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Review

Improving health through policies that promote active travel: A review of evidence to support integrated health impact assessment

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Abbreviations: ADMS, Atmospheric Dispersion Modeling System; CALINE, California Line source model; CO, Carbon Monoxide; CO_2, Carbon Dioxide; COPERT, Computer Programme to calculate Emissions from Road Transport; ERF, Exposure Response Function; GHG, Greenhouse Gasses; HEARTS, Health Effects and Risks of Transport Systems; HIA, Health Impact Assessment; IPCC, International Panel on Climate Change; MOBILE, Mobile source emission factor model; NO_x, Nitrogen Oxides; NO_2, Nitrogen Dioxide; PA, Physical Activity; PM_{10}, Particulate matter less than 10 µm; $PM_{2.5}$, Fine particles (less than 2.5 µm); THE PEP, Transportation, Health and Environment Pan-European Programme; UFP, UltraFine Particulates; VMT, Vehicle Miles Traveled; VOC, Volatile Organic Compound; WHO, World Health Organization.

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ABSTRACT

Background: Substantial policy changes to control obesity, limit chronic disease, and reduce air pollution emissions, including greenhouse gasses, have been recommended. Transportation and planning policies that promote active travel by walking and cycling can contribute to these goals, potentially yielding further co-benefits. Little is known, however, about the interconnections among effects of policies considered, including potential unintended consequences.

Objectives and methods: We review available literature regarding health impacts from policies that encourage active travel in the context of developing health impact assessment (HIA) models to help decision-makers propose better solutions for healthy environments. We identify important components of HIA models of modal shifts in active travel in response to transport policies and interventions.

Results and discussion: Policies that increase active travel are likely to generate large individual health benefits through increases in physical activity for active travelers. Smaller, but population-wide benefits could accrue through reductions in air and noise pollution. Depending on conditions of policy implementations, risk tradeoffs are possible for some individuals who shift to active travel and consequently increase inhalation of air pollutants and exposure to traffic injuries. Well-designed policies may enhance health benefits through indirect outcomes such as improved social capital and diet, but these synergies are not sufficiently well understood to allow quantification at this time.

Conclusion: Evaluating impacts of active travel policies is highly complex; however, many associations can be quantified. Identifying health-maximizing policies and conditions requires integrated HIAs.

Contents

1. Introduction

The past decade has seen an enthusiasm for planning cities for health, which had mostly been forgotten since the urban sanitarian movement in the mid-nineteenth century (Corburn, 2007). Triggers for this renewed interest include concerns about obesity, physical inactivity, pollution, climate change, and road traffic injuries. Physical inactivity is one of the most important health challenges of the 21st century because of its influence on the most deadly chronic diseases, contributing worldwide to 21.5% of ischemic heart disease, 11% of ischemic stroke, 14% of diabetes, 16% of colon cancer and 10% of breast cancer (Bull et al., 2004). The World Health Organization (WHO) recently estimated overweight and obesity to be responsible for 2.8 million deaths annually; physical inactivity is (separately) responsible for an additional 3.2 million deaths (WHO, 2009). The apparent limitations of classic individual-based physical activity (PA) and dietary interventions have raised the interest of health professionals in community-level solutions that encourage healthy behaviors in daily routines (Lavizzo-Mourey and McGinnis, 2003).

Disease and mortality associated with vehicle emissions also represent a substantial challenge in public health. Urban air pollution currently accounts for instance for ~3% of mortality from cardiopulmonary disease, and 1% of mortality from acute respiratory infections in children under 5 years, worldwide (Cohen et al., 2005). These figures may worsen as the proportion of the population living in cities continues to rise (currently 50%, projected to reach 70% in 2050) (U.N., 2010). Vehicle emissions also contribute to climate change, recognized as a widespread threat to human health (Haines et al., 2009). The share of transport activities in GHG emissions (23% worldwide) continues to grow at a faster rate than any other end-use sector and the reduction of on-road emissions has been identified as the most effective strategy to reduce radiative forcing (Unger et al., 2010). The magnitude of reductions in emissions required to slow the buildup of greenhouse gases (GHG) is such that multiple solutions are needed, including changes in travel behavior (Boies et al., 2009). Another health impact of vehicle usage is traffic injuries, which is the second leading cause of death for people age 5–29 (WHO, 2004b). The rapid increase of auto sales and use is thus likely to have important impacts on public health (HEI, 2010).

International groups including the World Health Organization (WHO), the United Nations (UN), and the Intergovernmental Panel on Climate Change (IPCC) have recommended policy changes to combat physical inactivity, pollution, climate change, and traffic injuries (IPCC, 2007; U.N., 2010; WHO, 2004a). Transportation and planning policies promoting walking and cycling as alternatives to using private motor vehicles can contribute to these goals, with the potential for gaining further co-benefits such as congestion mitigation. At the same time, concerns have been raised about the potential to increase the risks of injuries and exposure to air pollution for pedestrians and cyclists (de Hartog et al., 2010; de Nazelle et al., 2009; WHO, 2006; Woodcock et al., 2009). Changes in how we design and build cities are important, but little is known about the interconnections among the changes and policies being considered. Fortunately, awareness of this topic is increasing (Dannenberg et al., 2006).

Major connections among transportation policies, planning, and health are summarized in Fig. 1, and reviewed in the next sections. Further important indirect health and other co-benefits of policies that encourage active travel are not specifically addressed here but have been reviewed elsewhere. These include improved mobility (in particular, access to healthcare services), curtailed social inequalities, and reduced congestion and road and parking costs (Litman, 2008). Generally, congestion and vehicle emissions are the primary indicators considered in evaluations of planning and transportation decisions.

Additional evidence, tools and methods are needed to evaluate transportation policies and the full range of their health impacts. In this context we review current knowledge of how health is affected by active travel and associated policies or contextual factors. Our purpose is to develop a framework for conducting integrated health impact assessments (HIA, Briggs, 2008; Dannenberg et al., 2006) useful for decision makers to develop optimal policies for health-promoting environments. We identify important components of an HIA, assess the existence and applicability of exposure–response functions (ERFs) and environmental models available to quantify relationships linking active travel-related policies to environmental indicators and to health impacts, and discuss how various exposures and outcomes interact with each other. This article is not a systematic review but rather an evaluation of the pertinence and possibility of quantifying potentially relevant impacts. Our goal is to make a case for formally conducting such assessment to better inform policy decisions for healthier urban environments.

We first propose a conceptual framework to assess health effects of policies that promote active travel. The framework guides our literature review of the most relevant fields of behavior, environmental quality and health. We cover relationships for which the research is most extensive and the evidence strongest as well as the quantitatively less well-established links between active travel policies and health or health determinants. We limit our discussion to adults as they are the decision-makers for most travel choices, even though children are also affected in important ways by active travel policies (or lack thereof) (Marshall et al., 2010; Wilson et al., 2010).

