Health & Place 35 (2015) 79–84

Contents lists available at ScienceDirect

Health & Place

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

Predicting urban design effects on physical activity and public health: A case study

Jacqueline MacDonald Gibson [a,*], Daniel Rodriguez [b], Taylor Dennerlein [b], Jill Mead [c], Trisha Hasch [d], Grant Meacci [d], Stuart Levin [e]

[a] Department of Environmental Sciences and Engineering, Gillings School of Global Public Health, University of North Carolina at Chapel Hill, Campus Box 7431, Chapel Hill, NC 27599-7431, USA
[b] Department of City and Regional Planning and Department of Epidemiology, University of North Carolina at Chapel Hill, Chapel Hill, NC, USA
[c] Department of City and Regional Planning and Department of Health Behavior and Health Education, University of North Carolina at Chapel Hill, Chapel Hill, NC, USA
[d] Raleigh Urban Design Center, Raleigh, NC, USA
[e] Wake Internal Medicine Consultants and University of North Carolina School of Medicine, Raleigh, NC, USA

ARTICLE INFO

Article history:
Received 9 April 2015
Received in revised form
21 July 2015
Accepted 23 July 2015

Keywords:
Built environment
Health impact assessment
Environmental health
Chronic disease
Physical activity

ABSTRACT

With increasing global concerns about obesity and related health effects, tools to predict how urban form affects population physical activity and health are needed. However, such tools have not been well established. This article develops a computer simulation model for forecasting the health effects of urban features that promote walking. The article demonstrates the model using a proposed small-area plan for a neighborhood of 10,400 residents in Raleigh, North Carolina, one of the fastest-growing and most sprawling U.S. cities. The simulation model predicts that the plan would increase average daily time spent walking for transportation by 17 min. As a result, annual deaths from all causes are predicted to decrease by 5.5%. Annual new cases of diabetes, coronary heart disease, stroke, and hypertension are predicted to decline by 1.9%, 2.3%, 1.3%, and 1.6%, respectively. The present value of these health benefits is $21,000 per resident.

1. Introduction

Over the past decade, the role of the built environment in escalating obesity and chronic disease rates has been increasingly recognized (Jackson et al., 2013; Jackson, 2003; Papas et al., 2007; Adams et al., 2011; Kerr et al., 2007; MacDonald et al., 2010; Furie and Desai, 2012; Sallis et al., 2012). As a result, public health practitioners have recommended using health impact assessment (HIA) to focus the attention of city and transportation planners on the health consequences of their decisions (Wernham, 2011; Negev et al., 2012; Bhatia and Corburn, 2011; National Research Council, 2011; Hoehner et al., 2012; Bourcier et al., 2014). As an example, during 1999–2012, at least 34 HIAs of urban and transportation planning projects were completed in the United States (Supplementary file, Table S1).

Most U.S. HIAs follow a process recommended by the U.S. National Academy of Sciences, which also is consistent with global HIA practice (National Research Council, 2011). The recommended process includes an assessment step, which "analyzes and characterizes beneficial and adverse health effects of the proposal and each alternative." However, to our knowledge, no U.S. HIAs of urban planning projects have quantified expected changes in population health as mediated by physical activity (Dannenberg et al., 2012; Bhatia and Seto, 2011). Recent systematic reviews have identified a small number of U.S. academic studies that considered costs and benefits of projects to promote bicycling and walking, but none of these involved developing a predictive model to support a formal HIA (Doorley et al., 2015; Mueller et al., 2015). Many formal U.S. HIAs have identified physical activity as a key health determinant (Supplementary file, Table S1), yet their analyses are limited to qualitative discussions of whether health impacts are expected to be beneficial, detrimental, or neutral. To fill the gap in analytical methods for HIAs, this article develops and then demonstrates an approach for quantifying population physical activity and health effects of different urban designs.

We constructed a computer model that simulates time spent walking for transportation by each resident of a neighborhood as a function of multiple urban design variables (including intersection density, land-use mix, residential density, and retail floor area)

* Corresponding author. Fax: +1 919 966 7911.
E-mail address: Jackie.macdonald@unc.edu (J. MacDonald Gibson).

http://dx.doi.org/10.1016/j.healthplace.2015.07.005
1353-8292/

shown in previous epidemiologic studies to be associated with transportation walking (Frank et al., 2010; Sallis et al., 2009). For each simulated resident, the model then projects the corresponding effect of transportation walking on the risk of premature mortality, diabetes, coronary heart disease (CHD), stroke, and hypertension.

