3 times greater than the risk in Melbourne or London. Similarly, the estimated risk of death as a cyclist in São Paulo is 25 times greater than the risk in Copenhagen (see tables 1a and 1b).

Baseline DALYs for chronic disease (cardiovascular disease, diabetes, and respiratory disease) and road trauma (road deaths and serious injury) are summarised in tables 2a and 2b.

DALYs associated with cardiovascular disease, diabetes, respiratory disease, and road trauma vary widely between cities, reflecting observations in the recently released Global Burden of Disease Study 2013.[44] For instance, there are four- to five-fold differences in DALYs for cardiovascular disease, diabetes, and road trauma between the high-income city of Melbourne and the low- to middle-income city of Delhi. Estimated differences in respiratory disease between cities demonstrate smaller disparities, but the estimates for Delhi are almost twice those of Copenhagen. The disparity observed in cardiovascular disease between Delhi and the remaining cities may reflect the presence of risk factors that contribute to cardiovascular disease beyond those associated with the transport system; these include socioeconomic constraints, diet, exercise, tobacco use, and, potentially, a genetic predisposition to cardiovascular disease later in life.[86]

Opportunities for cities to enhance population health: a compact city model

Using the land-use and transport mode choice model illustrated in figure 1, we modelled a scenario designed to enhance population health in the six selected cities. In what we refer to as the compact cities model – a city of short distances that promotes higher residential density, mixed land-use, proximate and enhanced public transport, and an urban form that encourages cycling and walking[87] – we provided an alternative to each city's current land-use configuration and estimated the overall differences in the burden of disease under a compact city scenario. Under the compact cities model we increased land-use density by 30%, reduced the average distances to public transport options by 30%, and increased the diversity of land-use by 30%. We combined these changes with an additional transport policy initiative that supported a 10% modal shift away from private motor vehicle driver and passenger VKTs (excluding motorcycles) to either cycling (2/3 of the total shift) or walking (1/3 of the total shift). This modal shift is similar to the goals of transport policies currently being implemented in a number of European cities that impose barriers to private motor vehicle use.[88] The percentages of land-use changes and transport modal shifts across each city were selected on the basis that these were pragmatic and could be implemented over a reasonable time frame. For example, in a city such as Melbourne, a 30% reduction in average distances to public transport means reducing a journey from an average of 2 km to 1·6 km. That said, it is important to note that a 30% increase in land-use density in a city such as Delhi, which already has an estimated population density approaching 20 000 persons per square kilometre,[89] is unrealistic (and probably unnecessary) compared with achieving the same percentage increase in Melbourne or Copenhagen.

Figure 3 reports the estimated change in kilometres travelled per day by private vehicles, public transport, and walking and cycling (active transport) under the compact cities model. Table 3, outlines the change in travel-related METS and transport-related particulate emissions under the same model. Given the land-use changes imposed and the mode-shift from private motor vehicles, it is not surprising that an increase in public transport travel (trains, trams and buses) and walking and cycling is observed in each city. The largest

Europe PMC Funders Author Manuscripts

changes in walking and cycling are seen in Melbourne, Boston, and London. However, much of the increase in walking and cycling in these cities comes from building upon very low existing VKT in these modes. This means that the overall proportion of kilometres travelled by walking and cycling remains low (< 10%), even after land-use changes are applied. Nonetheless, as a consequence of the modal shift to walking and cycling, increases in estimated travel-related physical activity (as measured by METS per week) are observed in these cities.

Changes in transport-related particulate emissions due to modal shifts away from private vehicles and towards low-emission public transport was observed for all cities. Although estimated emissions reduced most notably in the highly motorised cities of Melbourne (12%), Boston (12%), London (10%), and Copenhagen (11%), emissions also reduced (to a lesser extent) in Delhi (3%) and São Paulo (5%) where VKT transfer from private to public transport was proportionately lower.

Table 4 shows the estimated health gains produced by the compact cities model. Health gains were observed for all cities for cardiovascular disease, respiratory disease, and diabetes. In addition to the reductions in estimated emissions described above, these figures were associated with enhancements to land-use that brought about a modal shift towards walking and cycling that resulted in increased transport-related physical activity for all cities. The greatest gains in transport-related physical activity were in the highly motorised cities of Melbourne (72%) and Boston (56%), where baseline active transport levels were low. Transport-related physical activity increases were also observed, albeit to a lesser extent, in London (39%), Copenhagen (29%), São Paulo (24%), and Delhi (19%).

Table 4 also reports that road trauma associated with serious deaths and injuries (DALYs per 100 000 people) was estimated to increase in Melbourne, Boston, and London under the compact city scenario. Differences in the other cities were estimated to be marginal or only slightly reduced (Delhi; see figure 4). Increases in road trauma DALYs were a direct consequence of the modal shift from private vehicles to walking and cycling, which carry a higher per kilometre risk of death or injury, even with the application of a safety in numbers[90] effect estimate. This highlights that while safety in numbers may reduce per kilometre risk, it should not be relied upon as a strategy to reduce absolute road trauma.[91, 92]

It is important to note that these road trauma estimates are limited to trauma associated with motor vehicle crashes. With the exception of São Paulo, the analysis does not include an estimate of the risk associated with cycle-only incidents. The inclusion of cycle-only crashes would likely add to the burden of road trauma associated with increases in cycle and pedestrian deaths and injuries.[93] There is also evidence that road deaths and serious injury alter as a function of long-term economic growth (see box 2) or short-term economic cycles.[94] Consequently, elements of a city's economy could attenuate (or amplify) the population health outcomes. We have not adjusted the estimates of road trauma for the potential economic fluctuations in each of the cities.

Europe PMC Funders Author Manuscripts

While modal shift toward active transport options resulted in increased road trauma, a considerable proportion of the DALYs gained across the chronic diseases in the compact cities model was contributed to by policies that encouraged walking and cycling uptake rather than land-use changes alone. This was particularly evident in the highly motorised cities of Melbourne, Boston, and London and underscores the importance of providing additional transport policy, pricing, or regulatory incentives[95] to encourage active transport if reductions in chronic disease are to be realised. In cities with existing high levels of walking and cycling, such as Copenhagen and Delhi, most benefit was gained from land-use changes that produced higher rates of walking and cycling rather than the promotion of public transport alone.

Understanding the complex relationship between land-use, transport and population health

Many countries concerned by costs associated with the mounting burden of lifestyle-related chronic disease[96] have developed plans and public policy initiatives that encourage greater levels of physical activity.[97–99] Although the extent to which these plans are successfully disseminated, enacted, and monitored varies,[100–104] the findings we report here suggest that if government policies are going to influence the overall health of growing city populations, the policies need to actively pursue land-use planning and urban design interventions that encourage a modal shift toward walking, cycling, and low-emissions public transport. From rapidly motorising to highly motorised cities, enhancements to urban design (such as increased land-use density, increased diversity, and a decrease in average distance to low-emission public transport) along with a modal shift of motorised trips to active transport options (such as walking and cycling) are essential to limit the rising burden of chronic disease associated with transportation systems. However, a move towards a compact city to mitigate the growing burden of chronic disease needs to be explored in more detail in cities such as Delhi and São Paulo where population density per square kilometre is already high. For example, these cities may respond better to other interventions such as access to proximate public transport or a mix of local destinations. In this paper, we have limited the modelling to a small number of urban and transport planning and design interventions and we have limited the outcomes to chronic disease. Infectious disease and heat-related mortality and morbidity are also direct consequences of excessive urban densities,[14, 105] and other interventions (eg, destination accessibility and demand management) will be important

Infrastructure investment for vulnerable road users—Despite the estimated health gains in chronic disease associated with the compact cities model, the modal shift towards a less private motorised transport and increased walking and cycling resulted in small to moderate increases in road trauma for Melbourne, London, and Boston. Given this, we estimated the extent of separated cycling and walking VKT that would be required to offset the estimated increase in DALYs associated with road deaths and serious injuries under the compact city scenario (see figure 5).