2. Conceptualization of transport policy impacts on health

The empirical evidence linking characteristics of city and regional land use and transport planning directly with health outcomes has

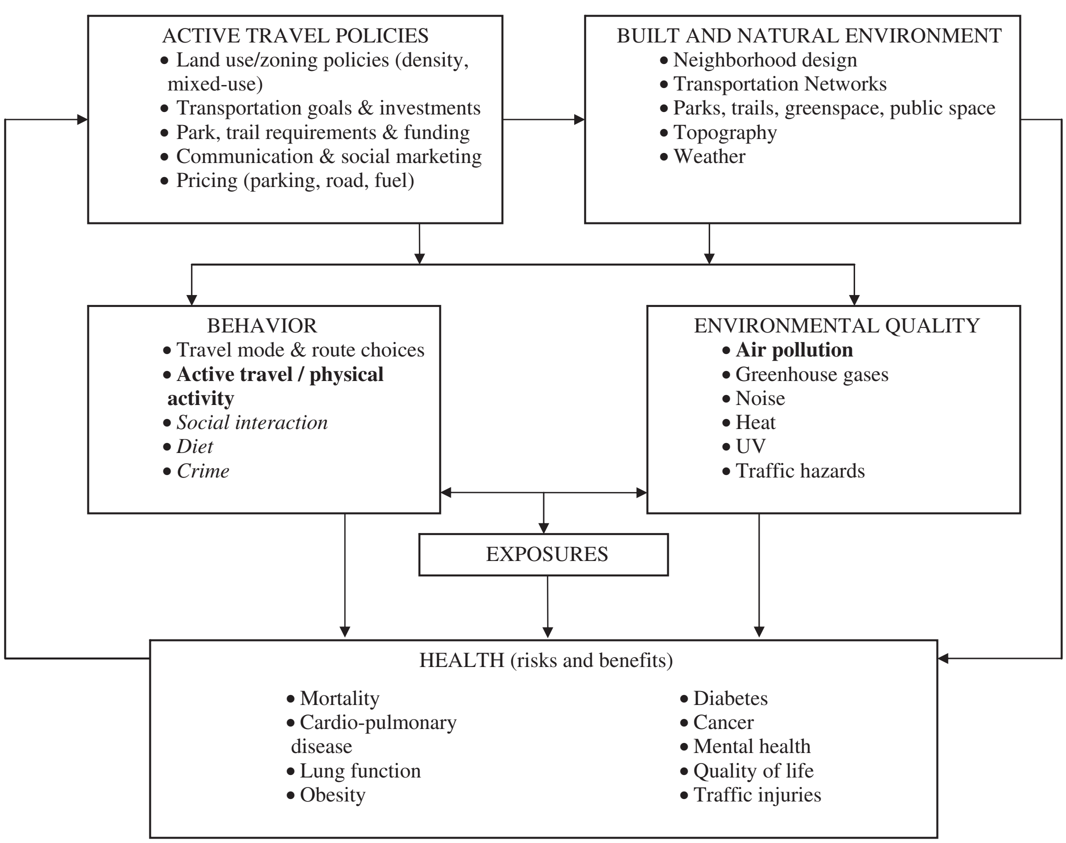

Fig. 1. Conceptual model of health impacts of active travel policies. In **bold** are shown behavioral and environmental quality variables recognized as having strongest exposure-health quantifications available, while variables in *italics* are the most uncertain to quantify.

mostly emerged in the past ten years. Pioneering studies showed that people living in areas of urban sprawl (dispersed low-density single use land patterns) were more likely to be overweight or obese (Ewing et al., 2003b; Lopez, 2004), suffer more from hypertension and other chronic diseases (Ewing et al., 2003b), and experience greater traffic fatalities, especially as pedestrians (Ewing et al., 2003a). Conversely, living in a more "walkable" neighborhood (with sidewalks, bike paths, parks, higher density, and stores within walking distance) was associated with a healthier weight status and better mental health (Frank et al., 2004; Giles-Corti et al., 2003; Sallis et al., 2009b). The connection between place and health in these studies was most often hypothesized to be linked to PA behavior.

A few recent HIAs have attempted to quantify various ways in which travel policies might affect health. Woodcock et al. (2009) and de Hartog et al. (2010) estimated health implications of hypothetical scenarios of mode shifts to walking or cycling in terms of benefits of PA and of reductions in air pollution exposure for the general population, and in terms of risks associated with increased traffic injuries. The latter study incorporated risks associated with increased air pollution inhalation while cycling; the former estimated greenhouse gas emission reductions. Both studies concluded that mode shifts towards active travel would generate public health benefits, mostly owing to increases in PA levels (and subsequent declines in diseases linked strongly to PA). Their findings suggest that PA benefits largely outweighed the additional risks due to road traffic crashes and increased pollution inhalation while cycling. An earlier WHO-sponsored project, HEARTS (WHO, 2006), attempted to link parts of the chain of effects from transportation policies to shifts in traffic, emissions, road crashes, exposures to air pollution and noise and their health outcomes, but not in a single full model. More recently the WHO proposed a unified approach to develop inclusive economic analyses of the health effects related to transport policies (WHO, 2009) and a toolbox (Transport, Health and Environment Pan-European Programme—THE PEP) describing case-studies that have been shown to be successful in addressing components of linkages between active travel policies and traffic injuries, noise, and climate change (WHO-UNECE, 2009). The toolbox can serve as a useful starting-point for policy evaluation; it provides quantifications of some specific case studies outcomes, but without an integrated assessment model.

These published studies provide indications of how transport policies may achieve their most substantial benefits from outcomes, such as PA, which are often not considered in urban planning. The studies stress opportunities for co-benefits of active travel policies, as compared to technological solutions to reduce emissions (cleaner vehicles) alone, and argue for integrating such considerations in the development of climate change mitigation policies. None of these previous efforts have provided a comprehensive assessment of active travel policies that integrate into one framework impacts of active travel policies in terms of (i) how the policies achieve behavior changes, (ii) other potential benefits (e.g. social capital), and (iii) optimal designs for positive net health benefits. Only the recently published de Hartog et al. (2010) study included unintended risks of active travelers' air pollution inhalation.