We demonstrated the model by applying it to support an HIA of a new small-area plan for a neighborhood in Raleigh, North Carolina (NC). In 2014, the United Nations ranked the Raleigh area as the second-fastest growing urban agglomeration in the United States (United Nations Department of Economic and Social Affairs, 2014). Until recently, growth in Raleigh was largely unchecked, and as a result the city was referred to by some as "Sprawleigh" (Goldberg, 2011). However, over the past several years, Raleigh has developed a new city plan intended to increase population density and limit sprawl.

Like many post-World War II neighborhoods in the United States, the neighborhood for which we demonstrate the HIA is characterized by low-density, auto-dependent development. Known as the "Blue Ridge Road Corridor" (BRRC) because it is bisected by Blue Ridge Road, the neighborhood is used not only by residents but also by employees and visitors to access a number of area attractions, including the NC Art Museum, NC Fairgrounds, PNC Arena, Rex Healthcare Center, and NC State University College of Veterinary Medicine. However, the neighborhood lacks pedestrian infrastructure (Supplementary file, Figs. S1–S3) and, apart from the main attractions, has few retailers. The limited local road network channels much of the traffic onto Blue Ridge Road.

One of us (S. Levin), a BRRC resident and physician, has observed a rise in obesity and chronic diseases among patients over the past two decades. This observation led to the establishment of a stakeholder group of neighborhood residents and landowners to advocate for change. In turn, the Raleigh Department of City Planning commissioned a new small-area plan and an HIA to analyze its potential health effects. The plan includes several features designed to convert the corridor into a pedestrian-friendly community.

Here, we show how our new simulation model can be used to quantify the health benefits of investing in implementation of the small-area plan. Specifically, one objective of this study was to simulate the potential effects of the new small-area plan on the incidence rates of premature mortality and new cases of diabetes, CHD, stroke, and hypertension over a 25-year period, a typical planning period for capital investment projects. The study also calculated the economic impacts of these avoided cases. An additional objective was to demonstrate a method for quantifying health impacts of new urban small-area plans that could be readily adapted to support future HIAs in other communities.

2. Methods

The simulation model (encoded in *Analytica* v. 4.5, Lumina Decision Systems, Los Gatos, Calif.) follows the framework of the World Health Organization (WHO) Health Economic Assessment Tools (HEAT) Tools for Walking and Cycling (Kahlmeier et al., 2011; Kahlmeier et al., 2014), but it builds on this framework in several important ways. First, it uses data on built environment features to estimate time spent walking for transportation, whereas the HEAT method relies on user-defined estimates of walking time. Second, it estimates chronic disease outcomes in addition to premature mortality. Third, it quantifies uncertainty via Monte Carlo simulation. Consistent with WHO recommendations, the model assumes that full benefits will begin accruing five years after completion (Kahlmeier et al., 2011). For the case study, we assume the small-area plan will be implemented by 2023, and we calculate health outcomes avoided during 2028–2048, consistent with the 20- to 30-year horizon often used in capital investment planning.

2.1. Health outcome selection

We selected for analysis health outcomes shown in previous epidemiologic studies to be associated with walking for transportation and for which estimates of relative risks of the outcome as a function of time spent walking for transportation were available as of the end of 2012, the year during which scoping of the HIA project occurred. At the time of project scoping, such information was available for premature mortality, CHD, stroke, hypertension, and diabetes. Although physical activity has been positively associated with reduced risks of other health outcomes (e.g., breast cancer), no studies specifically associating these outcomes with transportation walking were available when health outcomes were selected for inclusion in the HIA.

2.2. Health impact estimation

The HIA model carries out four steps:

Step 1: Simulate current transportation walking time. Current transportation walking time of each BRRC resident is simulated as a nonparametric probability distribution derived from 386 responses to an IRB-approved survey mailed to 1200 randomly selected BRRC residents in summer 2012. To estimate transportation walking for each respondent, the survey used questions drawn from the International Physical Activity Questionnaire (Supplementary file, Table S2) (IPAQ Group, 2002).