As shown in figure 5, the more highly motorised cities of Melbourne, Boston, and London would need the largest investments in separated pedestrian and cycling infrastructure

Europe PMC Funders Author Manuscripts

(equivalent to approximately 40%, 30%, and 35% of total pedestrian and cycling VKT, respectively) to offset the likely increase in road deaths and serious injuries associated with the compact city scenario. In contrast, Delhi, Copenhagen, and São Paulo are estimated to require minimal additional infrastructure to see no net increase in injury burden. These between-city differences reflect the comparatively high proportion of existing walking and cycling in Copenhagen, Delhi, and São Paulo (16%, 13%, and 7%, respectively) and the comparatively low level of increased risk associated with the greater number of vulnerable road users, which is in part due to the significant proportion of VKT also undertaken using public transport (56%, 31%, and 60%, respectively). This is not to say that further reductions in road trauma could not be made in these cities with changes to infrastructure, and does not mean that increased pedestrian and cyclist deaths would not occur. Instead, increased injury among pedestrians and cyclists may be matched by reductions for other transport modes (eg, drivers and passengers).

The compact city model presented in this paper presents a macro-level observation of the relationships between a limited number of land-use and urban design interventions and transport mode choices. The compact city model provides limited insight with respect to the interactions between individuals in entire city populations and how these interactions might influence transportation patterns and a city resident's health. While agent-based modelling has been used for some time in describing and studying simulated traffic flows in road and urban networks,[106] expanding the an approach beyond the scope of traffic engineering to incorporate aspects of health, safety, and individual behaviour offers great potential for not only estimating the health and safety effects of various urban scenarios but also for understanding the mechanisms that lead to optimised urban policy and planning settings.[107, 108]

We contend that a modal shift that reduces reliance on the private motor vehicle and an increased prevalence of walking and cycling (along with connected, accessible, and safe public transport) will lead to considerable population health benefits in relation to chronic disease. However, without the inclusion of adequate safe infrastructure, the introduction of additional cyclists and pedestrians within already highly motorised transport systems is likely to increase road trauma. Conversely, the introduction of additional cyclists and pedestrians may lead to decreased road trauma in cities with existing lower levels of motorization (eg, Delhi) or cities with existing high levels of infrastructure that ensures that walking and cycling can be undertaken in an environment of reduced risk (eg, Copenhagen). Policies that support walking and cycling within a safe urban environment are paramount to achieving gains in overall population health. Moreover, achieving these outcomes will require a comprehensive integrated approach, as the first paper in this series has highlighted.[9]

Cars, cities and health: new urban mobility

New urban mobility in which transport policies encourage walking, cycling, and public transport while reducing subsidies for private motor vehicle use are being supported by cities across many high-income countries.[109] Cities such as Helsinki, Finland and Zurich, Switzerland have seen modal shifts of significant magnitudes from private motor vehicle use

Europe PMC Funders Author Manuscripts

to walking, cycling, and public transport. For example, 52% of Zurich's daily VKTs are now undertaken by either walking or cycling, 19% are undertaken on public transport, and only 29% are undertaken using a private motor vehicle. The city has achieved this by limiting car parking, prioritising trams on road space and deliberately creating congestion with traffic signals providing access to streets to only a few cars at a time.88

Cities embracing the new urban mobility are setting ambitious targets to achieve safe and sustainable transport over the ensuing years and are building infrastructure to the quality previously built for motor vehicles. For example, Helsinki (which is not typical of other European cities because it was designed during a period of considerable motorisation) has embraced sustainable mobility and is transforming its car-dependent suburbs into denser and more walkable mixed-use precincts that are linked to the city centre by rapid and frequent public transport.110

Figure 7 illustrates the extensive infrastructure that is being delivered for cycling in Helsinki to support its proactive transport policy of achieving a cycling mode share of 15% of VKT by 2020.111 Cities that are embracing new urban mobility are doing so knowing that it delivers benefits in terms of reduced overall congestion, greater opportunities for multimodal travel and greater efficiency. This paper also highlights the considerable health gains that residents of these cities may also obtain by adopting low levels of motorised transport.

Many countries concerned by the costs associated with the mounting burden of lifestyle-related chronic disease96 have put in place plans and public policy initiatives that encourage greater levels of physical activity.97–99 Although the extent to which these plans are successfully disseminated, enacted, and monitored varies,100–104 the findings reported here suggest that government policies need to actively pursue integrated urban and transport planning and design interventions (particularly those focused towards achieving more compact cities) that support and encourage modal shifts away from private motor vehicles towards walking, cycling, and public transport (new urban mobility). This is required if city planners are to positively influence the overall health and sustainability of growing cities.

Acknowledgements

We acknowledge the support and contribution of data from the Boston Department of Health for injury statistics relating to Boston and the Technical University of Denmark for their assistance in providing travel and data relating to Copenhagen used in this study. MS and BG-C are funded by National Health and Medical Research Council (Australia) Research Fellowships (#1043091 and #1107672, respectively). THdS acknowledges funding from the São Paulo Research Foundation for his PhD (Fapesp, process number: 2012/08565-4) and the Brazilian Science without Borders Scheme from the National Council for Scientific and Technological Development (CNPq, process number: 200358/2014-6). JW works under the auspices of the Centre for Diet and Activity Research (CEDAR), a UKCRC Public Health Research Centre of Excellence which is funded by the British Heart Foundation, Cancer Research UK, the Economic and Social Research Council, the Medical Research Council, the National Institute for Health Research, and the Wellcome Trust MR/K023187/1. JW is funded by an MRC Population Health Scientist fellowship (MR/K021796/1).

References

1. Australian Bureau of Statistics. Population projections, Australia 2012 (base) to 2101. Canberra: Government of Australia; 2013.
2. Division UNDoEaSAP. World urbanization prospects. 2014 revision, Highlights. New York: United Nations; 2014.

