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Promoting Cycling for Transport: Research Needs and Challenges

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Promoting Cycling for Transport: Research Needs and Challenges

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ABSTRACT Cycling as a mode of transportation has many advantages for both cyclists and society: it is a low-cost, low-polluting, health-improving way to travel. In light of these benefits, a growing number of cities throughout the world are implementing policies to promote cycling, though they continue to struggle to identify the most effective ways to spend their limited resources. In response, transport researchers are also increasingly focusing their efforts on cycling, addressing a broader range of questions than in the past, including: how much cycling is there? What strategies will increase cycling? What are the benefits of increased cycling? This paper reviews the challenges that researchers face in providing answers to these questions by highlighting limitations of the existing research, identifying remaining research needs, and discussing methodological considerations for addressing those needs. Investments in cycling research can pay off by providing a basis for identifying the most effective strategies for increasing cycling and providing more accurate estimates of the benefits that would accrue.

1. Introduction

Cycling as a mode of transport has many advantages for both cyclists and society: it is a low-cost, low-polluting, health-improving way to travel. In light of these benefits, a growing number of cities throughout the world are implementing policies to promote cycling, citing the high levels of transport cycling in the Netherlands and Denmark as an indicator of the potential of this mode. Washington, DC, for example, experienced nearly a tripling of the share of work trips by bicycle from 1990 to 2008 following a significant expansion of the cycling network and the implementation of a bike-sharing system, while investments in bicycling infrastructure in Portland, Oregon contributed to a nearly sixfold increase in the share of commute cycling over the same period (Buehler & Pucher, 2012a). Still, Portland's 6% share was dwarfed by the 34% share in Amsterdam and the 37% share in Copenhagen. Overall, cycling accounts for just 1% of daily trips in the USA as well as Canada and Australia (Buehler & Pucher, 2012b).

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Cities in these parts of the world face two significant challenges in their efforts to increase transport cycling: identifying the most effective ways to spend the limited resources that have been allocated to cycling, and justifying the allocation of a greater share of their limited transport resources to cycling. Cycling investments can be a hard-sell in the face of increasing traffic congestion, deteriorating roadways, and declining transit budgets. In the USA, for example, the most recent federal transportation legislation reduced the amount of guaranteed funding for bicycling as well as walking. Although states and metropolitan regions continue to have the flexibility to spend some portion of their federal allocations on these modes, most have taken limited advantage of this flexibility in the past (Handy & McCann, 2011). Even in cities that have made a strong commitment to cycling, it helps to have solid evidence to effectively direct resources and maintain support for cycling investments.

Cycling research has an important role to play in providing this evidence. Until recently, research on transport cycling focused primarily on questions of engineering (e.g. how wide should bicycle lanes be) and on safety (e.g. do bicycle lanes reduce injuries and fatalities). Now, researchers are addressing a broader range of questions, motivated by the efforts of cities to increase transport cycling. The questions that policy-makers are asking — and that researchers are helping to answer — include the following:

- How much cycling is there? Who is cycling, where, when, and for what purposes?
- What strategies offer the most promise for increasing cycling?
- What are the benefits to cities if they succeed in increasing cycling?

This paper reviews the challenges that researchers face in providing answers to these questions by highlighting limitations of the existing body of research, identifying remaining research needs, and discussing methodological considerations for addressing those needs. The purpose of this paper is not to provide a comprehensive or systematic review of the existing research, nor to critique individual studies, but rather to describe the state-of-the-research on transport cycling from the standpoint of planning and policy-making. Our goal is to provide a framework that connects past and present research efforts to current policy questions and guides research priorities for the future. Our primary aim is to contribute to the science of cycling research, but to the degree that planning and policy-making are at least in part based on scientific evidence, they may benefit from this review as well.

2. How Much Cycling Is There?

As a starting point, policy-makers often want an understanding of current cycling activity: how many people own bicycles, how many people use their bicycles, how much, where and when, and for what kinds of trips. Having such data at multiple points over time is important for understanding trends in cycling (Pucher, Buehler, Merom, & Bauman, 2011) and for evaluating the impacts of policies and investments (Krizek, Handy, & Forsyth, 2009). Having data that are collected using consistent methodology across cities and countries is essential for comparative assessments of the effectiveness of policies and investments.

Such data are most often collected by public agencies, whether at the local, state, or national levels. Two basic approaches are most widely used: place-based and person-based. The place-based approach involves manual or automated counts of cyclists at selected locations. This approach, which can be relatively easy and inexpensive to implement, is good for measuring the number and location of cycling trips (though not necessarily the number of people cycling), but it provides little to no information, on its own, as to who is cycling, for how many miles, and for what kinds of trips (Krizek et al., 2009). The person-based approach involves population surveys, usually person or household-based, that ask about cycling trips specifically or about travel by all modes (e.g. using a travel diary surveys). This approach is good for identifying who cycles and why, but getting accurate measures of the amount of cycling can be challenging, as noted below. A hybrid approach is to use intercept surveys in conjunction with counts at selected locations. This approach provides good information about who is cycling, but not about who is not cycling.