Step 2: Simulate changes in transportation walking time if small-area plan is implemented. For each simulated resident, the model predicts changes in transportation walking time as a function of the walkability score, a measure developed by Frank et al. (2010). Previous research has documented that the walkability score provides a robust indicator of how different urban designs affect transportation walking time, with the magnitude of effects depending in part on household income (Adams et al., 2011; Frank et al., 2010; Sallis et al., 2009; Van Dyck et al., 2010; Frank et al., 2005). The walkability score is computed from

$$\textit{Walkability Score} = (2 \times Z_{intersection}) + (Z_{residential}) + (Z_{FAR}) + (Z_{land-use}) \quad (1)$$

where the Z variables represent normalized versions of intersection density ($Z_{intersection}$), the number of intersections divided by land area; residential density ($Z_{residential}$), the number of housing units divided by the residential land area; retail floor area (Z_{FAR}), the square footage of retail floor area divided by the square footage of land devoted to retail use; and land-use diversity ($Z_{land\text{-}use}$), computed as described in Cervero and Kockelman (1997). We computed raw values of each of the four component variables in Eq. (1) for the current and the redesigned BRRC using data compiled by the Raleigh Urban Design Center (Supplementary file, Table S3) and normalized them relative to built environment data in Sallis et al. (2009).

The model estimates a probability distribution of transportation walking under the redesigned BRRC, $f_{new}(w)$, according to

$$f_{new}(w) = WF \times f_{current}(w) \quad (2)$$

where WF is the ratio of transportation walking time measured by Sallis et al., (2009) in neighborhoods with walkability scores and median household incomes similar to those under the redesigned BRRC to that in neighborhoods with walkability scores and household incomes similar to those of the current BRRC (Supplementary file, Table S4). WF is approximately normally distributed with mean = 2.3 and standard deviation (SD) = 0.20.

Step 3: Simulate avoided adverse health outcomes resulting from increased transportation walking. The model uses an attributable fraction (*AF*) approach to simulate the health effects of changes in transportation walking, calculating the population *AF* for each health endpoint from (Hanley, 2001; Rothman et al., 2008).

$$AF = \frac{\int_{w=0}^{\infty}[1 - RR(w)]f(w)dw}{1 + \int_{w=0}^{\infty}[1 - RR(w)]f(w)dw} \tag{3}$$

where *RR(w)* is the relative risk of a specific adverse health outcome for an individual who spends *w* minutes per day walking for transportation, as compared to an individual who spends no time walking for transportation, and *f(w)* is the probability distribution of time spent walking for transportation. To estimate the benefits of the BRRC small-area plan, the model computes an *AF* representing the difference between risks under the current and future BRRC designs:

$$AF_{new} = \frac{\int_{w=0}^{\infty}[1 - RR(w)]f_{new}(w)dw - \int_{w=0}^{\infty}[1 - RR(w)]f_{current}(w)dw}{1 + \int_{w=0}^{\infty}[1 - RR(w)]f_{current}(w)dw} \tag{4}$$

where AF_{new} is the fraction of observed cases preventable by the redesign. The functions *RR(w)* were drawn from the following sources: Kelly et al. (2014) and WHO HEAT model (mortality); Hu et al. (2005) (stroke); Hu et al. (2007) (coronary heart disease); and Furie and Desai (2012) (hypertension and diabetes) (Supplementary file, Table S5) (Furie and Desai, 2012; Kahlmeier et al., 2011; Kahlmeier et al., 2014; Kelly et al., 2014; Hu et al., 2005; Hu et al., 2007). All functions are based on studies or meta-analyses that focused on the health benefits of walking for transportation. To estimate the cases avoided by the redesign, the *AF* for each health outcome is multiplied by the observed rate of each outcome. Mortality and disease incidence rates for Wake County were obtained from the NC State Center for Health Statistics and were adjusted to the BRRC population to reflect the neighborhood's age, race, and gender composition.

Step 4: Estimate economic benefits. The model estimates economic benefits of avoided deaths and diseases using value-of-a-statistical life guidelines from the U.S. Department of Transportation; (U.S. Department of Transportation, 2013); annual costs of coronary heart disease, stroke, hypertension, and diabetes estimated by Milken Institute economists (Supplementary file, Table S6); and a 3.5% discount rate (DeVol and Bedroussian, 2007).