3. Governments CoA. , editor. Council of Australian Governments. Review of capital city strategic planning systems. 2011.
4. Sallis JF, Frank LD, Saelens BE, Kraft MK. Active transportation and physical activity: opportunities for collaboration on transportation and public opportunities health research. Transportation Research Part a-Policy and Practice. 2004; 38(4):249–68.
5. British Medical Association. Healthy transport equals healthy lives. 2012
6. Gomez LF, Sarmiento R, Ordoñez MF, et al. Urban environment interventions linked to the promotion of physical activity: a mixed methods study applied to the urban context of Latin America. Soc Sci Med. 2015; 131:18–30. [PubMed: 25748111]
7. Kopits E, Cropper M. Traffic fatalities and economic growth. Accid Anal Prev. 2005; 37(1):169–78. [PubMed: 15607288]
8. Stevenson M, Jamrozik K, Spittle J. A Case-Control Study of Traffic Risk-Factors and Child Pedestrian Injury. Int J Epidemiol. 1995; 24(5):957–64. [PubMed: 8557453]
9. Giles-Corti B, Moudon AV, Reis R, et al. City Planning and population health: A global challenge. The Lancet. 2016; xx(xx)
10. Borrell LN, Diez Roux AV, Rose K, Catellier D, Clark BL, Atherosclerosis Risk in Communities S. Neighbourhood characteristics and mortality in the Atherosclerosis Risk in Communities Study. Int J Epidemiol. 2004; 33(2):398–407. [PubMed: 15082648]
11. Health Effects Institute (HEI) panel on the health effects of traffic-related air pollution. Traffic-related air pollution: A critical review of the literature on emissions, exposure and health effects. HEI special report, 17. Boston, MA: Health Effects Institute; 2010.
12. Fisher, GW., Rolfe, K., Kjellstrom, T., et al. Health effects due to motor vehicle air pollution in New Zealand. Ministry of Transport; Wellington: 2002.
13. van Beeck EF, Borsboom GJ, Mackenbach JP. Economic development and traffic accident mortality in the industrialized world, 1962-1990. Int J Epidemiol. 2000; 29(3):503–9. [PubMed: 10869323]
14. Alirol E, Getaz L, Stoll B, Chappuis F, Loutan L. Urbanisation and infectious diseases in a globalised world. Lancet Infect Dis. 2011; 11(2):131–41. [PubMed: 21272793]
15. Lozano R, Naghavi M, Foreman K, et al. Global and regional mortality from 235 causes of death for 20 age groups in 1990 and 2010: a systematic analysis for the Global Burden of Disease Study 2010. Lancet. 2012; 380(9859):2095–128. [PubMed: 23245604]
16. United Nations General Assembly. Resolution adopted by the General Assembly: improving global road safety, A/RES/64/255. 2010. [accessed March 19th 2013]
17. Research IfRS. [accessed March, 2013] Sustainable Safety. 2013. http://www.sustainablesafety.nl/index_uk.htm
18. Business Sweden. [accessed March 20th 2013] Vision Zero Initiative. 2013. http://www.visionzeroinitiative.com/
19. Ewing R, Cervero R. Travel and the Built Environment. J Am Plann Assoc. 2010; 76(3):265–94.
20. Dannenberg AL, Bhatia R, Cole BL, Heaton SK, Feldman JD, Rutt CD. Use of health impact assessment in the U.S.: 27 case studies, 1999-2007. Am J Prev Med. 2008; 34(3):241–56. [PubMed: 18312813]
21. World Bank. World Development Indicators. Washington DC: World Bank; 2012.
22. Murray CJ, Ezzati M, Flaxman AD, et al. GBD 2010: design, definitions, and metrics. Lancet. 2012; 380(9859):2063–6. [PubMed: 23245602]
23. Elvik R. The non-linearity of risk and the promotion of environmentally sustainable transport. Accid Anal Prev. 2009; 41(4):849–55. [PubMed: 19540975]
24. Jacobsen PL. Safety in numbers: more walkers and bicyclists, safer walking and bicycling. Inj Prev. 2003; 9(3):205–9. [PubMed: 12966006]
25. Schepers P. Does more cycling also reduce the risk of single-bicycle crashes? Inj Prev. 2012; 18(4):240–5. [PubMed: 22109243]
26. Ainsworth BE, Haskell WL, Herrmann SD, et al. 2011 Compendium of Physical Activities: a second update of codes and MET values. Med Sci Sports Exerc. 2011; 43(8):1575–81. [PubMed: 21681120]

27. Ainsworth BE, Haskell WL, Leon AS, et al. Compendium of physical activities: classification of energy costs of human physical activities. Med Sci Sports Exerc. 1993; 25(1):71–80. [PubMed: 8292105]
28. Brown BB, Yamada I, Smith KR, Zick CD, Kowaleski-Jones L, Fan JX. Mixed land use and walkability: Variations in land use measures and relationships with BMI, overweight, and obesity. Health Place. 2009; 15(4):1130–41. [PubMed: 19632875]
29. Frank LD, Saelens BE, Powell KE, Chapman JE. Stepping towards causation: do built environments or neighborhood and travel preferences explain physical activity, driving, and obesity? Soc Sci Med. 2007; 65(9):1898–914. [PubMed: 17644231]
30. Frank LD, Andresen MA, Schmid TL. Obesity relationships with community design, physical activity, and time spent in cars. Am J Prev Med. 2004; 27(2):87–96. [PubMed: 15261894]
31. Bassett DR Jr, Pucher J, Buehler R, Thompson DL, Crouter SE. Walking, cycling, and obesity rates in Europe, North America, and Australia. J Phys Act Health. 2008; 5(6):795–814. [PubMed: 19164816]
32. Ministry of the Environment Ontario. [accessed April 16th, 2013] Fine Particulate Matter. 2010. http://www.airqualityontario.com/science/pollutants/particulates.php
33. Victoria, T., editor. Transport Victoria. Victorian integrated survey of travel and activity. Melbourne: 2007.
34. Victorian Transport Accident Commission. Searchable road trauma statistics. Melbourne, Australia: Victorian Transport Accident Commission; 2013.
35. Tiwari G. Metro Systems in India: Case Study DMRC. 2011
36. Companhia do Metropolitano de São Paulo. Pesquisa de Mobilidade da Região Metropolitana de São Paulo: Principais Resuldados da Pesquisa Domiciliar. São Paulo: Secretaria dos Transportes Metropolitanos; 2013.
37. London Tf. , editor. Transport for London. Travel in London supplementary report: London travel demand survey (LTDS). London: 2011.
38. National Highway Traffic Safety Administration. [Accessed August] Fatality analysis reporting system encyclopedia. 2010. Available at: www-fars nhtsa dot gov
39. Denmark TUo. Danish National Travel Survey. 2013
40. Statistics Denmark. 2013.
41. Mohan D, Tsimhoni O, Sivak M, Flannagan MJ. Road safety in India: challenges and opportunities. 2009
42. Bhalla K, Ezzati M, Mahal A, Salomon J, Reich M. A risk-based method for modeling traffic fatalities. Risk Anal. 2007; 27(1):125–36. [PubMed: 17362405]
43. World Health Organisation. Global status report on road safety. Luxembourg: WHO Press; 2013.
44. World Health Organisation. Global Health Risks: Mortality and burden of disease attributable to major risks. 2015.
45. Warburton DE, Nicol CW, Bredin SS. Health benefits of physical activity: the evidence. CMAJ. 2006; 174(6):801–9. [PubMed: 16534088]
46. Lee CD, Blair SN, Jackson AS. Cardiorespiratory fitness, body composition, and all-cause and cardiovascular disease mortality in men. Am J Clin Nutr. 1999; 69(3):373–80. [PubMed: 10075319]
47. Mora S, Cook N, Buring JE, Ridker PM, Lee IM. Physical activity and reduced risk of cardiovascular events: potential mediating mechanisms. Circulation. 2007; 116(19):2110–8. [PubMed: 17967770]
48. Hamer M, Chida Y. Active commuting and cardiovascular risk: a meta-analytic review. Prev Med. 2008; 46(1):9–13. [PubMed: 17475317]
49. Weinstein AR, Sesso HD, Lee IM, et al. Relationship of physical activity vs body mass index with type 2 diabetes in women. JAMA. 2004; 292(10):1188–94. [PubMed: 15353531]
50. InterAct C, Ekelund U, Palla L, et al. Physical activity reduces the risk of incident type 2 diabetes in general and in abdominally lean and obese men and women: the EPIC-InterAct Study. Diabetologia. 2012; 55(7):1944–52. [PubMed: 22526603]