One of the challenges in any of these approaches is to separate transport cycling from other types of cycling (Krizek et al., 2009; Xing, Handy, & Mokhtarian, 2010). Through observation, sport cycling may be reasonably inferred based on the type of bicycle or the cyclist's attire, but separating transport cycling from more leisurely recreational cycling, which often uses the same types of bicycles, ridden at similar speeds, in similar clothing, on the same facilities, could be impossible. Through surveys, cyclists can be asked about transport cycling specifically, though not all surveys are effective in separating transport and recreational or sport cycling, and many leave out the latter. However, cycling trips that are motivated by the need to reach a destination may also serve as a form of recreation (e.g. when an individual chooses to cycle to the store rather than drive in order to get some exercise along the way). Conversely, cycling trips that are motivated by a desire for recreation may involve stops at destinations along the way. In some cases, policy-makers may not be concerned about this distinction, but it is important in evaluating the environmental and economic benefits of cycling, as discussed in Section 4.

Traditional travel diary surveys often do not adequately capture certain kinds of cycling trips, including the use of bicycles in conjunction with other modes and occasional rather than regular cycling (Krizek et al., 2009; Heinen & Maat, 2012). The use of bicycles in conjunction with transit, e.g. as a way of getting to or from the rail station, is well documented, and travel diary surveys are generally designed to capture these bicycle trips, but other cases where bicycling is used as a secondary mode may be undercounted. In addition, occasional cycle trips will be missed with one- or two-day diaries, and even with one-week diaries. With a large enough sample, the survey may accurately measure the total number of cycling trips (since some respondents will by chance have made a rare cycling trip during the survey period), but the results as to who is making such trips at what frequencies may be biased. As an alternative approach, the 2009 National Household Transportation Survey in the USA included questions on bicycling (and walking) trips in the previous week that yielded different estimates of cycling trip frequencies than did the one-day diary portion of the survey (McGuckin, 2012).

Researchers have an important role to play in helping public agencies improve their data collection. As a start, a survey of current data collection practices could help to identify best practices as well as aspects of the data collection process

where agencies are most in need of research help. Studies of different data collection methods with respect to their validity and reliability would help to improve practice, as would the development of standardized instruments, tested for validity and reliability, which could be applied across jurisdictions. The USA has seen examples of such efforts on the part of researchers (e.g. Forsyth, Krizek, & Agrawal, 2010) and on the part of the federal government (e.g. Krizek et al., 2006). The Federal Highway Administration's (2012) *Traffic monitoring guide* now includes a chapter on non-motorized traffic that provides guidance on place-based data collection. The BICY Project, funded by the European Regional Development Fund, recently developed a standardized intercept survey to collect comparable data in seven central European countries. Such standardization of data collection instruments and methods is more common in physical activity research than in the transport field.

3. What Strategies Will Increase Cycling?

The many possible strategies to promote cycling can be grouped into the categories of travel-related infrastructure, end-of-trip facilities, transit integration, promotional and other programs, bicycle access, and regulations (Pucher, Buehler, Bassett, & Dannenberg, 2010). Policy-makers can benefit from guidance on which of the possible strategies are likely to increase cycling and to what degree. Research can help provide such guidance in two general ways. First, studies that compare people or places — cross-sectional studies — can identify key factors associated with higher levels of transport cycling. The findings from such studies can point to potentially effective strategies. For example, if bicycling ability is a significant factor, then training programs could make sense. Second, studies that measure cycling before and after the implementation of strategies provide an evaluation of their effectiveness that communities can use to improve or expand their strategies, or that other communities can use in justifying their own adoption of these strategies. Such studies are especially important for new strategies initially developed through trial-and-error. An evidence-based approach to policy can help to avoid waste of limited resources as well as failures that undermine public support.

3.1 *Studies Identifying Key Factors*

The number of studies examining key factors associated with transport cycling has grown quickly in recent years, paralleling the interest on the part of cities in increasing transport cycling. Some of the studies are 'aggregate' in nature, in that they use cities as the unit of analysis; others are 'disaggregate' in that they use individuals or households as the unit of analysis, often using a sample drawn from a specific city or sometimes an entire country. Most of these studies use data collected through surveys (e.g. people-based) rather than observations or counts (e.g. place-based). Qualitative techniques have also been used, for example, interviews and focus groups for disaggregate studies (e.g. Heinen & Handy, 2011), and comparative case studies of cities or countries at the aggregate level (e.g. Pucher & Buehler, 2006; Pucher & Buehler, 2008). Studies often focus on commute trips (Heinen, van Wee, & Maat, 2010), most likely because better data tend to be available for these trips than for other types of trips.

Although a thorough review of the results of these studies is beyond the scope of this paper, a look at the key findings helps to highlight questions that researchers have yet to address:

- *Distances*: One of the most consistent factors to emerge from existing studies is distance: in general, longer distances to work or other destinations make cycling less likely (e.g. Buehler, 2012; Handy & Xing, 2011; Heinen, Maat, & van Wee, 2011). Distances are a reflection of land use patterns, both the density of development and the mixing of land uses, which are sometimes measured instead of distances. A possibility not yet studied is whether the effect of distance is non-linear. For example, it is possible that at short distances, the effect of distance on cycling is positive, as greater distances mean more exercise and thus greater benefit to the cyclist. Conversely, at longer distances, each additional increment of distance may have a larger negative effect for cycling than it does for other modes, given limits on physical exertion.
- *Bicycle infrastructure*: Many studies also show that the availability of bicycle infrastructure is positively associated with cycling for transport. These studies often measure infrastructure in terms of miles of bicycle lanes or of all types of bicycle facilities (e.g. Buehler & Pucher, 2012c; Dill & Carr, 2003), while some studies include parking and other facilities at the worksite (e.g. Buehler, 2012; Heinen, Maat, & van Wee, 2013). The importance of access to other kinds of infrastructure that may be important, such as access to bicycle shops, repair facilities, or air pumps, have not been examined. The aggregate studies especially tend to examine its general availability in the area rather than its availability along the route for specific trips. Evidence on the effectiveness of different kinds of facilities (e.g. bike lanes vs. paths vs. cycle tracks) comes from studies of route choice, though it is important to note that these studies generally measure the preferences of existing cyclists rather than the ability of such facilities to entice new cyclists (e.g. Broach, Dill, & Gliebe, 2012).
- *Bicycle access*: Access to a bicycle is obviously a necessary condition for cycling, and studies show strong correlations between bicycle ownership and bicycle use (e.g. Buehler, 2012; Heinen et al., 2012; Moudon et al., 2005). The emergence of bike-sharing (also called cycle-hire) programs expands access to bicycles without ownership (Shaheen, Guzman, & Zhang, 2012). Studies of these programs tend to focus on who is using them and for what purposes, but some attempts have been made to quantify the impact of these programs on levels of cycling overall (Pucher, Dill, & Handy, 2010); these studies fall into the category of 'evaluation' studies, described below.
- *Bicycle equipment*: Almost no research has been done on the role of bicycle equipment, including bicycles themselves, gear that attaches to the bicycle, or gear that attaches to the bicyclist (Lovejoy & Handy, 2012). Equipment may have a significant effect on the feasibility, comfort, convenience, and safety of cycling, and could thus have a significant effect on an individual's decision to cycle. The growing popularity of motorized bicycles, particularly 'e-bikes', has spawned a number of studies exploring who is purchasing these bicycles, for what reasons, and for what types of travel (e.g. Dill & Rose, 2012).
- *Costs*: Although general studies of travel behavior consistently show that cost is an important factor, few studies have examined its association with cycling. Of

course, cycling is almost cost free, with the exception of the initial purchase of the bicycle and some ongoing maintenance costs. But evidence suggests that the cost of alternative modes, e.g. parking fees and tolls as well as financial incentives such as free parking or subsidized transit passes, affect cycling by making the alternatives more or less attractive (Buehler, 2012; Handy & Xing, 2011).

- *Individual factors*: Studies show that socio-demographic characteristics have a strong connection to cycling, particularly gender, income, and age. In addition, studies show that cycling ability is an important predictor of who cycles and how frequently (Handy, Xing, & Buehler, 2010). Recent studies have also begun to unravel the attitudes and preferences that affect cycling (Dill & Voros, 2007; Gatersleben & Appleton, 2007; Heinen et al., 2011; Li, Wang, Yang, & Ragland, 2013; Titze, Stronegger, Janschitz, & Oja, 2008). Still, compared to other modes of transport relatively little is known about the possible dimensions of cycling attitudes and preferences and about the formation of these factors. The role of cycling habits and their formation is another important research need.
- *Social environment*: The influence of the social environment on cycling has so far been addressed in only a handful of studies (e.g. Titze et al., 2008). Social influences may take the form of encouragement from or information sharing among friends or family (Bartle, Avineri, & Chatterjee, 2013). The cultural norms of the larger community may also influence individual behavior (Aldred, 2013; Bonham & Koth, 2010; Daley & Rissel, 2011; Steinbach, Green, Datta, & Edwards, 2011). For example, if cycling is seen as a normal way to get places, residents may be more inclined to cycle themselves, further reinforcing the community norm. Conversely, if cycling is seen as an activity for children or as a competitive sport, residents may be less inclined to cycle as a means of transport.

Although the list of well-documented factors is growing, several overarching methodological challenges remain to be explored in depth. These challenges relate to possible interaction, bidirectional, and higher-level effects. Below we discuss these effects from the perspective of cycling research. Both quantitative and qualitative methods can be used to examine these effects; we discuss promising statistical methods for addressing them in the appendix.

Interaction effects arise whenever the size of the effect of an independent variable on a dependent variable is affected by another independent variable. In the context of cycling behavior, for example, one study found that the influence of health and environmental beliefs became stronger with increasing distance to work (Heinen et al., 2011), while another study found an interaction between season and region of residence (Stinson & Bhat, 2004). Potentially important interactions that have not been systematically studied include, for example, the interaction between cycling ability and facility type. If such an interaction occurs, installing bicycling lanes on busy streets may have little impact on cycling for individuals with little bicycling experience.

Bidirectional effects between cycling behavior and its assumed determinants present another methodological challenge. Such effects are especially likely in the case of subjective factors, like attitudes, preferences, and habits. For example, people with a strong cycling habit are likely to cycle often, but cycling often, in turn, will also strengthen their cycling habit. To date, studies that

address these subjective factors have only considered the one-way effects from attitudes to behavior. Travel behavior studies, however, long ago established that bidirectional effects exist between attitudes and behavior (Dobson, Dunbar, Smith, Reibstein, & Lovelock, 1978; Golob, Horowitz, & Wachs, 1979; Tardiff, 1977). In addition, bidirectional relationships may also exist between factors that influence bicycle use. For example, it is likely that community norms and cycling infrastructure have reciprocal effects on each other: communities where cycling is seen as normal are more likely to invest in bicycling infrastructure which in turn tends to reinforce the cycling norm.