We propose a framework for assessing impacts of policies for promoting active travel that is broader in scope than previous efforts. While the framework would be applicable in the larger context of transportation and urban planning policies, we frame the discussion more narrowly around outcomes and conditions most relevant to walking and cycling. The conceptual model depicting putative pathways from active transportation-related policies to health, shown in Fig. 1, guides the ensuing review of the state-of-the art in research in the relevant fields. Our review is focused on policies that may directly or indirectly affect behaviors, which in turn, impact environmental quality and exposures. We distinguish between exposures in the general population, versus to the active travelers; the latter may modify his exposures via behavioral change. We then review how behaviors and exposures have corresponding positive and negative health implications, some with competing benefits and adverse impacts on the same outcome.

3. Active travel policies and behaviors

3.1. Active transportation policies and interventions

A growing body of literature suggests likely positive impacts of travel policies and interventions to increase walking and cycling (Pucher et al., 2010). The little research providing direct evidence based on rigorous longitudinal assessment designs shows moderate, albeit consistent, effectiveness of such interventions in changing behaviors (Ogilvie et al., 2007; Yang et al., 2010). Bundles of strategies are often implemented together, ranging from promotional campaigns to changes in the physical infrastructure (e.g. sidewalk improvement and bike lanes), making it difficult to isolate specific elements that may change travel behaviors but also suggesting that multi-pronged strategies are most effective at creating change. Specifically, comprehensive multi-level interventions, including infrastructure improvements (walking and cycling-friendly environments) combined with promotional campaigns (such as through schools and workplaces) may have greatest potential (Ogilvie et al., 2004; Pucher et al., 2010; WHO-UNECE, 2009). THE PEP case-study reviews (WHO-UNECE, 2009) stress the importance of vehicle speed reduction and investments in infrastructure focused on safety, as well as disincentives to car use such as high parking fees. Based on systematic reviews, the UK's National Institute of Health and Clinical Excellence (NICE, 2008) adds recommendations to counter urban sprawl, invest in urban renewal, and centralize location of firms to discourage the use of the private car and to promote the use of public transport.

Walking and cycling rates are higher in cities and countries where policies are put in place to encourage such behaviors (Pucher et al., 2010; VTPI, 2010). For example the presence of sidewalks, traffic volume, and safe crosswalks all are important determinants of the amount of walking and cycling in areas otherwise similar in wealth and geography (Jacobsen et al., 2009). In the Netherlands and Denmark, countries known for their commitment to active transportation, cycling reaches up to a third of the mode share in cities—in sharp contrast to the US and southern-European countries where cycling represents only 1–2% of trips (Pucher and Buehler, 2008). Walking exhibits similar contrasts across countries (Pucher and Dijkstra, 2003).

Some policies or interventions that promote active travel do not necessarily target walking and cycling per se, but instead have an indirect effect by discouraging auto travel and thereby promoting alternatives. Examples include road and parking pricing, or improving public transport which necessarily has an "active" component. London for example has seen a doubling of levels of cycling following the introduction of a congestion charge, but also significant investment in cycling infrastructure. Bike share of trips more than doubled in cities such as Berlin, Paris, Barcelona and Bogotá following comprehensive promotion programs including constructing bicycle facilities and bike sharing systems (Pucher et al., 2010). It is unclear which of the components contribute most among improvement in safety, access to bicycles, efforts to reduce traffic, and recognition of benefits of active travel (from promotional strategies). Importantly, cultural shift may occur when cycling and walking increase to a certain "critical mass", signaling to others that these are safe and enjoyable and perhaps even fashionable activities (Gatersleben and Appleton, 2007). Moreover, a significant increase in pedestrians or cyclists may lead to more demands for active travel policies, greater political influence of cyclists and pedestrians in shaping local transport policies, and more restrictions to the use of automobiles (Pucher et al., 2010). Quantifying effects of comprehensive policies becomes a challenge not only because of the lack of clarity of effectiveness of each component and their combined effect, but also because of the potential non-linear effect from changing social norms.

3.2. Built environment determinants of travel behavior

Health practitioners and transport planners are increasingly turning towards environmental solutions to promote PA and non-motorized transportation. These strategies can benefit all community members in contrast to targeted behavior change programs that only address one person or household at a time (Ogilvie et al., 2004). We review in this section research that has specifically assessed influences of the built environment on walking and cycling. We treat the two modes separately when possible, as they do not necessarily share the same determinants.

Recent research on determinants of walking and cycling for utilitarian or recreational purposes has focused on influences of the built environment (Heath et al., 2006; Saelens and Handy, 2008; Saelens et al., 2003). Land use measures of density and mix are probably the most examined built environment characteristic in relation to transportation behavior. Measures of residential or employment density are consistently associated with higher public transport use, higher walking, and lower driving (Ewing and Cervero, 2010; Marshall, 2008). However, many built environment attributes are strongly associated with higher densities making it difficult to isolate their effects. Still, after controlling for other land use and socio-demographic variables, US studies have found that doubling residential density might reduce VMT by 5 to 12% and potentially as much as 25% (NRC, 2009). Increasing density also increases the exposure potential (intake fraction) of emissions; as a result, increasing density might decrease VMT and emissions yet increase air pollution exposures, because people are in proximity to the (now-reduced) emissions (Marshall et al., 2005).

As with density, land use mix has been consistently associated with additional walking and transit use, and less distance driven. Having retail destinations, bus stops, offices, and similar land uses within walking distance from one's home is associated with a higher probability of walking and using transit (Ewing and Cervero, 2010). Table-S1 in the Online Supplementary Material (OSM), which is based on a literature review by Ewing and Cervero (2010), summarizes associations between transportation choices and their determinants.

Another important aspect of the built environment is transportation infrastructure. More and better-quality sidewalks are associated with adults having a higher likelihood of walking, using transit, and driving less (Table-S1). High street connectivity (measured by, e.g., intersection density or by the percentage of street crossings within an area that are four-way) shortens walking distances and provides multiple paths to reach destinations. Connectivity has been associated positively with higher transit use, and with higher walking and lower driving rates. There is a significant variation in the elasticity estimates calculated, as evidenced by the standard deviations, suggesting that these point estimates should be used with caution. Other factors that have been associated with walking and cycling, albeit less consistently, include the traffic environment, esthetics, safety, and pedestrian amenities (Lin and Moudon, 2010).

For cycling, concerns about traffic and lack of adequate and safe infrastructure are a major impediment to its use. Although the evidence is limited to a few studies, some cyclists appear willing to go out of their way and will ride larger distances to cycle on safe infrastructure (Dill, 2009; Parkin et al., 2007; Tilahun et al., 2007). In a study of US cities, a one percent increase in the length of on-street bicycle lanes was associated with a 0.31% increase in bicycle commuters (Dill and Carr, 2003). Other barriers to cycling include fear of crime/vandalism, bad weather, social pressure, hills, multiple stops along a route and long trip distances (Gatersleben and Appleton, 2007; Rietveld and Daniel, 2004).