51. Woodcock J, Givoni M, Morgan AS. Health impact modelling of active travel visions for England and Wales using an Integrated Transport and Health Impact Modelling Tool (ITHIM). PLoS ONE. 2013; 8(1):e51462. [PubMed: 23326315]
52. Woodcock J, Franco OH, Orsini N, Roberts I. Non-vigorous physical activity and all-cause mortality: systematic review and meta-analysis of cohort studies. Int J Epidemiol. 2011; 40(1): 121–38. [PubMed: 20630992]
53. Rowland TW. The biological basis of physical activity. Med Sci Sports Exerc. 1998; 30(3):392–9. [PubMed: 9526885]
54. Eisenmann JC, Wickel EE. The biological basis of physical activity in children: revisited. Pediatr Exerc Sci. 2009; 21(3):257–72. [PubMed: 19827450]
55. Woodcock J, Edwards P, Tonne C, et al. Health and Climate Change 2 Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport. Lancet. 2009; 374(9705): 1930–43. [PubMed: 19942277]
56. Delaney, W., Marshall, A. Victorian air emissions inventory for 2006; 20th Clean Air and Environment Conference, 2011; Auckland: 2011. 2011
57. Delaney, W. Air Monitoring Report, 2010. 2011.
58. Guttikunda SK, Goel R. Health impacts of particulate pollution in a megacity—Delhi, India. Environmental Development. 2013; 6:8–20.
59. Guttikunda, SK., Jawahar, P. Road Transport in India 2010-30: Emissions, pollutions and health impacts. 2012.
60. Andrade MD, de Miranda RM, Fornaro A, et al. Vehicle emissions and PM(2.5) mass concentrations in six Brazilian cities. Air Qual Atmos Health. 2012; 5(1):79–88. [PubMed: 22408695]
61. Kelly F, Armstrong B, Atkinson R, et al. The London low emission zone baseline study. Res Rep Health Eff Inst. 2011; (163):3–79.
62. Wood HE, Marlin N, Mudway IS, et al. Effects of Air Pollution and the Introduction of the London Low Emission Zone on the Prevalence of Respiratory and Allergic Symptoms in Schoolchildren in East London: A Sequential Cross-Sectional Study. PLoS ONE. 2015; 10(8):e0109121. [PubMed: 26295579]
63. Transport for London. London low emissions zone impacts monitoring baseline report. London, UK: Transport for London; 2008.
64. Sindhwani R, Goyal P. Assessment of traffic-generated gaseous and particulate matter emissions and trends over Delhi (2000-2010). Atmos Pollut Res. 2014; 5(3):438–46.
65. Veronez DV, Kulay LA, Saldiva PHN, Miraglia SGEK. A cost-benefit evaluation of the air quality and health impacts in Sao Paulo, Brazil. J Environ Prot. 2012; 3:1161.
66. Jayaratne ER, Ristovski ZD, Meyer N, Morawska L. Particle and gaseous emissions from compressed natural gas and ultralow sulphur diesel-fuelled buses at four steady engine loads. Science of the Total Environment. 2009; 407(8):2845–52. [PubMed: 19185331]
67. Franchini M, Mannucci PM. Air pollution and cardiovascular disease. Thromb Res. 2012; 129(3): 230–4. [PubMed: 22113148]
68. Simkhovich BZ, Kleinman MT, Kloner RA. Air pollution and cardiovascular injury epidemiology, toxicology, and mechanisms. J Am Coll Cardiol. 2008; 52(9):719–26. [PubMed: 18718418]
69. Pope CA 3rd, Kanner RE. Acute effects of PM10 pollution on pulmonary function of smokers with mild to moderate chronic obstructive pulmonary disease. Am Rev Respir Dis. 1993; 147(6 Pt 1): 1336–40. [PubMed: 8503541]
70. Laden F, Schwartz J, Speizer FE, Dockery DW. Reduction in fine particulate air pollution and mortality: Extended follow-up of the Harvard Six Cities study. Am J Respir Crit Care Med. 2006; 173(6):667–72. [PubMed: 16424447]
71. Jerrett M, Burnett RT, Ma R, et al. Spatial analysis of air pollution and mortality in Los Angeles. Epidemiology. 2005; 16(6):727–36. [PubMed: 16222161]
72. Janssen NA, Hoek G, Simic-Lawson M, et al. Black carbon as an additional indicator of the adverse health effects of airborne particles compared with PM10 and PM2.5. Environ Health Perspect. 2011; 119(12):1691–9. [PubMed: 21810552]

73. Karakatsani A, Analitis A, Perifanou D, et al. Particulate matter air pollution and respiratory symptoms in individuals having either asthma or chronic obstructive pulmonary disease: a European multicentre panel study. Environ Health. 2012; 11:75. [PubMed: 23039312]
74. Tamura K, Jinsart W, Yano E, Karita K, Boudoung D. Particulate air pollution and chronic respiratory symptoms among traffic policemen in Bangkok. Arch Environ Health. 2003; 58(4): 201–7. [PubMed: 14655899]
75. Sanhueza PA, Torreblanca MA, Diaz-Robles LA, Schiappacasse LN, Silva MP, Astete TD. Particulate air pollution and health effects for cardiovascular and respiratory causes in Temuco, Chile: a wood-smoke-polluted urban area. J Air Waste Manag Assoc. 2009; 59(12):1481–8. [PubMed: 20066914]
76. Schwartz J. Particulate air pollution and chronic respiratory disease. Environ Res. 1993; 62(1):7–13. [PubMed: 8325268]
77. Brunekreef B, Forsberg B. Epidemiological evidence of effects of coarse airborne particles on health. Eur Respir J. 2005; 26(2):309–18. [PubMed: 16055881]
78. Cohen AJ, Ross Anderson H, Ostro B, et al. The global burden of disease due to outdoor air pollution. J Toxicol Environ Health A. 2005; 68(13–14):1301–7. [PubMed: 16024504]
79. Kumar R, Joseph AE. Air pollution concentrations of PM2.5, PM10 and NO2 at ambient and kerbsite and their correlation in Metro City - Mumbai. Environmental Monitoring and Assessment. 2006; 119(1–3):191–9. [PubMed: 16541301]
80. Kendall M, Pala K, Ucakli S, Gucer S. Airborne particulate matter (PM2.5 and PM10) and associated metals in urban Turkey. Air Quality Atmosphere and Health. 2011; 4(3–4):235–42.
81. Office of Transportation and Air Quality. , editor. United States Environmental Protection Agency. Average Annual Emissions and Fuel Consumption for Gasoline-Fueled Passenger Cars and Light Trucks. 2008.
82. Office of Transportation and Air Quality. , editor. United States Environmental Protection Agency. Average In-Use Emissions from Urban Buses and School Buses. 2008.
83. Lumina Decision Systems. Analytica Professional. Lumina Decision Systems. 2012
84. Schackman BR, Gold HT, Stone PW, Neumann PJ. How often do sensitivity analyses for economic parameters change cost-utility analysis conclusions? Pharmacoeconomics. 2004; 22(5):293–300. [PubMed: 15061679]
85. Ainsworth BE, Haskell WL, Herrmann M, Meckes N, Bassett DR. The compendium of physical activities tracking guide. 2011 [accessed November 30th, 2012]
86. Gersh BJ, Sliwa K, Mayosi BM, Yusuf S. Novel therapeutic concepts: the epidemic of cardiovascular disease in the developing world: global implications. Eur Heart J. 2010; 31(6):642–8. [PubMed: 20176800]
87. Gordon P, Richardson HW. Are compact cities a desirable planning goal? J Am Plann Assoc. 1997; 63(1):95–106.
88. Stone J, Taylor E, Cole A, Kirk Y. ACOLA Securing Australia's Future. 2014
89. Burdett, R., Rode, P., Shankar, P. Governing urban futures. London, United Kingdom: London School of Economics and Political Science; 2014.
90. Jacobsen PL, Ragland DR, Komanoff C. Safety in Numbers for walkers and bicyclists: exploring the mechanisms. Inj Prev. 2015; 21(4):217–20. [PubMed: 26157109]
91. Bhatia R, Wier M. "Safety in Numbers" re-examined: can we make valid or practical inferences from available evidence? Accid Anal Prev. 2011; 43(1):235–40. [PubMed: 21094319]
92. Thompson J, Savino G, Stevenson M. Reconsidering the safety in numbers effect for vulnerable road users: an application of agent-based modeling. Traffic Inj Prev. 2015; 16(2):147–53. [PubMed: 24761795]
93. Christie N, Pike I. Is it safe in numbers? Inj Prev. 2015; 21(4):276–7. [PubMed: 26203163]
94. Cotti C, Tefft N. B E J Econom Anal Policy. 2011
95. Frank L, Kavage S. A national plan for physical activity: the enabling role of the built environment. J Phys Act Health. 2009; 6(Suppl 2):S186–95. [PubMed: 20120128]