This last example also points to a final methodological challenge, namely the role of higher-level effects, meaning the influences on cycling of variables that operate on a higher (or more aggregate) level than the individual one (Vandenbulcke et al., 2011). The 'higher level' might be households, neighborhoods, communities, cities, or countries. For example, Winters, Friesen, Koehoorn, and Teschke (2007) included city-level climatic characteristics as higher-level variables affecting individual cycling frequency. In a similar fashion, studies could investigate the extent to which the amount of cycling on the community level (as a higher-level variable) influences individual cycling behavior; this might occur through the effect of 'safety-in-numbers' or social norms, for example. Another avenue of exploration is the possible contextual effects of higher-level variables on lower-level relationships. For example, individual preferences for cycling may matter less in communities where cycling is a common mode of transport. Higher-level effects are an important consideration in studies of cycling behavior across various countries, where relationships between individual factors can be expected to differ for different (types of) countries. Note that such studies require consistent data on cycling as well as potential determinants across a substantial number of places (see discussion in Section 2).

While the majority of the studies on cycling behavior are quantitative, qualitative approaches also have an important role to play. Indeed, some questions particularly lend themselves to exploratory research using qualitative methods such as interviews or focus groups. Examples include attitudes toward cycling as well as the role of families and friends in encouraging cycling and the contribution of childhood cycling experiences to adult cycling behavior. The 'mobility biographies' or 'life course' approach to studying travel behavior (e.g. Bonham & Wilson, 2012; Lanzendorf, 2003) has proved useful in exploring the latter question and others. Chatterjee, Sherwin, and Jain (2013), for example, examined the role of life events (e.g. having a child, child starts school, retired from job) as a trigger for changes in cycling behavior. Qualitative methods have also been used to explore more subtle influences on cycling, such as identities, social stigma, legitimacy, and image (Aldred, 2013; Bonham & Koth, 2010; Daley & Rissel, 2011; Steinbach et al., 2011). More generally, qualitative methods are useful in exploring the complexities of cycling behavior in a holistic way (e.g. McKenna & Watling, 2007). In addition to being used on their own, qualitative methods can support quantitative methods in important ways (Clifton & Handy, 2003): qualitative studies can help to shape the design of quantitative studies in which hypothesized relationships are statistically tested (e.g. Spencer, Watts, Vivanco, & Flynn, 2013), and they also have a role to play as a follow-up to quantitative studies, to validate the conclusions that are extracted from statistical analysis and to explore in more depth the relationships it reveals, as illustrated by Pooley et al. (2011).

3.2 Studies Evaluating Strategy Effectiveness

While the cross-sectional studies described above can help policy-makers understand which factors to target with their strategies, they have two important limitations. First, as researchers well know but policy-makers sometimes do not realize, they establish correlation but not causality, in that they do not directly show that a change in one of the factors associated with cycling leads to an increase in cycling. Second, showing that a change in one of the factors leads to an increase in cycling is not necessarily equivalent to showing that a particular strategy leads to an increase in cycling. This is because the process usually involves two steps: the strategy must change the factor, and the change in the factor must change the behavior. For example, training programs only lead to a change in cycling if they in fact change succeed in changing cycling ability.

As a result, studies that directly evaluate the effectiveness of strategies in changing behavior are also needed. These studies (variously called 'intervention studies', 'natural experiments', or 'pre- and post-evaluations') measure behavior before and after the implementation of a strategy and test the significance of the behavior change that results (as well as the significance of the change in the mediating factor, e.g. cycling ability in the above example). Ideally, changes are also measured for a control group, i.e. one that does not experience the strategy, to ensure that the observed changes in behavior can in fact be attributed to the strategy. A recent review found few studies meeting these criteria for cycling-related infrastructure, programs, and policies, not surprising, given the challenges associated with collecting data at multiple points in time, identifying an appropriate control group, and separating the effects of strategies adopted around the same time (Pucher, Dill, & Handy, 2010). Such studies are becoming more common, however. For example, in the USA, a rigorous before-and-after evaluation of the implementation of 'green lanes' (bicycle lanes painted green) in six cities is currently underway.

As an alternative, some researchers have employed stated-preference surveys. In these studies, participants are asked about what they would do in response to different strategies or under different conditions. Of course, there is no guarantee that people will actually do what they said they would do in the survey. Still, such studies can provide important insights into the potential impact of proposed policies or projects, or at least the relative magnitude of their impacts. This approach has been especially popular in studying the factors that influence route choice (e.g. Bernhoft & Carstensen, 2008; Caulfield, Brick, & McCarthy, 2012; Winters & Teschke, 2010). Stated-preference surveys can be a useful approach in situations where the local context differs significantly from places where the proposed strategy has previously been implemented and evaluated. A strategy that worked well in one place will not necessarily work well in another place, and stated-preference surveys can provide a way to assess the transferability of the strategy ahead of its implementation.

The 'stages of change' model widely used in the field of public health can also be useful in assessing the potential of proposed strategies to change behavior. In this approach, surveys are used to classify individuals by their readiness to change behavior. At one end of the spectrum are individuals who have never contemplated cycling, while at the other are those who regularly cycle already. Different strategies are appropriate for each stage of change, to move individuals toward the adoption of cycling. Using this approach, a study in the UK found that while

most people had never contemplated cycling, a sizable group expressed an interest in cycling under the right circumstances (Gatersleben & Appleton, 2007). A study in the USA used the stages of change model to predict the effectiveness of different strategies in moving commuters from one stage to another (Driller, Thigpen, & Handy, 2014). Another US study divided cyclists into four types, with 60% falling into the 'interested but concerned' category, and identified appropriate bicycle facilities for each type (Dill & McNeil, 2013).