2.3. Sensitivity and uncertainty analysis

Health benefits calculations for each resident were simulated 5000 times, and the population mean values and 95% confidence intervals (CIs) were recorded. In addition, sensitivity analyses were conducted by varying the three main uncertain inputs (*WF*, *RR(w)*, and $f_{current}$) in the model according to plausible high and low estimates. *WF* and *RR(w)* were set at their lower and upper 95% CIs. The distribution $f_{current}$ was modified by multiplying it by a factor of 0.5 (low estimate) and by a factor of 2 (high estimate), hence representing that survey respondents could have over- or under-estimated their transportation walking time.

2.4. Cost estimation

Costs of installing sidewalks along each street in the redesigned BRRC, for streets not already having sidewalks, were computed as a yardstick by which to measure the relative value of health benefits. Implementing the small-area plan would increase total sidewalk length from 5.0 to 24.2 miles. Costs per linear foot of sidewalk (including curb installation) were estimated at $80.92 by inflating 2002 estimates from the Federal Highway Administration to 2013 costs (Federal Highway Administration, 2002).

3. Results

3.1. Overall health impacts

When compared to the current neighborhood design, the new design would prevent 59 (95% CI: 10–102) deaths over a 25-year period (Table 1, Fig. 1), representing a 5.5% (95% CI: 0.88–9.4%) decrease in the BRRC mortality rate. In addition, the new design is predicted to prevent 25 (95% CI:1–64) new diabetes cases, 12 (95% CI: 5–21) CHD cases, 13 (95% CI: 1–33) strokes, and 91 (95% CI: 4–247) hypertension cases over 25 years (Table 1).

3.2. Physical activity impacts

The median and mean daily time spent walking for transportation are 4 and 13 min (SD=23) per day under current conditions. Overall, 41% of survey respondents reported no walking for transportation, while, 3.1% reported more than 60 min per day of transportation walking (Fig. 2). The simulation model predicts that the new neighborhood plan would increase the median and median transportation walking time to 9 and 30 (SD=54) minutes per day, respectively. Due to limitations of existing epidemiologic evidence linking built environment features to walking behavior, the model is unable to simulate future transportation walking behavior for those currently not walking for transportation. However, the results show that the distribution of walking time (Fig. 2) would shift to the right (toward more walking time) under a redesign.

3.3. Economic impacts

An estimated $234 million (95% CI: $53.6–393 million) in health benefits are expected to accrue as a result of increases in transportation walking among BRRC residents over the 25-year-period after the redesign is completed (Table 1)—a total of $21,000 for every current BRRC resident. These estimates include $215 million in avoided premature mortality, calculated using value-of-statistical-life estimates, plus $19 million in avoided nonfatal illness costs. Increasing the appeal of walking over driving as a means of transportation in the BRRC will require many changes to the built environment, including new neighborhood streets and intersections with crosswalks and traffic lights, sidewalks and walking paths, and additional retail stores and restaurants. Some of these costs (e.g., retail developments) will be borne by the private sector and others (e.g., street lights) by the public sector.

Table 1
Total benefits during years 2028–2048 of implementing the BRRC small-area plan.

Health outcome	Cases prevented (95% CI)	Percent of total cases (95% CI)	Present value, $millions (95% CI)[a]
Deaths (premature)	59 (10–102)	5.5% (0.88–9.4%)	$215 ($35.9–$373)
Diabetes (new cases)	25 (1–64)	1.9% (0.086–4.8%)	$3.5 ($0.16–$8.9)
CHD (new cases)	12 (5–21)	2.3% (0.90–3.9%)	$1.7 ($0.61–$2.9)
Stroke (new cases)	13 (1–33)	1.3% (0.063–3.2%)	$3.2 ($0.16–$8.2)
Hypertension (new cases	91 (4–247)	1.6% (0.066–4.3%)	$11.0 ($0.46–$29.4)
Total			$234 ($55.8–$395)

[a] Discount rate=3.5%.