96. Murray CJ, Vos T, Lozano R, et al. Disability-adjusted life years (DALYs) for 291 diseases and injuries in 21 regions, 1990-2010: a systematic analysis for the Global Burden of Disease Study 2010. Lancet. 2012; 380(9859):2197–223. [PubMed: 23245608]

97. Australian Government. [accessed 01/08/2013] Measure up. 2013. http://measureup.gov.au/internet/abhi/publishing.nsf/content/home

98. [accessed 01/08/2013] National Physical Activity Plan. 2012. www.physicalactivityplan.org

99. Heath GW. The role of the public health sector in promoting physical activity: national, state, and local applications. J Phys Act Health. 2009; 6(Suppl 2):S159–67. [PubMed: 20120125]

100. Bornstein DB, Pate RR, Pratt M. A review of the national physical activity plans of six countries. J Phys Act Health. 2009; 6(Suppl 2):S245–64. [PubMed: 20120133]

101. Evenson KR, Brownson RC, Satinsky SB, Eyler AA, Kohl HW 3rd. The U.S. National Physical Activity Plan: dissemination and use by public health practitioners. Am J Prev Med. 2013; 44(5):431–8. [PubMed: 23597804]

102. Brownson RC, Ballew P, Brown KL, et al. The effect of disseminating evidence-based interventions that promote physical activity to health departments. Am J Public Health. 2007; 97(10):1900–7. [PubMed: 17761575]

103. Brownson RC, Ballew P, Dieffenderfer B, et al. Evidence-based interventions to promote physical activity: what contributes to dissemination by state health departments. Am J Prev Med. 2007; 33(1 Suppl):S66–73. quiz S4–8. [PubMed: 17584593]

104. Brownson RC, Jones E. Bridging the gap: translating research into policy and practice. Prev Med. 2009; 49(4):313–5. [PubMed: 19555708]

105. Stone B Jr, Vargo J, Liu P, et al. Avoided heat-related mortality through climate adaptation strategies in three US cities. PLoS ONE. 2014; 9(6):e100852. [PubMed: 24964213]

106. Renner CZ, Nicolai TW, Nagel K. Agent-based land use transport interaction modeling: state of the art. 2014

107. Epstein, JM. Agent zero: toward neurocognitive foundations for generative social science. New Jersey: Princeton University Press; 2013.

108. Thompson J, Savino G, Stevenson M. A model of behavioural adaptation as a contributor to the safety-in-numbers effect for cyclists. Transportation Research Part A: Policy and Practice. 2016; 85:65–75.

109. Initiative CotEF, Innovation Union C. Roadmap to a Single European Transport Area—Towards a competitive and resource efficient transport system. White Paper, COM; 2011. (2011)

110. unit HCPDgp. Urban plan - the new Helsinki city plan Vision 2050. City of Helsinki: 2013.

111. City of Helsinki Traffic Planning Division. [accessed August 20th, 2015] Promotion of Cycling. 2015. http://www.hel.fi/www/Helsinki/en/maps-and-transport/cycling/promotion/

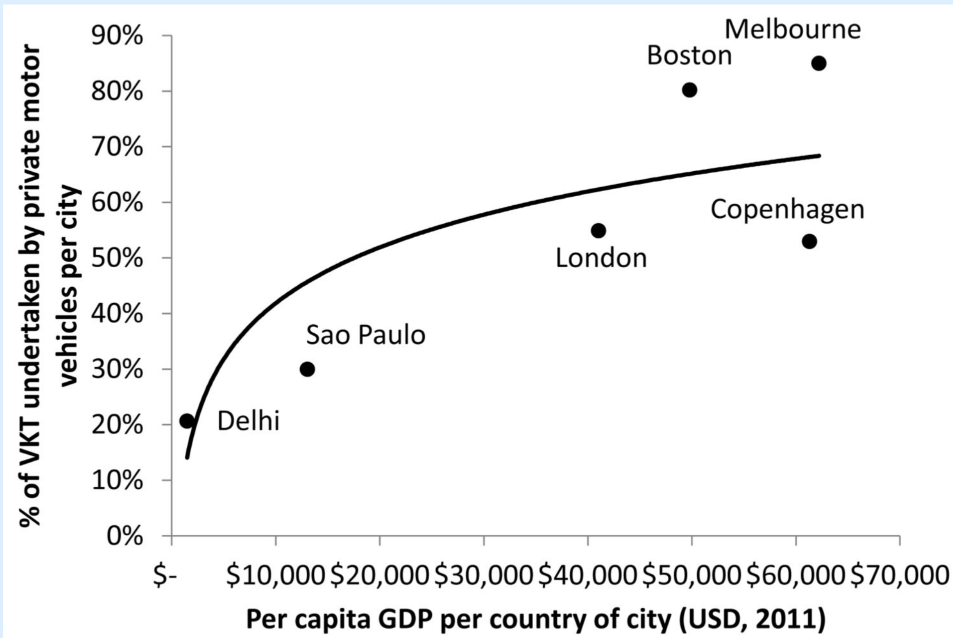
Box 1

Variation in city plans. In the maps below, Melbourne and Boston (with populations of approximately 4·5 million residents each) demonstrate the most grid-like road networks designed around the predominant use of motorised transport. In contrast, older cities such as London and São Paulo (8 and 12 million residents, respectively) have medium levels of motorisation combined with a dense spaghetti-like road network. Copenhagen and Delhi (with 0·6 million and 17 million residents, respectively) have sparse road networks reflecting low levels of infrastructure dedicated to motorised transport.

Europe PMC Funders Author Manuscripts

Box 2

The proportion of private motorised transport in cities demonstrates a relationship with gross domestic product per person. For cities with a high gross domestic product, uptake of private motorised transport is only offset by investment in public transport and active transport infrastructure (as in London and Copenhagen). In creating a future transport system that enhances both mobility and health, cities such as Delhi and São Paulo have the opportunity to invest in public and active transport to reduce reliance on private motorised transport and avoid the mobility and negative health consequences that are associated with highly motorised cities.