Qualitative methods can also be helpful in understanding the impact of strategies. Interviews with those targeted by a particular strategy can illuminate the various factors that explain any observed changes in behavior. For example, Fishman, Washington, and Haworth (2012) conducted focus groups with cyclists and non-cyclists to explore barriers and facilitators to their use of a bicycle sharing scheme. Using a mobility biography approach, Chatterjee et al. (2013) concluded that changes to the bicycle environment enabled changes in cycling behavior when life events occurred but were not themselves generally the cause of changes in behavior. Qualitative methods can thus contribute to a deeper understanding of why strategies have the effects they do.

4. What Are the Benefits of Increased Cycling?

A broader, more comprehensive assessment of the benefits of cycling would help to justify investments in cycling infrastructure or the adoption of other strategies to promote cycling and increase access to bicycles. Large investments can be especially hard to sell based solely on traditional transport planning concerns such as congestion reduction. This may be particularly true in places where cycling currently represents a very small share of travel and where bicycle infrastructure would replace automobile infrastructure, physically and/or financially. However, empirical studies of the benefits of increased cycling present challenges for researchers, as does cost-benefit analysis (CBA) and other approaches used in deciding whether or not to adopt cycling strategies.

4.1 Empirical Evidence of Benefits

The environmental benefits of transport cycling seem obvious and are widely assumed: reduced energy consumption, air pollutant emissions, and greenhouse gas emissions; less need for and wear-and-tear on roadways, etc. In fact, the magnitude of such benefits depends on the degree to which cycling substitutes for driving. Depending on the context, cycling may replace transit more than driving, and some cycling trips may be new trips, that is, trips that would not otherwise have been made. Few studies explicitly address this question. A pilot study in the USA used an intercept survey to estimate that between 26 and 68% of cycling trips replaced driving trips on that occasion but concluded that long term substitution could be substantially higher in places where cycling as a mode of transportation is common (Krizek, Handy, & Piatkowski, 2011). Which cycling trips should get credit for reducing driving is difficult to determine. In addition to the question of mode substitution is the question of destination substitution: in choosing cycling over the (usually) faster mode of driving, individuals may also shift to closer destinations, as suggested by the theory of constant travel time budgets (e.g. Mokhtarian & Chen, 2004). As a result, quantifying the reduction in driving can be difficult, since it requires knowledge of the distance

individuals would have traveled if they had not switched modes, and measuring only the cycling distance could lead to an underestimate of the reduction in driving distance. This makes quantifying the environmental benefits of cycling also difficult.

The health benefits of cycling are also not automatic or easily quantified. Studies have clearly established that as a form of physical activity, cycling helps to improve cardiovascular fitness and may help to manage weight (Gordon-Larson et al., 2009; Huy, Becker, Gomolinsky, Klein, & Thiel, 2008; Oja et al., 2011). These benefits are potentially offset, however, at least to some degree, if cyclists face increased exposure to air pollutants and to crash risks. For example, cycling injuries and fatalities are much higher in the USA than they are in Northern Europe, where cycling is more pervasive (Buehler & Pucher, 2012a). Thus, the net health benefits to an individual depend in part on context, though studies have shown that the benefits of commute cycling clearly outweigh the risks in the Netherlands (de Hartog, Boogaard, Nijland, & Hoek, 2010) and Denmark (Andersen, Lawlor, Cooper, Frobert, & Andersen, 2000). The health benefits are also offset if cycling for transport substitutes for other forms of physical activity rather than adding to total levels of physical activity. Few studies have explicitly examined this question, though aggregate studies suggest that active travel has a net positive contribution to physical activity (Pucher, Buehler, et al., 2010). Still, assuming that all cycling represents additional physical activity could lead to an overestimate of health benefits. The direction of causality is also hard to establish: more cycling may lead to better health, but better health might also lead to more cycling. In addition to individual health benefits, cycling may also confer substantial health benefits for the entire community, for example, through reduced air and noise pollution (Garrard, Rissel, & Bauman, 2012), at least to the degree that cycling substitutes for driving, as discussed above.

Another potential health-related benefit is an increase in general well-being for cyclists, beyond the benefits of increased physical activity (Garrard et al., 2012). Positive well-being effects of cycling were found in Rasciute and Downward (2010), Barton (2009), Pretty et al. (2007), Witaker (2005), and McKenna and Watling (2007). The number of studies in this area is still limited, and some of them are based on low numbers of interviews. The results are difficult to interpret because the direction of causality is not clear: people who feel a high level of well-being might tend to cycle more. Cycling might also affect well-being indirectly, for example, by expanding access to jobs, which in turn affects well-being. The role of cycling as a 'feeder mode' for transit or as an option where transit service is sparse could be especially important in producing such benefits, particularly in low-income areas. In these areas, access to bicycles may present an initial hurdle.