Because different components of the built environment co-occur, comparing overall neighborhood patterns may provide better estimates of the built environment contributions to behavioral and health outcomes. Studies have shown associations between active travel and neighborhood scores of “walkabililty” or classifications indicating “pedestrian-friendly-” versus “auto-oriented-” designs. A systematic review of the literature found sufficient evidence for implementing both street-scale and community-wide urban designs that are pedestrian-friendly as effective means of increasing walking and cycling (Heath et al., 2006). Two recent studies using objective measures of walkability and total PA found that residents of walkable neighborhoods spent 35–49 more minutes per week of PA than those in low- walkable areas (Sallis et al., 2009b; Van Dyck et al., 2010). In contrast, a study in Minneapolis found that neighborhood type impacted the purpose of PA (for travel, versus for recreation or at a gym) but not the total amount of PA (Forsyth et al., 2008).

Much of the research on built environment determinants of walking and cycling has been conducted in the US, but results have been confirmed internationally. For example, a study of 11 countries, including multiple European nations, found that when adults reported having nearby shops, public transit, sidewalks, bicycle facilities, and recreational facilities, they were 20–50% more likely to meet PA guidelines than if they lacked these amenities. Those with all the favorable attributes were twice as likely to be active as those with no favorable attributes (Sallis et al., 2009a). For developing-country contexts, the literature lacks robust evaluation of these and most other issues considered in this paper.

What is often not clear in most studies of active travel behavior, due to the lack of longitudinal data, is an understanding of the characteristics of the individuals who change their behavior and sustain it, following policy interventions. For example, there is limited evidence from population-level studies of interventions to promote walking and cycling to suggest that sedentary people are encouraged to change behavior, while a few studies of cycling promotion interventions have reported data suggesting that existing cyclists making more trips may account for much of the observed overall increase in cycling (Ogilvie et al., 2004). Furthermore, most studies are cross-sectional; they are therefore unable to identify causation.

3.3. Other behaviors related to active travel policies

Social interactions, crime, and dietary habits are not typically included as outcomes or inputs in HIAs. Although research in these fields is broad, there are not well-established ERFs. Next, we briefly discuss these behaviors, but without deriving quantitative relationships.

One of the benefits of pedestrian-oriented urban planning such as mixing land uses, increasing density and providing walking, cycling and transit facilities, is to offer neighborhood amenities that bring life to the streets by increasing pedestrian traffic and providing spaces for spontaneous social interactions (Appleyard, 1981; Jacobs, 1961). Having places to walk to, public spaces, mixed land-uses, and residential density improve social capital such as knowing neighbors, trusting others, and being socially engaged (Leyden, 2003; Skjaeveland and Gärling, 2002). Further, architectural designs that provide “eyes on the street” (Jacobs, 1961) as a form of natural surveillance and natural space for social contact are shown to deter crime and reduce fear of crime (Mair and Mair, 2003), and promote physical functioning of elders (Brown et al., 2008). On the other hand, time spent driving is a strong negative predictors of social capital (Besser et al., 2008; Putnam, 2000).

Healthy eating habits may also result from active-travel-friendly environments in two ways. First, good land-use mix may provide access to retailers offering healthy foods (Sallis and Glanz, 2009; Smiley et al., 2010). Studies on such links, however, have largely been conducted in suburban US and Australia and may not universally apply. Second, diet and PA are linked: observational studies document that healthier diets and adequate PA tend to cluster (Tormo et al., 2003).

4. Environmental quality

Large-scale travel mode conversions from conventional-vehicle trips to active travel will reduce vehicle emissions, greenhouse gases, noise, and perhaps urban heat island effects. We first review traffic emissions and environmental quality, and in Section 4.2 discuss implications for exposures in the population. Health impacts are covered in Section 5.

4.1. Traffic emissions

A variety of modeling tools exist to predict changes in vehicle emissions and air pollution concentrations; however real-world examples are scant. Reductions in traffic due to active travel policies may occur from mode shifts to non-motorized travel for short trips, but also from policies that bring destinations closer to each other (higher density and mixed use) so that trips are shortened (hence lower emissions per vehicle trip) and non-motorized transport becomes more viable (hence some vehicle trips are foregone) (Frank et al., 2006). In addition, policies and planning decisions that increase walking and cycling can also reduce household vehicle ownership rates and vehicle speeds, and improve public transit travel, meaning that non-motorized travel may potentially have a leverage effect. Nevertheless, improvements in walkability through traffic calming can partly offset reductions in car use because of increased stop-and-go traffic and neighborhood congestion that increase emissions per trip (Ericsson, 2000). As an example, more walkable neighborhoods were recently shown in Vancouver to experience higher air pollution concentrations than less walkable neighborhoods for traffic-related primary pollutants (but not for ozone, a secondary pollutant) (Marshall et al., 2009). As mentioned above, urban form changes that reduce emissions may or may not reduce exposures, depending on shifts in proximity between emissions and people (Marshall et al., 2005).

The most formal and detailed approach to predict changes in ambient pollution concentrations due to traffic reduction involves linking a suite of traffic assignment, emissions, and dispersion models. One challenge is that non-linear effects such as vehicle operating conditions, chemical reactions, and pollutant dispersions make predictions of changes in emissions and concentration a complex and uncertain task. Connecting these various models can be complicated as they are generally developed independently and not necessarily linked, and depend on input availability (WHO, 2006).

Common vehicle emissions models include COPERT (widely used in Europe) and MOBILE6 (more common in the US) (Holmes and Morawska, 2006; Vardoulakis et al., 2003). We provide examples of emissions reductions scenarios in OSM Table-S2. A US analysis shows that if mode shifts were to occur solely from already short trips, the reductions in emissions would be modest (e.g. a mode conversion of 13% of short auto trips leads to 2% or less reduction in total CO, CO_2, VOC and NO_x emissions from private vehicles), despite the greater contribution of the high cold start emissions per mile in short trips (de Nazelle et al., 2010). In a European example, a 30% VMT reduction from passenger cars and two-wheelers is estimated to decrease emissions from the urban vehicle fleet by 12% for NO_x to 26% for VOCs (Table-S2).

Real world interventions highlight the difficulty in attaining and demonstrating air quality improvements. For example, a study on the London Congestion Charge presents equivocal results, and with contrasting beneficial and adverse air quality impacts for different pollutants in different neighborhoods (Atkinson et al., 2009). The congestion charge trial scheme in Stockholm resulted in a 15% drop in VMT leading to emissions reductions of 8.5% for NO_x, 13% for PM_{10} and CO_2, and 14% for CO in the inner city (1 to 3% emissions reductions in greater Stockholm). A dispersion model found changes in NO_x concentrations to be commensurate to changes in traffic in modeled streets, but NO_2 and PM_{10} reductions were smaller (e.g., on one street, an 8% traffic reduction led to 3% and 5% reductions in NO_2 and PM_{10} respectively) (Johansson et al., 2009). Temporary reductions in traffic during specific events, such as Olympic Games (Friedman et al., 2001; Wang and Xie, 2009) and military conflict (Yuval et al., 2008), have been shown to improve air quality significantly; however the special conditions under which these occur may not be relevant for long-term policy interventions.