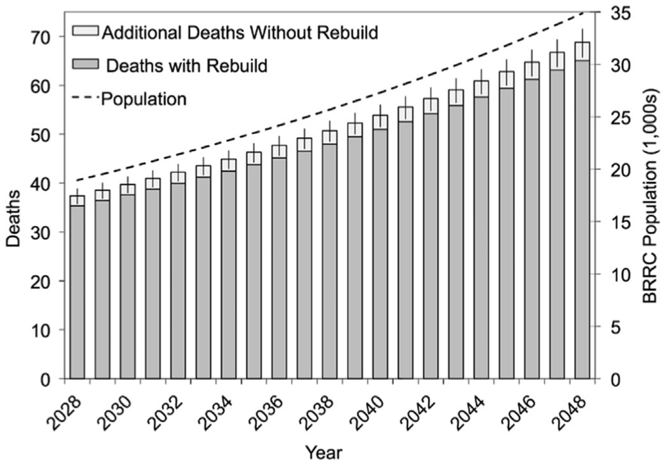

Fig. 1. Annual premature deaths avoided by BRRC small-area plan implementation. "Additional deaths without rebuild" indicates deaths prevented by the redesign. Total expected deaths without the redesign are the sums of additional deaths without rebuild and expected deaths with rebuild.

Total costs will vary substantially depending on, for example, the design details of new residential and retail developments. A comprehensive cost estimation was beyond the scope of the HIA. Nonetheless, because sidewalks are essential for safe pedestrian transit, sidewalk costs are a useful yardstick by which to measure the relative magnitude of health benefits. Installing sidewalks along every street in the redesigned BRRC would cost approximately \$8.2 million. The ratio of health benefits to sidewalk costs is therefore \$234/\$8.2 million=29 (95% CI: 6.5–48).

3.4. Sensitivity analysis

While current walking behavior and health status data were drawn from local sources, the simulation model's predictions about future changes rely on two information sources from previous studies: the *WF* (representing the change in walking time as a function of walkability score) and *RR(w)* (representing the reduction in health risk when walking *w* minutes per week for transportation). These variables are uncertain due to both the limitations of previous study designs and the need to generalize from the populations studied to the BRRC population. To explore the influence of these uncertainties, we estimated how the simulated health benefits would change if each variable were adjusted to a plausible high or low value (represented by the upper and lower bounds of the variables' 95% confidence intervals). We

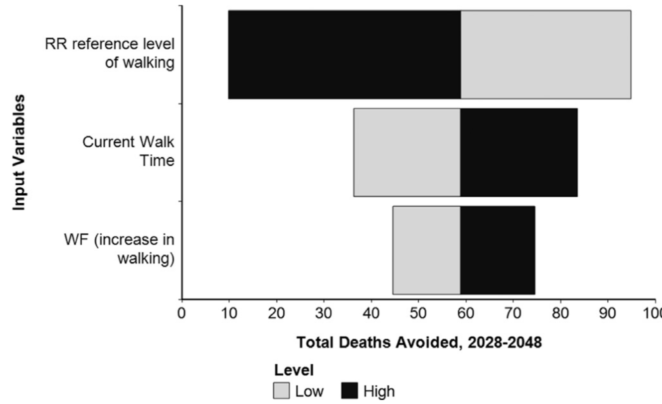

Fig. 3. Effects on estimated premature deaths avoided of varying HIA model input variables from baseline estimates to plausible low and high values.

also assessed the potential effects on the health impact estimates if survey respondents either over- or under-estimated their current walking time by a factor of two. Figs. 3 and 4 show the sensitivity analysis results as tornado charts, which display how changing each uncertain input variable to its low or high value affects the estimated health benefits. The width of the bar corresponding to a given input variable indicates the variable's influence on the estimated benefits, with wider bars corresponding to stronger influence.

Overall, Figs. 3 and 4 show that for all health outcomes, the predicted health benefits are most sensitive to *RR*. Plausible low and high values of *RR* for mortality change the mean estimated number of prevented premature deaths from 59 to 94 and 10 (Fig. 3). Similarly, low and high values change the median estimate of avoided cases of diabetes from 25 to 5.0 and 59, CHD from 12 to 5.0 and 20, stroke from 13 to 26 and 2.6, and hypertension from 91 to 18 and 204. Predictions are also sensitive to reported time spent walking for transportation but less so than to *RR*, demonstrated by the narrower widths of the bars corresponding to current walking time in Figs. 3 and 4 (which assume survey responses on transportation walking were off by a factor of two). Mortality estimates were sensitive to *WF*. However, predicted benefits of avoided nonfatal health outcomes were not sensitive to *WF*, because the *RR*s for these outcomes plateau at 21.3 min per day (diabetes and hypertension) or 29 min per day (CHD and stroke), so shifting walking time beyond these values does not increase health benefits. This latter finding demonstrates the importance of obtaining more information on the shape of the dose–response functions linking transportation walking to nonfatal health outcomes, in