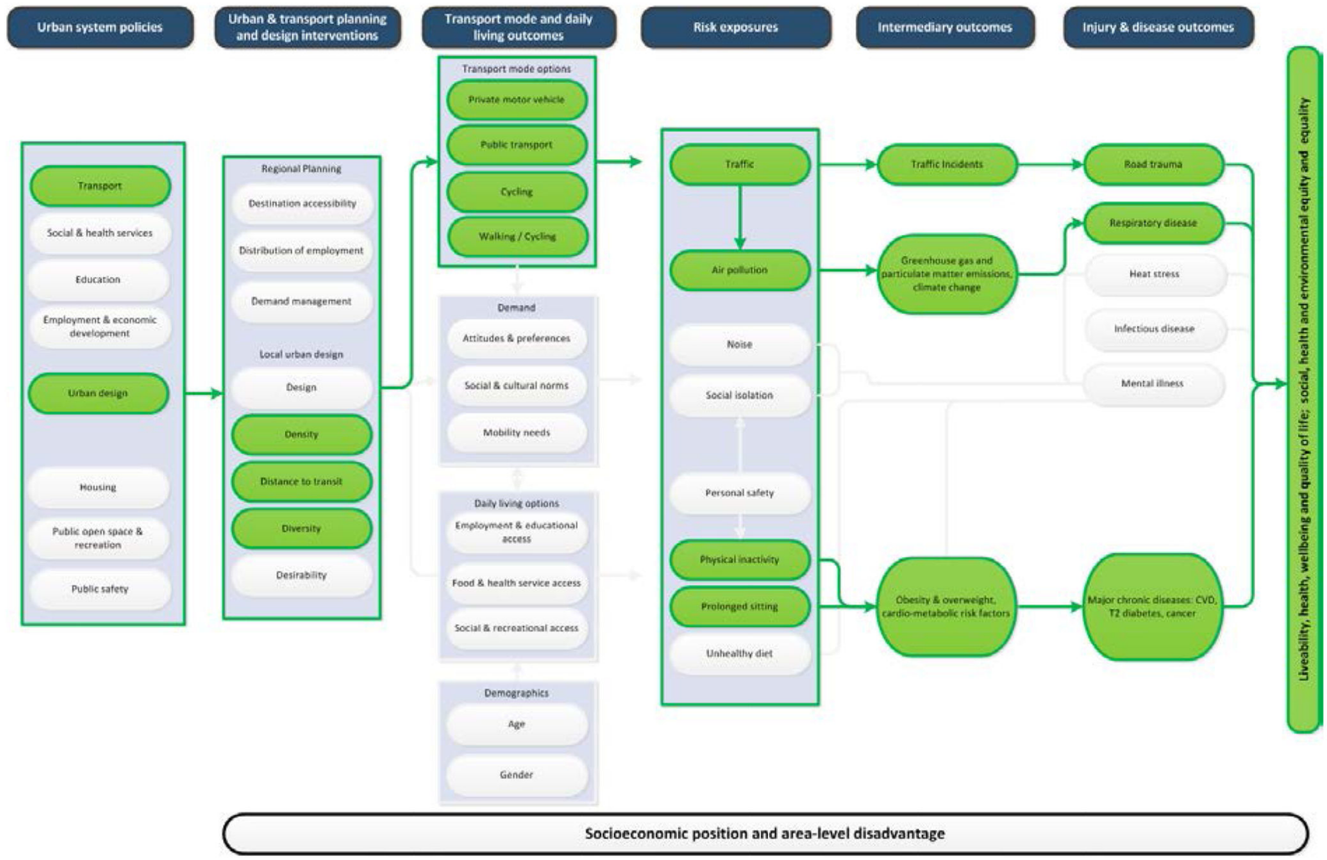


Figure 1. Land-use, transport mode choice and population health model.

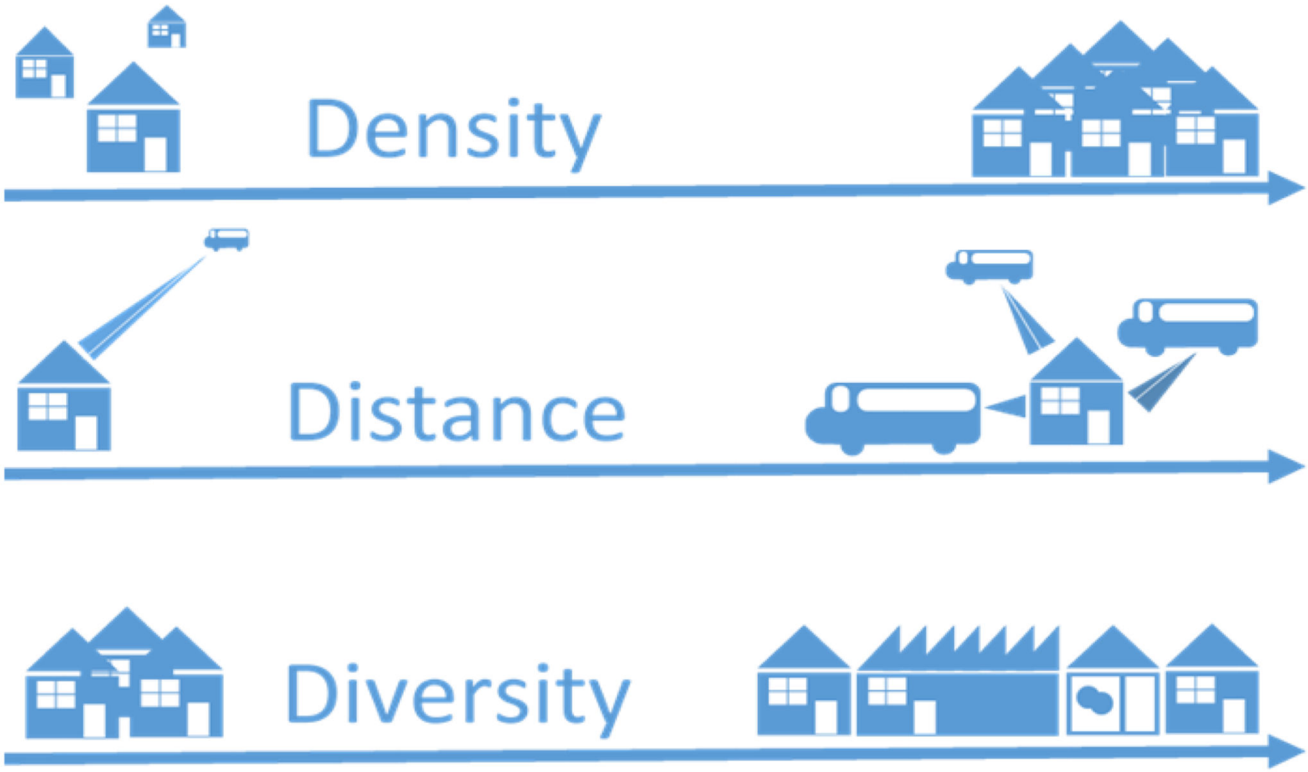


Figure 2. Illustration of the terms density, distance, and diversity as applied in the land-use, transport, population health model.