Fewer models and studies exist for assessing traffic impacts on noise and heat than for air pollution. Automobile traffic is one of the main sources of urban noise, along with rail and air transports. Databases are becoming more available as the EU has recently required large conurbations to develop noise maps, using models such as the NMPB-routes-96 (EC, 2002). In the US, an urban noise map showed increased noise with higher traffic (Seto et al., 2007). Studies have reported varying correlations (0.2–0.8) between noise and traffic-related contaminants NO_2 and NO_x (Davies et al., 2009). Traffic contributes to climate change via GHG emissions but in a more immediate relationship, transportation infrastructure and land use patterns contribute to urban heat islands. Sprawled (auto-oriented) development leads to loss of open space surrounding cities and to greater impervious surfaces, which increase urban temperatures (Frumkin, 2002; Stone, 2009; Xiao et al., 2007).

4.2. Exposures to environmental hazards

Active travel policies that result in reductions in VMT may reduce ambient air pollution and noise emissions, which may reduce pollution exposures. For some individuals, time commuting is a significant contributor to daily non-occupational exposure to traffic-related air pollution (Fruin et al., 2008; WHO, 2006). Individuals who shift to active travel may change their exposures because of changes in times spent in proximity to vehicles and increased inhalation rates. We thus need to distinguish exposures of the general population from travelers' exposures.

4.2.1. General population exposures

Travel policies are likely to affect exposures in different neighborhoods differentially (Atkinson et al., 2009), reducing concentrations where traffic is reduced and potentially increasing concentrations where traffic is displaced. For example, converting traffic lanes into bike lanes and larger sidewalks could substantially reduce air and noise pollution in these streets, especially in canyon streets where vehicle exhaust gets trapped (Vardoulakis et al., 2003). These changes would affect long-term exposures for people living in or nearby the traffic streets. Policies that lead to net traffic reductions rather than route changes are thus more likely to reduce population exposures to air and noise pollution—if they do not simultaneously increase congestion.

4.2.2. In-travel exposures

Traffic-related air pollution exposures tend to be higher during travel than in most non-occupational microenvironments, because of proximity to other vehicles. One exception is ozone, which typically exhibits higher concentrations at further distances from heavy traffic (McConnell et al., 2006). Exposure differences can vary considerably by travel mode (see examples in OSM Table-S3), as well as by local traffic and meteorological conditions (Kaur and Nieuwenhuijsen, 2009). Car and bus travel appear to lead to the highest exposures to vehicle emissions, particularly to gasoline-powered vehicle emissions such as CO and VOCs. For PM exposures, cars may have some exposure reduction advantage if windows are closed, while subways and busses appear worse on average (but not always) compared to other modes of travel (Nieuwenhuijsen et al., 2007) .

Due to their greater distance (on average) from direct vehicle emissions, walking and cycling often show lower exposures to CO, VOCs or PM than other travel modes, although still elevated compared to ambient levels (Briggs et al., 2008; Kaur et al., 2007). Steep pollution gradients exist on and near roadways (HEI, 2010), so small changes in position relative to vehicles and/or the center of the road, as well as choice of high- or low-traffic routes, can have large effects on exposure (Adams et al., 2001b; Kaur et al., 2005; McNabola et al., 2008). Cyclists and pedestrians often have the advantage of choosing their routes, using detours or parallel paths to take quieter low-traffic streets to minimize their exposures (Adams et al., 2001a; Hertel et al., 2008).

Importantly, though, walking and cycling may lose some of their exposure advantage when increased inhalation and possibly longer duration of travel are taken into account, as several recent studies have shown (Int Panis et al., 2010; McNabola et al., 2008; Zuurbier et al., 2010) (see also illustration in OSM Table-S3). For example, McNabola et al. (2008) estimated that while $PM_{2.5}$ concentration measurements alone were highest for bus travel, followed by car travel, cycling and walking, the highest inhaled dose of $PM_{2.5}$ was seen in cyclists. Zuurbier et al. (2010) found similar patterns with cyclists inhaling 10 to 200% higher doses of PM_{10}, soot, $PM_{2.5}$ or ultrafine particles (UFP) than bus or car occupants, while buses or cars experienced the highest concentrations.

Noise, UV radiation and heat exposures may also be higher during travel than in other non-occupational settings, but there is limited evidence of this aspect. The few studies on travel mode noise exposures have found at times high noise levels especially in some subway systems (Neitzel et al., 2009). They have also found comparable noise exposures for pedestrian and car travel, and higher exposures for motorcycles (Boogaard et al., 2009; Dias and Pedrero, 2006). Active travel may increase exposures to heat (due to physical exertion) and UV, depending on modifying factors such as the presence of tree canopies and cloud cover, although we found no studies considering such relationships. Glass panes in car and bus travel filter out most of UVB, but not necessarily UVA (Tuchinda et al., 2006). UVB is required for vitamin D production; UVA is not. Optimal health-enhancing policies may incorporate walking or cycling corridors with tree shading which reduce microenvironmental temperatures (Reid et al., 2009). Such designs may lower heat vulnerability for the greater population of urban areas as well as for the travelers.

5. Health impacts of active travel policies

5.1. Health benefits of PA and active commuting

A substantial body of research has provided compelling evidence of associations between regular PA and various health outcomes in adults. Health agencies generally recommend 30 min or more of moderate-intensity PA on most days of the week for good health (Haskell et al., 2007; US DHHS, 2008). These recommendations correspond to weekly energy expenditures of ~8 MET-hr, or 750 kcal, over basal levels, and are associated with ~30% reductions in all-cause mortality, cardiovascular disease and type 2 diabetes (Haskell et al., 2009). Daily PA goals can be met cumulatively over separate sessions of 10-minute bouts of activity rather than at one time. More vigorous or longer duration of activity may incur greater benefits; however, the largest benefit comes simply from avoiding inactivity. Some studies indicate a curvilinear dose-response relationship in preventing chronic disease or reducing all-cause mortality, meaning increase in benefits becomes less and less for any given increase in the amount of PA (US DHHS, 2008). For conditions such as colon cancer, type 2 diabetes, depression, osteoporosis, hypertension, and weight status the shape of the dose-response relationship remains particularly unclear and may vary depending on the outcome and the population being evaluated (Haskell et al., 2007; Rankinen and Bouchard, 2002).