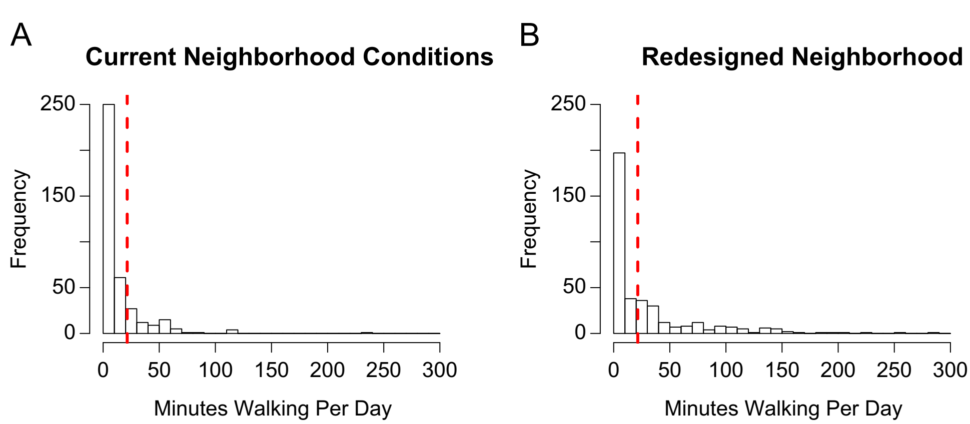

Fig. 2. (a) Distribution of daily time spent walking for transportation among 386 respondents to a survey of BRRC residents. (b) Expected transportation walking time if the BRRC small-area plan is implemented. The red dashed line indicates the minimum daily physical activity recommended by the WHO and U.S. Centers for Disease Control and Prevention. If the neighborhood is rebuilt according to the plan, then 29% of BRRC residents are expected to meet this guideline through transportation walking alone (as compared to 16% of residents under the current design).

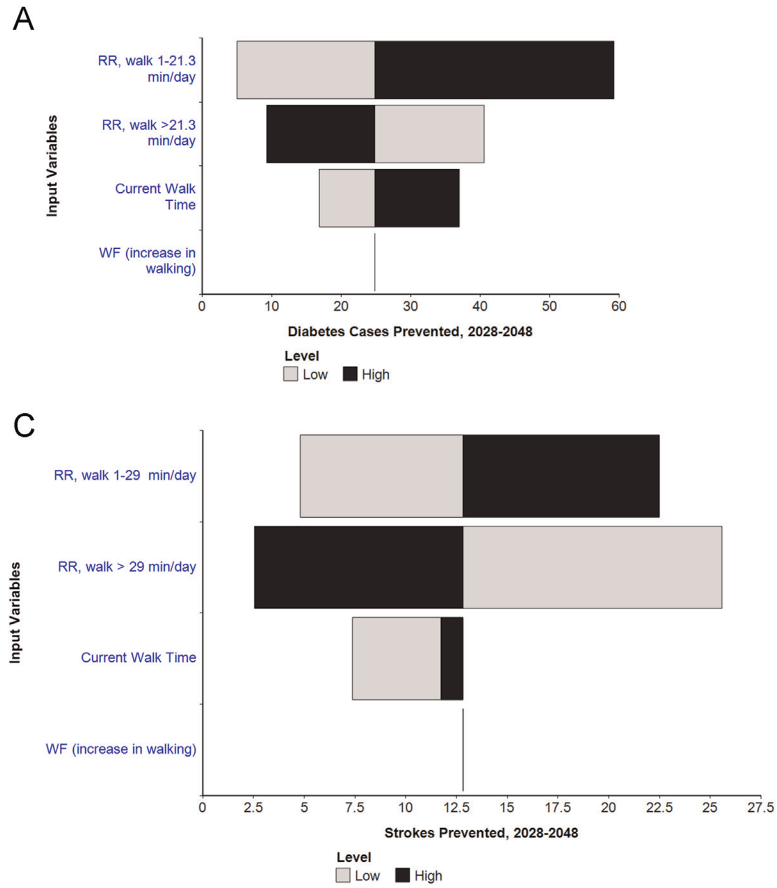

Fig. 4. Effects on estimated avoided cases of diabetes (A), CHD (B), stroke (C), and hypertension (D) of varying HIA model input variables from baseline estimates to plausible low and high values.

particular to determine at what point such plateaus in benefits occur.