Europe PMC Funders Author Manuscripts

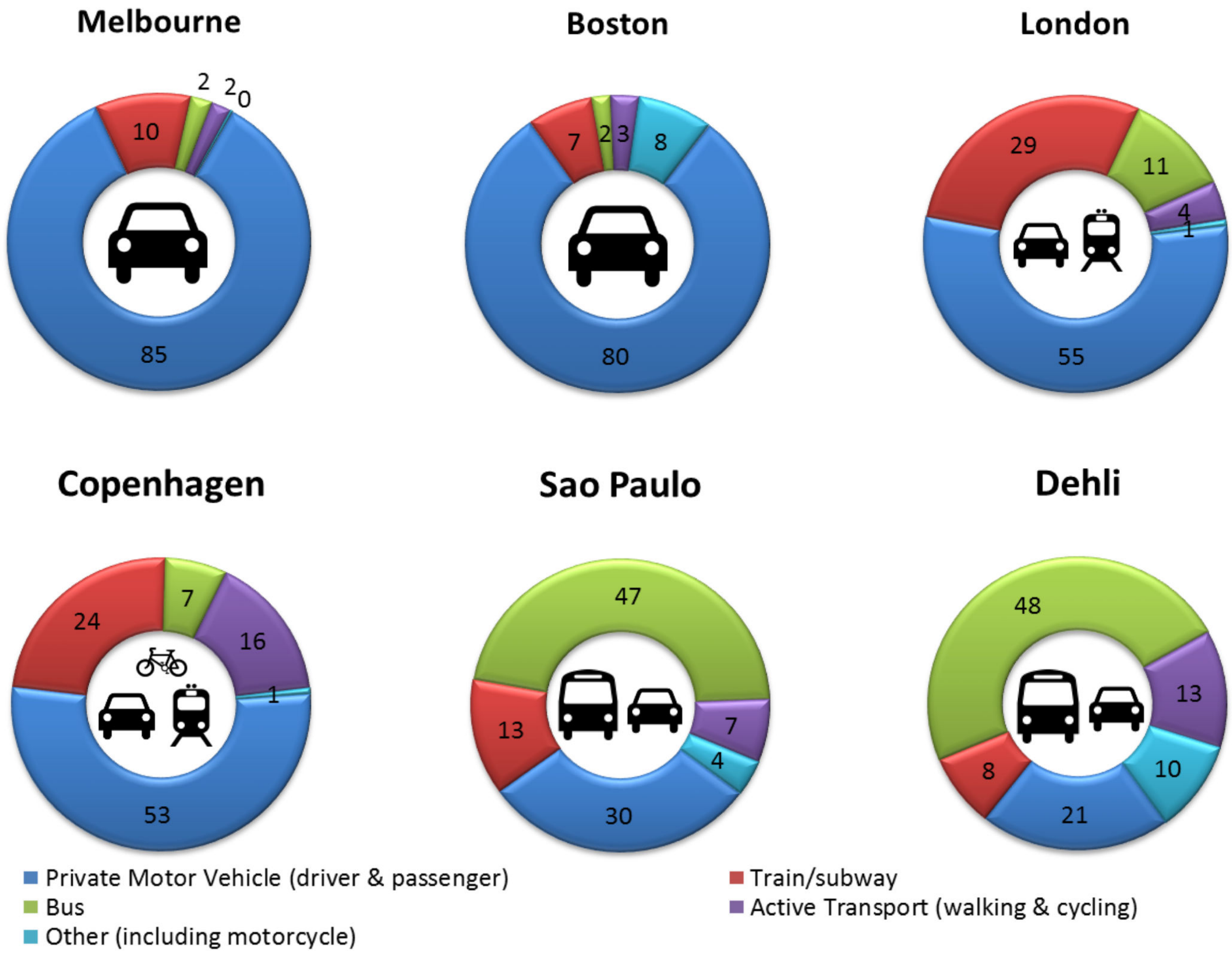


Figure 3. Vehicle kilometres travelled (VKT) by mode in each city at baseline with dominant transport odes (>15% of total VKT) highlighted.

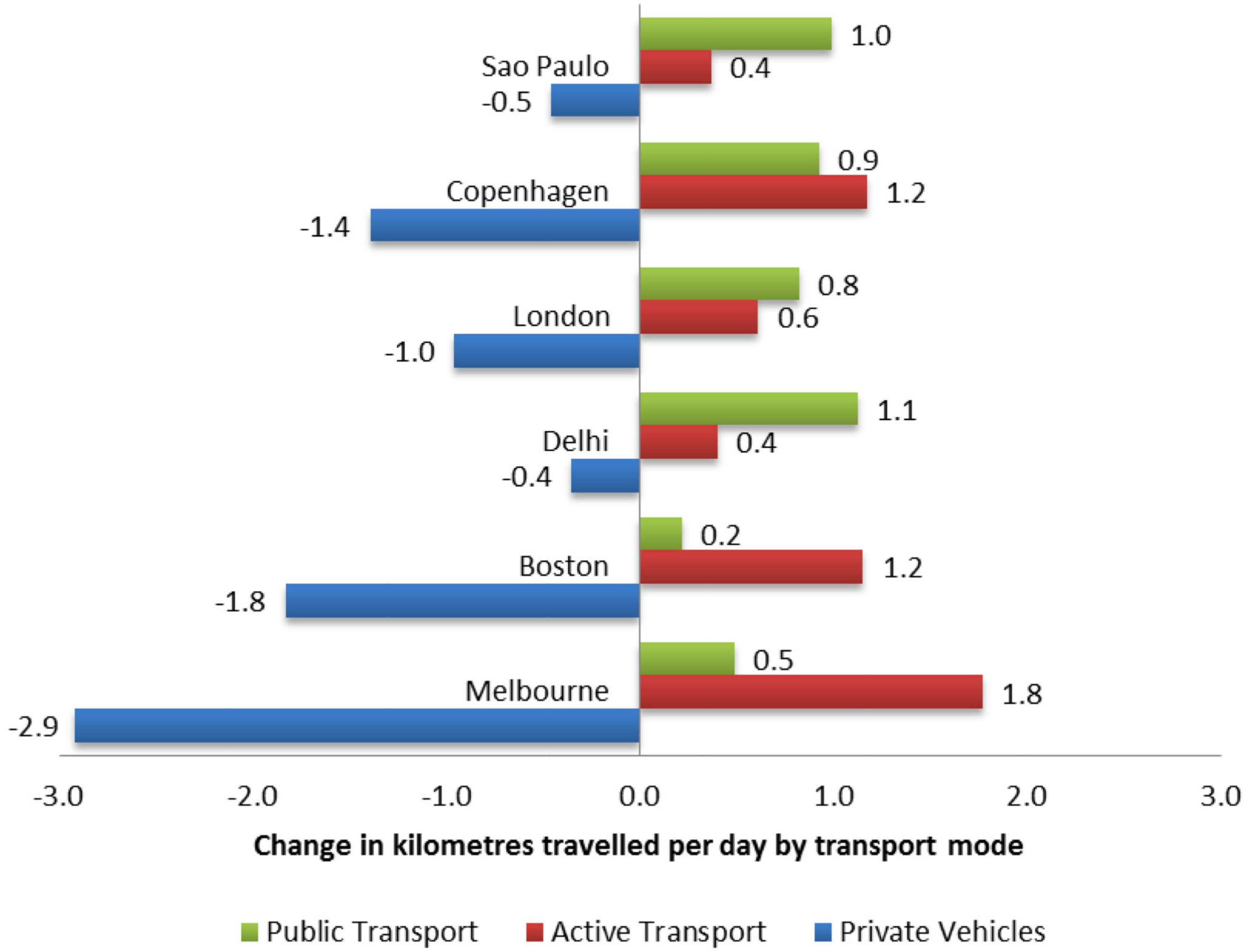


Figure 4. Estimated change in total kilometres travelled per day by mode of transport under the compact cities model for each city.

Europe PMC Funders Author Manuscripts

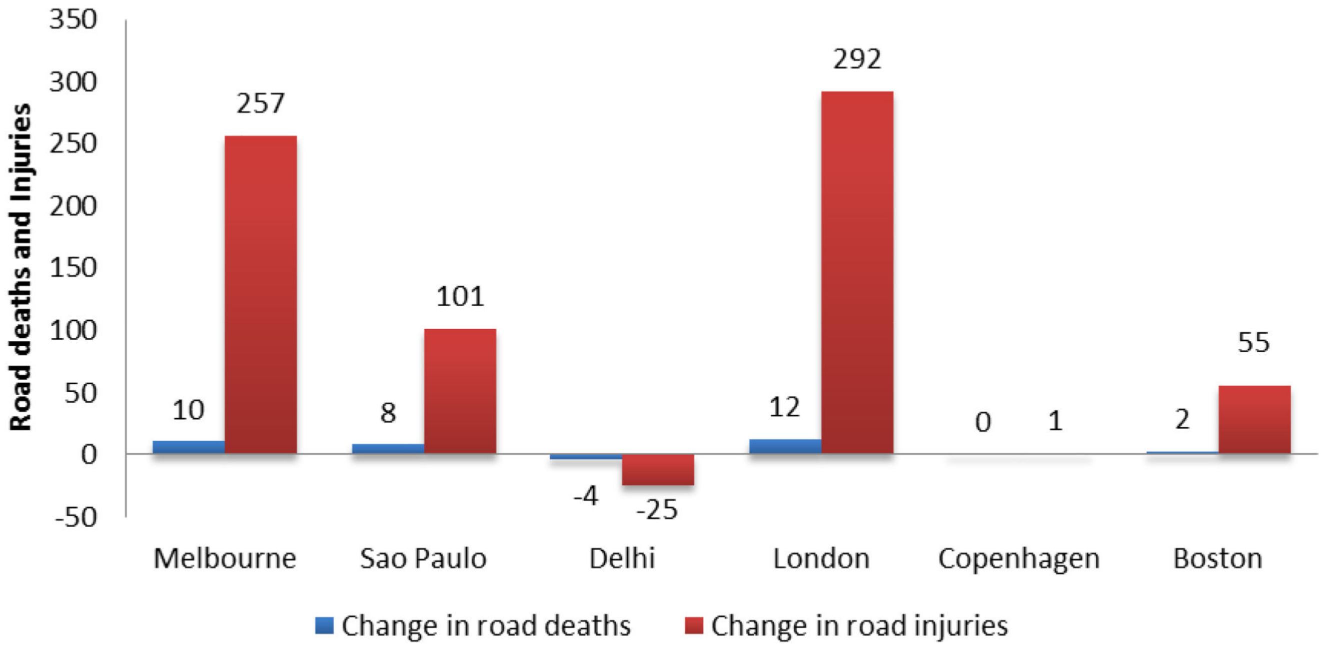


Figure 5. Estimated change in road deaths and recorded injuries under the compact cities model for each city per year.