Cities are increasingly touting the economic benefits of cycling, but few academic studies have documented them (Krizek, 2007). Most widely discussed are the economic benefits that derive from health benefits, including reduced health care costs and fewer sick days for employers. Beyond these savings, economic benefits may derive from savings on transport costs, improved access to businesses, cycling-based tourism, and work productivity. In the first category, cyclists save money over transit or driving, meaning they can spend more on other things; cities save money on infrastructure costs and can invest it in other ways. Cyclists can be important for businesses: one study shows that cyclists spend as much if not more than other customers (Clifton et al., 2013), though studies have not yet documented whether good cycling access contributes to a

net increase in revenues for businesses or the impact on commercial property values from proximity to bicycle facilities. Studies have documented an association between residential property values and proximity to bicycle facilities (e.g. Krizek & Johnson, 2006), but this effect may have more to do with recreational rather than transport cycling. Studies on cycling-based tourism also tend to focus on recreational and sport cycling, rather than transport cycling (e.g. Adventure Cycling Association, 2012). Finally, although physical activity has been shown to improve work productivity (Shephard, 1986), we know of no studies to date that have examined the effects of transport cycling on productivity.

Determining the benefits of cycling requires more sophisticated methods than have generally been used. Cross-sectional studies that compare levels of cycling and levels of desired outcomes in different places are helpful in establishing the possibility that cycling in fact produces these outcomes. But carefully designed longitudinal studies showing that changes in the outcomes follow changes in cycling provide stronger evidence that cycling causes these outcomes. As Oja et al. (2011) note, although the evidence for health benefits is strong, more 'intervention' studies are needed. The ideal study would use an experimental design to measure changes in the desired outcomes for a sample of individuals randomly assigned to a 'treatment' group that increases cycling in comparison to changes in outcomes for individuals assigned to a 'control' group that does not. But such studies can be difficult to carry out in practice, particularly for community-level outcomes such as economic benefits.

4.2 *Assessing Benefits and Costs*

In many parts of the world, an assessment of the benefits of cycling strategies relative to their costs is a critical step toward their adoption, whether because of official requirements for such an assessment or because policy-makers are reluctant to act without one. In western countries, CBA is widely used to evaluate the effects of infrastructure investments of all sorts (e.g. Bristow & Nellthorp, 2000; Grant-Muller, MacKie, Nellthorp, & Pearman, 2001; Hayashi & Morisugi, 2000). A CBA essentially consists of a list of all (important) pros and cons, quantified and expressed in monetary terms as much as possible. The final results of a CBA are expressed as indicators such as benefits minus costs, the benefit-cost ratio, or the return on investment. It is essential that all important benefits and costs are included in the CBA, both those that impact gross domestic product (GDP) (such as reduced travel times for trucks or business travel) as well as those that have no impact on GDP (such as reduced travel times for social trips, or lower noise levels). Note that while all reductions in travel time should be included, even those that do not impact GDP (at least not directly), the analysis should account for the fact that the marginal value of time differs by the trip purpose as well as mode (Börjesson & Eliasson, 2012). For investments in cycling infrastructure, the benefits discussed in Section 4.1, including environmental, health, economic, and well-being benefits, should all be included in CBAs.

The uncertainty around the magnitude of the benefits of cycling, as described above, present a challenge in applying CBA to cycling policies (see Cavill, Kahlmeier, Rutter, Racioppi, & Oja, 2008 for a review). For example, Saelensminde (2004) evaluated the pros and cons of walking- and cycling-track networks (after their implementation) in three Norwegian cities, and included safety

effects, external effects (air pollution, noise), car parking costs, and health effects due to improved fitness. Although he concluded that the benefits were at least four to five times the costs, Saelensminde noted the limited state of knowledge for many of the cycling benefits. As an example, Börjesson and Eliasson (2012) argued that health benefits are overestimated in CBA because cyclists already include them in their decisions, resulting in so-called double counting if they are evaluated using Saelensminde's (2004) method. Thus, while CBA can help to support the implementation of cycling strategies, additional research is needed to reduce uncertainties around benefits as well as costs.

In addition, CBA users must be aware of its inherent limitations. As many have argued, 'sound' policies meet three criteria: effectiveness, efficiency, and equity (fairness) (e.g. Young & Tilley, 2006). A major limitation of conventional CBA is that while it includes effectiveness and efficiency effects, it does not include equity effects. If proposed cycling policies aim to increase equity in one way or another (e.g. increase levels of access to jobs or other activities for the poor or vulnerable, or decrease levels of social exclusion), CBA (alone) may be inappropriate (Van Wee, 2012). In such cases, a multi-criteria analysis (MCA) or the combination of a CBA and MCA is preferable. MCA explicitly considers multiple criteria (cost and/or other effects, qualitative and/or quantitative, monetary and/or non-monetary) and applies criteria weights in evaluating project or policy alternatives.

Examining trade-offs may be important in facilitating the implementation of cycling strategies. For example, if the perceived risks of cycling are a barrier to the implementation of cycling policies, an explicit comparison of health-related effects, translated into losses or gains in life years, could be useful. In this vein, de Hartog et al. (2010) estimated the net change in life years that would accrue (due to improved health from increased physical activity and reduced health from higher exposure to pollutants and accidents) if people in the Netherlands were to shift from driving to cycling. They concluded that the 'gains' would be substantially larger than the 'losses'; however, because the Netherlands is a relatively safe country for cyclists, the results may not translate to other countries. In each situation, it is important to first understand the barriers to cycling strategies (such as perceived safety effects) and then to analyze the trade-offs associated with those barriers in that situation.