Most studies do not differentiate on the type of PA but rather just consider effects of different metabolic equivalent (MET) intensity levels. Few studies have investigated the specific health impacts of active travel. An important limitation of some studies is the lack of control for other forms of activity, which is needed to assess the independent effect of walking or cycling. Comparing different forms of activity, Matthews et al. (2007) found that leisure-time exercise and cycling for transportation were both inversely and independently associated with all-cause mortality (25% to 35% reduction in risk for activities above 3.5 MET-hours/day compared to none). The first large scale prospective study found that bike commuting in Copenhagen could reduce the risk of premature mortality by approximately one third (Andersen et al., 2000). In a meta-analysis of active commuting (walking and cycling), Hamer and Chida (2008a) found an 11% decrease in cardiovascular risk associated with the behavior in adults (in fully adjusted models including for other forms of activity, but with a crude binary measure of active commuting). In another meta-analysis, Hamer and Chida (2008b) found that walking was strongly associated with cardiovascular risk reductions, with similar impacts on all cause mortality and indications of a dose-response relationship. The authors observed that pace (intensity) was more important than volume (duration) for reducing risk. Zheng et al.'s (2009) meta-analysis found a 19% reduction in coronary heart disease risk for a weekly increment of 8 MET-hr by walking. Other studies have found favorable associations of active commuting with type 2 diabetes, obesity, cancer, and levels of metabolic risk factors for CVD, and fitness (Gordon-Larsen et al., 2009a; Gordon-Larsen et al., 2009b; Hu et al., 2003). The evidence for morbidity impacts of walking and cycling is weaker than for mortality. A review by Woodcock et al. (2009) surveyed the literature on moderate-intensity PA as a surrogate for active commuting. They conclude that the evidence was robust for diabetes, cardiovascular disease, breast cancer, colon cancer and dementia. (OSM Table-S4 summarizes risk estimates obtained from systematic reviews.)

5.2. Health impacts of exposures

5.2.1. Air pollution—population wide impacts

While air pollution reductions attributable to active travel policies may be small, health-risk benefits could be widespread (impacting all individuals in an urban area). Traffic-related air pollution has been shown to contribute to morbidity and mortality through a variety of mechanisms linked to respiratory, cardiovascular, reproductive, and neuro-developmental effects (HEI, 2010). A review by the Health Effects Institute (HEI, 2010) found the evidence “suggestive but not sufficient” for a causative role of traffic-related air pollution on mortality (especially cardiovascular mortality), cardiovascular morbidity, onset of childhood asthma, and exacerbation of respiratory symptoms in adults. For other outcomes in adults, including asthma onset, chronic obstructive pulmonary disorder, cancer, and birth outcomes, associations were generally consistent yet insufficient to establish a causal role for traffic exposure. Only exacerbation of symptoms in asthmatic children was found to meet the criteria for a causal relationship with traffic-related air pollution. Other reports have concluded more definitive causal relationships between ambient air pollution and mortality and morbidity outcomes, but they have not examined the specific role of traffic pollution (e.g. Brook et al., 2010; Chen et al., 2008).

HIAs typically apply ERFs derived from long-term air pollution exposure studies to estimate effects from changes in ambient air quality. OSM Table-S5 provides example ERFs from systematic reviews of long-term studies or large single studies on all-cause mortality and exposures to $PM_{2.5}$, PM_{10}, UFP, and NO_x. Other endpoints often considered include cardio-pulmonary mortality and morbidity, lung cancer, and lung function. For example, the US EPA in its current risk assessment for the revision of the $PM_{2.5}$ standard chose to use risk estimates from an extended analysis of the American Cancer Society Study (Krewski et al., 2009), including long-term exposure mortality hazard ratios associated with 10 μg m^{-3} increments in $PM_{2.5}$ for all causes (HR = 1.06: 95% CI, 1.04–1.08), ischemic heart disease (HR = 1.24; 95% CI, 1.19–1.30), cardiopulmonary disease (HR = 1.14, 95% CI, 1.11–1.17), and lung cancer (HR = 1.14, 95% CI, 1.06–1.22).

While health-effects relationships associated with NO_2 may be less robustly quantified than for $PM_{2.5}$, NO_2 is important to study as it may reflect better the spatial distribution of traffic-related pollution. For instance, a fine scale exposure assessment within the city of Toronto led to estimates of 17% and a 40% increase in all-cause mortality and circulatory mortality respectively for a 4 ppb contrast (interquartile range) in NO_2 (Jerrett et al., 2009b). Ozone may also be of interest, given documented effects on mortality, independent of PM (Jerrett et al., 2009a), and specific concerns of effects of exposures while exercising on respiratory diseases (McConnell et al., 2002). High ozone exposures generally occur away from high traffic sources and city centers (Marshall et al., 2006). Evidence is emerging for exposure-health relationships for UFP (Hoek et al., 2009) and black carbon (Smith et al., 2009) effects on mortality, which are good markers of traffic-related exposures, particularly diesel. It is sometimes difficult to determine which specific contaminants to use in an HIA, as many pollutants are markers of pollutant mixtures from specific sources; as such, the pollutant itself may or may not have independent impacts on health (HEI, 2010).

5.2.2. Air pollution—impacts on commuters

Few studies have evaluated health effects from the short-term exposures to high air pollution levels during commuting. Studies have found lung function decrements and inflammation (2-hour walks in London, asthmatics, McCreanor et al., 2007), nonfatal myocardial infarction (Augsburg, all modes of transport, Peters et al., 2004), physiological changes in heart function (8-hour work shifts of US troopers, Riediker et al., 2004), lung function decrements and airway inflammation, (1-hour cycling, healthy volunteers, Strak et al., 2009), and DNA base damage (90-minute cycling, healthy volunteers, Vinzents et al., 2005). The studies of real world exposures, however, currently provide an incomplete basis for deriving ERFs for use in HIAs, because of the limited evidence base, different study designs and inconsistent results.

5.2.3. Noise, UV, and heat

Exposures to road traffic and aircraft noise have been associated with annoyance, sleep disturbance and myocardial infarction in long-term exposure studies (Kempen van and Houthuijs, 2008; Miedema and Oudshoorn, 2001; Miedema and Vos, 2007). OSM Table-S6 provides suggested ERFs. An issue for the road traffic studies is how much of the effects can be attributed to noise or air pollution. Currently, no exposure-health relationships can be derived specifically from travel-time exposure studies. If noise deters walking and cycling, then the impact on physical activity may reflect an indirect effect of noise on health (van Lenthe et al., 2005).