4. Discussion

Our results provide further evidence that urban designs encouraging walking as a means of transportation can yield health benefits outweighing the costs of pedestrian infrastructure. We found that, compared to the current automobile-centric design of Raleigh's BRRC neighborhood, a proposed pedestrian-friendly design would decrease deaths from all causes by about 5.5% a year and, in addition, decrease annual new cases of CHD, stroke, diabetes and hypertension by about 1–2%. The economic benefits of preventing these adverse health outcomes ultimately should be compared against the total costs of implementing the small-area plan. Sidewalks alone are estimated to cost $8.2 million (about 2.6% of the value of health benefits), leaving another $226 million that could be invested in neighborhood improvements while maintaining a non-negative net present value.

To our knowledge, this study is the first in the United States to quantify the physical activity and related health effects of a new urban small-area plan as part of an HIA. Most previous urban planning HIAs provided extensive literature reviews of physical activity effects on health and of epidemiologic and survey-based studies investigating effects of urban design on physical activity. However, they did not translate this existing literature into quantitative estimates of the health effects of the projects under consideration. Typically, health impacts were reported as summary tables with symbols indicating whether the proposed project is expected to have a positive, negative, or neutral effect on physical activity.

Qualitative HIAs can serve a valuable role in raising awareness among decision-makers about the potential health impacts of their choices. Indeed, some qualitative HIAs have motivated decision-makers to consider alternative plans (Singleton-Baldrey, 2012). A drawback of providing only qualitative analysis, however, is that such analyses cannot be used to convince skeptical decision-makers about the potential economic pay-back that may result from larger up-front investments in urban designs and infrastructure that promote physical activity.

The major limitation of our simulation model arises from the scarcity of previous epidemiologic studies using built environment features as independent variables to predict physical activity. In a literature review, we identified 12 studies linking physical activity to built environment variables, but only four measured time spent walking for transportation (Supplementary file, Table S7) (Jackson et al., 2013). Available studies linking the walkability score to walking behavior are cross-sectional rather than longitudinal so may not reflect factors other than the built environment, such as self-selection into walkable neighborhoods, that could affect transportation walking. In addition, these studies provide insufficient information to quantify potential walking behavior changes of the 41% of BRRC residents who currently report no walking for transportation. The inability to predict the uptake of transportation walking among this large segment of the population suggests we have under-estimated the benefits, even if we could have controlled for self-selection into walkable neighborhoods.

An additional limitation is that this analysis overlooks other potential health effects, such as psychological health or air pollution exposure, associated with the built environment (Jackson et al., 2013; Jackson, 2003). Furthermore, it overlooks benefits expected to accrue to in-migrating BRRC residents. On the other hand, the analysis does not consider the presence of co-morbidities, such as the occurrence of diabetes and coronary heart disease in a single patient, and in this sense may have over-estimated health benefits. Overall, however, we believe the limitations of this analysis may have resulted in an under-estimate of the small-areas plan's potential health benefits.

5. Conclusion

The quantitative health impact estimates developed through this research will help the Raleigh City Council and NC Department of Transportation, which must allocate funds to implement the small-area plan, understand the health benefits of such funding. The monetized health benefits total about $21,000 per resident over a 25-year period and exceed the costs of constructing sidewalks throughout the neighborhood. Such information facilitates the consideration of health benefits as the city and Department of Transportation decide among the many competing demands on their limited budgets. To ensure that health benefits are included in economic assessments of urban planning and transportation infrastructure decisions, quantitative impact calculations ideally would become a routine part of such HIAs in the United States. The California Department of Public Health has begun to develop quantitative tools to support impact assessments of alternatives for reaching the state's goal of reducing greenhouse gas emissions to 80% of 1990 levels by the year 2050 (Maizlish et al., 2013). However, quantitative analysis such as presented here is not yet routine in HIA practice the United States.

Role of the funding source

This research was supported by a grant from the BlueCross BlueShield of North Carolina Foundation. The funding source had no role in the study design; in the collection, analysis and interpretation of data; in the writing of the report; or in the decision to submit the article for publication.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.healthplace.2015.07.005.

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