CBA, MCA, and analyses of trade-offs all require, as input, a forecast of the effects of proposed strategies on travel behavior, and regional travel demand forecasting models are widely used to provide these forecasts. However, conventional models have entirely omitted cycling (as well as walking) or included it in a cursory way (e.g. by reducing the number of estimated trips by a fixed percentage to reflect the level of bicycling in the community). In the USA, several metropolitan planning organizations (MPOs) have or are in the process of incorporating non-motorized modes into their models in order to more effectively estimate the benefits of investments in these modes. For example, the Metropolitan Transportation Commission (2012), the MPO for the San Francisco Bay Area, includes walk and bike as separate modes in the mode-choice sub-model of its activity-based travel demand model. Research on cycling behavior, as described in Section 3, provides an important foundation for incorporating cycling into travel demand forecasting models in a realistic way. Other countries tend to put less emphasis on both forecasts and CBA than the USA in deciding upon cycling investments.

5. Conclusions

Motivated by the potential for significant environmental, economic, and health benefits, cities and countries throughout the world are adopting a wide variety of strategies that aim to increase cycling as a mode of transport. Researchers are working to support these efforts by providing answers to the critical questions discussed here: How much cycling is there? What strategies will increase cycling? What are the benefits of increased cycling? Although policy-makers often move forward without solid evidence as to the likely effectiveness and possible benefits of proposed strategies, an evidence-based approach can help to avoid waste of limited resources as well as failures that would reduce public support. Investments in cycling research can pay off by providing a basis for identifying the most effective strategies for increasing cycling and providing more accurate estimates of the benefits that would accrue.

Researchers can also help by addressing yet one more question: why are some cities so far ahead of others in their efforts to promote transport cycling? Case studies of these cities may provide important insights into the conditions that can lead to investments in bicycle infrastructure and the adoption of bicycle-friendly policies (see Pucher & Buehler, 2012). For example, in Davis, CA, where the share of workers commuting by bicycle is higher than anywhere else in the USA, a combination of strong advocates, sympathetic policy-makers, and willing traffic engineers led to the development of an extensive network of bicycling facilities over several decades (Buehler & Handy, 2008). Another US study found that the availability of federal funding for bicycle infrastructure led to the construction of bicycling infrastructure in regions where state policies supported such investments and advocacy groups pushed for them, but not in regions where these forces were absent (Handy & McCann, 2011). Another recent study examined the diffusion of bike-sharing programs across Europe and North America and identified factors contributing to their adoption (Parkes, Marsden, Shaheen, & Cohen, 2013). Others have examined institutional barriers to the adoption of sustainable transport strategies more generally (e.g. Banister, 2008; Curtis & Low, 2013). In-depth case studies, guided by the political science literature, the 'new mobility' paradigm, or other appropriate frameworks, are needed to illuminate the different conditions that led communities to efforts to prioritize cycling.

Cycling research appears to be expanding at an exponential rate, as illustrated by the high proportion of citations in this article published within the last year or indeed yet to be published. Addressing the challenges outlined in this paper in future research would help to significantly advance understanding of the potential of cycling strategies to produce the hoped-for benefits. Improvements are needed in methods for measuring how much cycling there is by whom and for what purpose, and in the design of studies for assessing which strategies are most effective and in the development of solid evidence and effective tools for predicting what benefits they will produce (Table 1). Many different approaches — qualitative and quantitative methods, cross-sectional and longitudinal studies, case studies as well as statistical analyses — have a role to play in improving our understanding of the potential effectiveness of strategies for supporting and promoting increased cycling.

But how likely are policy-makers to read the peer-reviewed articles that researchers produce? If research is to have any role in informing infrastructure

Table 1. Summary of research needs and challenges

Question	Needs	Challenges
How much cycling is there?	<ul style="list-style-type: none"> • Data on how much, by whom, where, when, for what purpose • Consistent data over time to track trends • Consistent data across places to enable comparisons • Standardized data collection methods, tested for reliability and validity 	<ul style="list-style-type: none"> • Place-based vs. person-based approaches • Separating transport cycling from other types of cycling • Use of bicycles in conjunction with other modes • Occasional cycling
What strategies offer the most promise?	<p><i>Factor identification</i></p> <ul style="list-style-type: none"> • Nonlinear distance effects • Importance of other kinds of infrastructure • Role of bicycle equipment • Impact of costs of competing modes • Cycling attitudes and their formation • Cycling habits and their formation • Role of social influences <p><i>Evaluation studies</i></p> <ul style="list-style-type: none"> • Change in cycling resulting from implementation of a strategy 	<ul style="list-style-type: none"> • Interaction effects between factors • Bidirectional effects between factors and cycling • Bidirectional effects between two or more factors • Effects of higher-level factors <ul style="list-style-type: none"> • Before and after measurement • Identification of control group • Separating strategy effects from other factors • Transferability of results from one place to another
What are the benefits?	<p><i>Empirical evidence</i></p> <ul style="list-style-type: none"> • Reductions in driving • Net health benefits by context • Effects on well-being • Community-wide economic benefits <p><i>Assessing benefits and costs</i></p> <ul style="list-style-type: none"> • CBA • Trade-off assessment • Forecasts of cycling levels 	<ul style="list-style-type: none"> • Mode and destination substitution • Physical activity substitution • Bidirectional effects between cycling and health • Transport vs. recreational cycling effects <ul style="list-style-type: none"> • Uncertainty of magnitude of benefits • Equity considerations • Incorporating cycling into regional travel demand models

investments and policy adoption, it must be accessible to those charged with making such decisions. Making research accessible can be a challenge, no matter what the research approach, but is especially a challenge for studies using more sophisticated methods. Researchers thus face an important trade-off. While more sophisticated methods tend to increase the scientific quality of the research, the results may be harder to convey to policy-makers. Conversely, studies using simpler methods or focusing on particular cases may be easier for policy-makers to grasp, even if their results are less conclusive or generalizable. If the goal is an evidence-based approach to cycling policy, both kinds of studies can thus contribute.