Both UVA and UVB can cause adverse health effects. UV exposure increases the risk of three common types of skin cancer (Armstrong and Kricker, 2001; Reichrath, 2009). UVB is needed to produce endogenous vitamin D. Breast and prostate cancer, autoimmune diseases and hypertension are associated with Vitamin D deficiency. The optimum sunlight exposure has been debated and there appears to be a turning point in the ERF beyond which risks outweigh benefits of UV exposure; however, the exact level is unclear and depends on personal characteristics (Mead, 2008). Currently there is not quantitative evidence on whether the net health effect from UV exposure during increased walking and cycling would be beneficial or detrimental.

Elevated temperatures affect mortality in urban areas throughout the world, although temperature thresholds vary by location. Basu (2009) in a recent review found direct comparisons across studies difficult, but reported for example that a 1 °C increase above threshold in Mediterranean cities was associated with 3% increase in daily mortality; effects were similar in the US and stronger in Korea (Basu, 2009; Kovats and Hajat, 2008). Heat island effects may impede night-time cooling and thus may enhance heat-related adverse outcomes in urban environments (Kovats and Hajat, 2008). Heat may act synergistically with ozone and particulate matter to worsen health (Basu, 2009).

5.3. Traffic injuries

Three thousand lives are lost daily in the world due to road crashes (Peden et al., 2004). Pedestrians and cyclists are especially vulnerable to injuries: in the US in particular, pedestrians (cyclists) are 23× (12×) more likely to die in a crash than car occupants per kilometer traveled (Pucher and Dijkstra, 2003). However, the specific metric of comparison matters. For example, measuring injuries per hour of travel tends to produce more commensurate risks for cars and bicycles, but still for walking risk per hour is three times higher than for driving in Europe (Peden et al., 2004). The reason for this difference is that automobiles drive more "safe km" (on highways designed for cars) than cyclists riding fewer km on much more dangerous urban roads (in part due to poor bicycle facilities). Important differences exist between countries and across cities, e.g., fatality risks are nearly 6 times greater for cyclist per km traveled in the US compared to Holland (1.1 fatality per km traveled in the Netherlands versus 5.8 in the US) (Pucher and Buehler, 2008).

One protective factor for active travel is the effect of "safety in numbers". Meta-analyses of crash data show that the more people walk and cycle, the safer walking and cycling are per person (Elvik, 2009; Jacobsen, 2003). Models of accidents or injury (e.g. number of fatalities), I, have been fit to the equation $I = aE^b$, where E is a measure of amount of walking or cycling, and a and b are empirical parameters. Studies find that b is consistently below 1 (generally between 0.1 and 0.7), indicating the risk of injury or crash declines with increased active travel. Jacobsen (2003) finds that in the most likely case, the doubling of people walking would lead to 32% increase in total injuries, and therefore a 34% reduction in each walker's individual risk. A "tipping point" hypothesis put forth by Elvik (2009) suggests that a sufficient number of transfers from motorized vehicles to walking or cycling could even lead to a reduction in overall number of accidents. In cities such as Berlin, London, Amsterdam and Copenhagen, substantial increases in bicycle use have been accompanied by reductions in the incidence of serious injuries to cyclists (Pucher et al., 2010).

Features of the built environment that can improve cycling and pedestrian safety include physical separation between cars and cyclists or pedestrians, reduced vehicle speed, and cues for avoiding risky behaviors by any traveler. Traffic calming can reduce traffic injuries by 15% to 25% (Elvik, 2001). On-road marked bike lanes and separated cycle tracks on a roundabout increase cycling safety, while roundabouts with multiple traffic lanes or with a marked bike lane are more hazardous for cyclists (Reynolds et al., 2009). Traffic calming not only improves safety, it also enhances the perception of safety, which thereby may encourage more cycling and walking. Because of the "safety in numbers" effect mentioned above, the increases in cycling and walking then reduce risks for all active travelers.

5.4. Other health impacts of active travel policies

Studies have linked directly walkable neighborhoods to the physical and mental health of its residents. Access to greenspace, in particular, some forms of which (such as longitudinal parks and tree canopies) would provide amenities for pedestrians and cyclists, has been shown to improve health, particularly mental health and quality of life (Tzoulas et al., 2007). Some possible underlying mechanisms explaining health benefits of exposure to greenspace have been hypothesized and tested, including increase in physical activity or social contact; however, available evidence is not conclusive (Maas et al., 2009; Tzoulas et al., 2007). Large amounts of auto use on the other hand has been linked to negative mental and social impacts such as road rage and time spent away from family (Frumkin, 2002). Social capital is shown to have positive effects in reducing crime and improving physical and mental health (Kawachi and Berkman, 2000). For example, residents of US states with the lowest levels of social capital have 22% to 48% higher odds of fair to poor health compared to those living in states with the highest social capital indicators (Kawachi, 1999). Social isolation or the lack of social support or social networks were demonstrated to increase the risk of dying prematurely from all causes in cohort studies in the US, Europe, and Japan (Berkman and Glass, 2000).

The diet and PA linkages mentioned in terms of behaviors in Section 3.3 extend to effects on health. Numerous trials report that without dietary modification, exercise is unlikely to be effective for achieving significant weight loss (Caudwell et al., 2009). Moreover, PA and diet have synergistic effects on health outcomes besides obesity. Compared to either factor individually, diet and PA in combination have been found to be more strongly associated with outcomes such as reversal of metabolic syndrome, cancer survival, and reduced risk of Alzheimer's disease (Anderssen et al., 2007; Pierce et al., 2007; Scarmeas et al., 2009). Finally, obesity and other diet-related disorders such as diabetes influence susceptibility to adverse effects of exposure to air pollutants such as inflammation and cardiovascular events (Chen et al., 2007; Zeka et al., 2006).

Reduced mobility and lack of access to economic and social opportunities and health services is also linked to poor health, with unequal distribution across the social spectrum. In fact, transport has been identified as one of the most important social determinants of health (Wilkinson and Marmot, 2003), with car-dependent urban forms affecting children, the elderly and low-income groups the most. For example, in the US 21% of those aged above 65 do not drive, and these older non-drivers take 15% fewer trips to the doctor and 65% fewer trips to friends and family for lack of other transportation options (Bailey, 2004). In addition to physical barriers to accessing services, the burden that larger transportation-costs can impose on lower-income people can cause stress and reduce money available for medical care. Social injustice may also be further perpetuated by unequal hazardous exposures and susceptibility to adverse health outcomes (Northridge et al., 2003).

6. Discussion

We reviewed evidence for the relationships between active travel and components of active travel policies and health, indicating potential synergistic, feedback or competing effects of different components of policies, and highlighting relationships for which knowledge is strongest or weakest for integration in a quantitative HIA (Fig. 1: variables in **bold** are those identified having the most robust exposure-health quantifications available, while those in *italics* are those for which the least robust quantitative evidence is available).