Europe PMC Funders Author Manuscripts

Extent of separation between motor vehicles and active transport users (pedestrians and cyclists)

	0%	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%	100%
Melbourne	34	31	27	23	19	15	11	6	2	-3	-8	-14	-20	-26	-33	-41	-49	-59	-71	-88	-141
Boston	42	37	31	25	18	12	5	-2	-10	-18	-26	-35	-44	-55	-66	-78	-92	-108	-128	-155	-240
Delhi	-2	-15	-29	-43	-57	-73	-88	-105	-122	-140	-159	-180	-201	-225	-250	-279	-310	-347	-393	-455	-653
London	41	36	30	25	19	14	8	1	-5	-12	-20	-27	-36	-45	-54	-65	-77	-91	-109	-133	-208
Copenhagen	1	-4	-10	-16	-23	-29	-36	-43	-51	-59	-67	-76	-85	-96	-107	-119	-133	-149	-168	-196	-281
Sao Paulo	5	-3	-11	-19	-28	-37	-47	-57	-67	-78	-89	-101	-114	-128	-143	-160	-179	-201	-228	-266	-384

Estimated Disability Adjusted Life Years (DALYs) attributed to road trauma for each city

Figure 6. Estimated effect of additional separation of active transport VKT from traffic required to offset additional road trauma DALYs for each city under the compact cities scenario (positive numbers represent estimated increases in road trauma).

Figure 7. Extensive infrastructure in cities such as Helsinki is being delivered to support greater levels of safe cycling.

Europe PMC Funders Author Manuscripts

Table 1a

Risk of road death and injury per 100 million kilometres travelled by transport mode for Melbourne, São Paulo, and Delhi.

	Melbourne		São Paulo		Delhi	
Transport mode	**Deaths per 100 million km**	**Injuries per 100 million km**	**Deaths per 100 million km**	**Injuries per 100 million km**	**Deaths per 100 million km**	**Injuries per 100 million km**
Vehicle driver	0·2	7·3	1·7	38·1	0·4	2·5
Vehicle passenger	0·2	7·1	1·9	106·7	0·4	2·5
Train or tram	0·1	0·2	0·0	0·1	1·5	8·7
Bus	0·1	0·7	0·0	7·1	0·2	1·4
Walking	7·6	108·6	16·6	216·6	20·9	125·3
Cycle	1·4	79·8	25·8	472·7	4·3	25·8
Other (including motorcycle)	16·5	495·1	23·6	826·5	9·1	54·3

Table 1b

Risk of road death and injury per 100 million kilometres travelled by transport mode for London, Boston, and Copenhagen.

	London		Boston		Copenhagen	
Transport mode	**Deaths per 100 million km**	**Injuries per 100 million km**	**Deaths per 100 million km**	**Injuries per 100 million km**	**Deaths per 100 million km**	**Injuries per 100 million km**
Vehicle driver	0·2	3·5	0·9	2·2	0·3	3·7
Vehicle passenger	0·2	3·5	0·5	1·7	0·3	3·5
Train or subway	0·0	0·2	0·0	0·1	0·1	0·6
Bus	0·1	2·5	0·0	0·2	0·3	0·7
Walking	5·9	64·8	2·7	12·0	3·2	50·0
Cycle	4·4	140·8	2·5	23·0	0·6	26·6
Other (including motorcycle)	13·1	229·0	0·1	3·5	3·4	171·0

Table 2a

Disability-adjusted life years (DALYs) lost related to cardiovascular disease, diabetes, respiratory disease, and road trauma for Melbourne, São Paulo, and Delhi.

	Melbourne		São Paulo		Delhi	
Population health outcomes	**DALYs lost per 100 000 population**	**Total city DALYs**	**DALYs lost per 100 000 population**	**Total city DALYs**	**DALYs lost per 100 000 population**	**Total city DALYs**
Cardiovascular disease	3277	136 622	4961	558 286	13 770	2 306 920
Type 2 diabetes	606	25 265	1116	125 589	2996	501 927
Respiratory disease	1642	68 457	1623	182 644	3927	657 900
Road trauma	536	22 346	1447	162 838	2892	484 504

Europe PMC Funders Author Manuscripts

Table 2b

Disability-adjusted life years (DALYs) lost related to cardiovascular disease, diabetes, respiratory disease, and road trauma for London, Boston, and Copenhagen.

	London		Boston		Copenhagen	
Population health outcomes	**DALYs lost per 100 000 population**	**Total city DALYs**	**DALYs lost per 100 000 population**	**Total city DALYs**	**DALYs lost per 100 000 population**	**Total city DALYs**
Cardiovascular disease	4579	374 251	5092	236 310	4315	24 261
Type 2 diabetes	368	30 077	868	40 282	976	5488
Respiratory disease	2191	179 075	2126	98 663	2268	12 752
Road trauma	411	33 592	635	29 469	454	2553

Europe PMC Funders Author Manuscripts

Table 3

Changes in physical inactivity, and particulate emissions associated with the compact cities model application in each city.

	City					
Physical Inactivity	**Melbourne**	**Boston**	**London**	**Copenhagen**	**Delhi**	**São Paulo**
Change in travel-related METS per week	72·1% (38·9%:119·5%)	55·7% (26·8%:99·0%)	39·1% (10·4%:78·6%)	28·9% (−2·2%:69·5%)	18·5% (−6·7%:54·4%)	24·1% (−4·3%:65·2%)
Particulate Matter						
Change in transport-related particulate emissions	−12·4% (−17·3%:−6·8%)	−11·8% (−16·3%:−6·9%)	−10·1% (−14·3%:−5·4%)	−10·9% (−15·3%:−5·8%)	−3·2% (−4·9%:−1·4%)	−4·9% (−6·8%:−2·8%)

Note: Figures in parentheses are 95% confidence bounds. Other vehicles, including powered 2- and 3-wheelers, were not modelled within the scenarios because the proportion of travel within this mode was assumed to remain stable. All transport mode changes refer to change in vehicle kilometres travelled from baseline.

Europe PMC Funders Author Manuscripts

Table 4

Disability-adjusted life years (DALYs) gained per 100 000 population under the compact cities model for each city.

	City					
Change in population health outcomes	**Melbourne**	**Boston**	**London**	**Copenhagen**	**Delhi**	**São**
Cardiovascular disease (ICD-AM I00-I99)	622 (1071:312)	765 (1386:355)	582 (1053:244)	337 (832:4)	565 (1117:169)	363 (915:14)
Type 2 diabetes (ICD-AM E10-E14)	86 (159:40)	94 (189:41)	27 (61:7)	53 (146:−4)	28 (91:-10)	55 (155:−9)
Respiratory disease (ICD-AM J30-J98)	2 (4:1)	3 (5:-1)	8 (14:4)	2 (4:1)	22 (42:8)	3 (5:1)
Road trauma (ICD-AM V00-V89)	−34 (−7:−64)	−34 (−1:−66)	−41 (−19:−64)	−1 (20:−22)	2 (51:−48)	−4 (62:−71)
Total	679 (1181:330)	826 (1553:352)	581 (1084:216)	393 (967:5)	620 (1233:167)	420 (1029:12)

Note: Negative numbers indicate healthy years lost (DALYs lost). Figures represent 50th percentile estimates. Figures in parentheses are 95% confidence bounds. Aggregated individual estimates may not equal the total due to rounding and Monte Carlo estimation.