One important tool for bringing the available evidence to policy-makers is syntheses of the relevant research, written up in a non-academic and non-technical style.

Many research institutes and advocacy organizations now publish such syntheses with the explicit aim of bridging the gap between research and policy (see, for example, the research briefs published by the Active Living Research program¹, or the Dutch KennisInstituut voor Mobiliteitsbeleid (KiM Netherlands Institute for Transport Policy Analysis²)). Researchers can help to ensure the accuracy of these syntheses, both as authors and as peer-reviewers. On the whole, the development of effective mechanisms for sharing research results with policy-makers itself merits attention.

Ultimately, the communication must work in both directions. Just as it is important that policy-makers draw on research to make evidence-based decisions in their efforts to promote transport cycling, it is important that researchers connect their efforts to the questions that policy-makers are asking.

Notes

1. See <http://activelivingresearch.org/toolsandresources/researchbrief>.
2. See www.kimnet.nl/en/.

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Appendix. Potential applications of advanced statistical models in cycling research

Structural equation models (SEM)	The exploration of bidirectional effects requires the use of more advanced methods like SEM (Bollen, 1989). This method allows the testing of whole model structures (with indirect and direct effects between multiple exogenous and multiple endogenous variables) and has been used in at least one study of cycling behavior (Xing, 2012). This method can easily be extended to include repeated measurements, i.e. panel data
Cross-lagged panel models	The cross-lagged panel model is a popular of specification of SEM for panel data (Finkel, 1995). The model has been used in numerous transportation studies (Golob & Meurs, 1987, 1988; Klöckner & Matthies, 2012; Simma & Axhausen, 2003; Thogersen, 2006). In short, this model estimates the (lagged) effects between the variables of interest (i.e. attitudes and behavior) over time, while controlling for the initial association between the variables and their relative stability. In contrast to cross-sectional studies, it thereby allows the researcher to test the criterion of time precedence empirically

Latent growth models and latent difference score models

The latent growth and latent difference score models (Ferrer & McArdle, 2003) are also possible specifications for panel data. These models are appropriate when the behavior under investigation grows or develops over time. For example, in educational studies growth (e.g. in intelligence test scores) can be attributed to learning. While we are unaware of applications of such models in the field of travel behavior, such models may be appropriate in the case of cycling as this behavior too has to be learned over time. Especially under difficult circumstances (e.g. with heavy traffic, hilliness or the need to carry loads) and when people learn to cycle in later life, fully mastering how to cycle may take several years. It would be interesting to develop and apply models that can reveal this learning process and explore the exogenous factors that influence it

Hierarchical or multi-level models

Multi-level or hierarchical models can be specified to study the effects of high-level (or more aggregate) variables while controlling for individual variables (Bryk & Raudenbush, 2002). Potentially relevant higher-level variables in cycling research include households, neighborhoods, communities, cities, and countries. The multi-level approach provides an effective framework to study cycling behavior across various countries, where relationships between individual factors can be expected to differ for different (types of) countries. Note that such studies require consistent data on cycling as well as potential determinants across a substantial number of places

Cluster methodologies

Cluster methodologies enable a person-centered approach that focuses on identifying homogenous groups of people with similar behavioral and/or attitudinal patterns. In the field of travel behavior, a combination of factor analysis and (K-means) cluster analysis is typically used to uncover these groups and their patterns of behavior (Anable, 2005; Haustein, 2012; Hunecke, Haustein, Bohler, & Grischkat, 2010). Other cluster methodologies, such as Q-methodology (Cools, Moons, Janssens, & Wets, 2009; van Exel, de Graaf, & Rietveld, 2011), correspondence analysis (Diana & Pronello, 2010) or latent class analysis (Beckman & Goulias, 2008), have also been used in travel behavior research. While most of these studies focus on car and public transport use, a recent study aimed to identify various cycling segments (Li et al., 2013).

Multiple behavioral indicators can and are typically included in person-centered approaches. If applied to cycling behavior, this approach could reveal the various ways in which people integrate the use of the bicycle into their mobility patterns, which, in turn, allows an assessment of cycling potential for various groups. The general rationale behind the use of person-centered approaches is to support the design of strategies that suit the motivations, needs, and desires of particular target groups, thereby increasing their probability of success and ensuring that limited resources are effectively targeted

Cluster methodologies with panel data

The extension of the person-centered approach to multiple moments in time with the use of panel data, as yet unexplored in travel behavior research, offers intriguing possibilities. Measuring (the same) clusters on multiple occasions can expose the transition of individuals between clusters (i.e. different cycling patterns) over time. It can then be assessed which cycling patterns are most stable and which are most instable. Next, by assessing the exogenous factors that determine cluster membership, the conditions that support stable cycling patterns may be revealed. In addition, models can also show how exogenous factors or specific events in the period between the measurements (e.g. a house move or job change or a shift from one life cycle stage to another) explain the transitions between cycling patterns. Recent advances in statistical modeling have made it possible to implement these steps in a single probabilistic model, namely the latent class transition model (Collins & Lanza, 2010). Practically, this approach can provide valuable information on the moments in time at which cycling strategies are most likely to succeed