We found strong evidence that environmental factors related to walkability (transportation infrastructure and land use patterns) are associated with more active transportation and less driving. Comprehensive multi-level policies may be most effective in promoting healthy transportation behavior changes, but their effects are more difficult to quantify. Notably, there may be positive feedback effects when beyond a certain level of participation in the population, walking and cycling become socially expected and desirable as well as safer behaviors. Linking the policies to actual changes in behaviors and to resulting levels of air pollution and noise may be one of the most challenging steps in the assessment of active travel policies.

We identified clear PA-related health benefits with quantifiable relationships for walking and cycling, as well as robust ERFs of health benefits of pollution reductions for certain traffic-related air pollutants. Active travel policies have the potential to generate large health benefits to the population health through increases in PA of active travelers, and smaller benefits through reductions in exposures of air pollution in the general population. Substantial improvements in air quality and noise are improbable through active travel policies alone; however, small changes that affect long-term population exposures can have meaningful impacts. There is potential for risk trade-offs for individuals who shift to walking and cycling and consequently increase their inhalation of air pollutants and exposures to noise, heat and traffic hazards. However, insufficient knowledge exists today of the health effects of environmental exposures during travel. While more work is needed in this area, ERFs could be derived from current studies as a first approximation to evaluate potential unintended adverse health impacts of increased air pollution inhalation during active travel. For example, assumptions can be made about travel duration and associated inhalation rate to infer dose-response functions from existing studies as in the methods used in Pope et al. (2009) or de Hartog et al. (2010). Quantifying risks of traffic injuries due to mode shifts to cycling and walking is feasible because numerous studies exists, but the task is complex because of many contributing factors that vary greatly across communities. Well-implemented active travel policies that address pedestrian and cyclist risk factors could lead to a reduction in traffic injuries, including for other road users as vehicle use decreases.

More challenging to quantify are the relationships between active travel policies and social capital, crime, greenspace, and diet, including all feedback effects. For example, fear of crime may decrease PA, a change in PA may affect diet, both of which combined will have a synergistic effect on health, as well as an interactive effect with air pollution. The extent of the complex non-linear combined effect of active travel policies on these outcomes is not currently well understood. Yet, they may contribute sufficiently important improvements in quality of life and health to make well-designed active travel policies that enhance such outcomes (e.g. by providing public spaces, benches, and other amenities for pedestrians) attractive options.

A problem found in many of the relationships related to transportation and PA is that ERFs are mostly derived from cross-sectional studies. This poses questions regarding the strength of causal inference and the characteristics of the population that might be affected by the changes. For example, there is only limited evidence that people behave in part as a consequence of their surrounding environment, rather than simply choosing to live in locations that allow them the lifestyle they desire (Cao et al., 2009). There are insufficient longitudinal data to ascertain what specific policy or change in the built environment would result in a change in travel habits. In addition, the socio-demographic profiles of those who may change to and sustain active travel, including age, baseline health, and lifestyle factors (e.g. diet and baseline PA levels) are not currently well understood. Yet, these factors are important determinants of health impacts of PA or hazardous exposures (de Hartog et al., 2010). More research is needed with pre-post intervention assessments. Confounding and measurement error is present in all studies reviewed, contributing to uncertainties in the quantification of relationships. For example, important sources of uncertainty in establishing ERFs include the description of the built environment in travel studies, characterization of exposures and choice of pollutants in air pollution studies, quantification of energy expenditure in PA studies, and under-reporting of accidents in traffic injury studies.

Despite caveats on the causality of the relationships, the characteristics of the population affected and limitations of real-life human research, several of the associations reviewed can be quantified. With adequate attention to the characterization of uncertainty, evidence is sufficient to begin formulating a comprehensive impact assessment of urban transport policies. Two recently published comparative risk assessments (de Hartog et al., 2010; Woodcock et al., 2009) present the first such broad analysis. Both studies find that the greatest benefits of active travel come from increased PA for those who shift to active modes, dwarfing benefits that would be obtained from air pollution reductions, and largely compensating increased risks of traffic injuries or air pollution inhalation for active travelers.

A limitation of the Woodcock and de Hartog studies is the lack of consideration of how policies act to change behaviors and how optimal policy scenarios can be developed. Policies typically come in bundles (e.g. bike lane network + tree canopies + traffic calming measures). Assessing such "packages" may not only represent a more realistic view of policy processes but also allow considerations of further co-benefits beyond changes in PA and air pollution. Other than well-known attributes of walkable neighborhood (mixed and dense land uses), examples of urban design features that provide a pleasant and encouraging environment for cyclists and pedestrians and enhance health benefits include: (i) tree canopies, (ii) bike and pedestrian networks separated from traffic, (iii) public amenities (benches and public spaces), and (iv) green space. Such solutions respectively provide the added benefits of (i) cooling the air and protecting active travelers from heat; (ii) minimizing exposure to traffic air pollution, noise and crash hazards; (iii) encouraging social interaction; and (iv) improving mental health and well-being. Inter-relationships are not straightforward and surprising outcomes may emerge, such as natural greenery shown in one study to discourage trail use, perhaps owing to perception of unsafe conditions (Reynolds et al., 2007). The full and synergistic impacts of travel and planning policies are important to note, as although multiple solutions can be found to enhance health, policy-makers do not always perceive that the built environment has an impact on the health of people or the environment (Leyden et al., 2008).

We have argued for a broad perspective in assessing impacts of active travel policies and framed the issue to include outcomes not yet integrated in assessments of urban travel policies. We have inevitably still excluded a large range of health effects. We did not review health impacts considered too distal, such as through effects of climate change (e.g. weather disasters, changing dynamics of disease vectors, climatically-related production of photochemical air pollutants, and risk of conflict over depleted natural resources) (McMichael et al., 2003), or through changes in ecosystems and on water quality and quantity (e.g. impacts of sprawl on land fragmentation) (Frumkin, 2002).

7. Conclusion

Policy decision-making, whether concerning the environment, health, or urban planning, has often been criticized for being piecemeal and selective (Duany, 2002). With the growing interest in active travel as a solution to physical inactivity, urban air pollution, and climate change, it is important to recognize the complexity of interactions among people, places, and the natural environment. This review contributes to making the case for more integrative approaches to decision-making, in particular considering possible unintended consequences of policies and solutions to mitigate risks, and integrating synergies and impacts that are not classically considered but could be important predictors of quality of life. The goal of an urban transport policy impact assessment could thus be to identify promising opportunities for simultaneously meeting society's transportation and public health objectives.

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Appendix A. Supplementary data

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