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Ralph Buehler & Jennifer Dill

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Bikeway Networks: A Review of Effects on Cycling

RALPH BUEHLER*§ AND JENNIFER DILL**

**Urban Affairs and Planning, School of Public and International Affairs, Virginia Tech, Alexandria Center 1021 Prince Street, Suite 200, Alexandria, VA 22314, USA; **Nohad A. Toulan School of Urban Studies and Planning (USP), Portland State University, Portland, OR, USA*

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ABSTRACT *Research linking bikeway infrastructure and cycling levels has increased significantly over the last 20 years — with the strongest growth since 2010. The research has evolved from the study of lanes and paths, to include analyses of the role of intersection treatments, and finally to studies that attempt to measure the whole bike network. Most studies suggest a positive relationship between bikeway networks or aspects of the network and cycling levels. Stated and revealed-preference studies suggest a hierarchy of cyclist and non-cyclist preferences may exist, favoring separate paths and/or lanes over cycling on roadways with traffic — particularly with high volumes of fast-moving motorized traffic. Revealed- and stated-route-choice studies indicate that intersections have negative effects on the cycling experience, but that certain features can offset this. The research correlating link and node characteristics to cycling implies that networks of such facilities would have positive effects, though very few empirical studies link complex measures of the network to cycling levels. In spite of an increase in studies and general agreement among findings, several important research gaps remain, including empirical studies using comprehensive network measures and studies of specific facility designs and new types of facilities (including intersection treatments). Improved research methods are necessary, including better sampling, longitudinal studies, greater geographic diversity, and incorporating more control variables, including policies.*

Introduction

During the last 20 years, national, state, and local governments in Western Europe, North America, and Australia have promoted cycling to increase the sustainability of transport systems (Pucher & Buehler, 2012). Increasing cycling levels in cities and countries during the same time period suggest success of these policies. Packages of policies implemented to boost cycling vary, but virtually all cities and countries that have attempted to promote cycling have expanded their network of bike facilities, including bicycle lanes, cycle tracks, paths, traffic calming of neighborhood streets, and special accommodations for cyclists at intersections. The practice of providing cycling facilities is currently evolving from a focus on how to best install and design individual lanes or paths toward planning for entire networks of bicycle facilities. For example, the US Department of Transportation has identified network implementation and documentation as a priority

§Corresponding author. Email: ralphbu@vt.edu

in developing its new Strategic Agenda for Pedestrian and Bicycle Transportation (2014).

During the same time period research on determinants of cycling in general and the role of bikeway networks has increased significantly. This literature review builds on and expands previous reviews of determinants of bicycling — by focusing on the link between bikeway networks and cycling levels. Pucher, Dill, and Handy (2010) analyzed peer-reviewed and non-peer-reviewed 'gray' literature on the relationship between bicycle infrastructure, programs, and policies to increase cycling. Heinen, van Wee, and Maat (2010) reviewed correlates of bike commuting only. Handy, van Wee, and Kroesen (2014) identified research needs and challenges for promoting cycling for transport. In contrast to some aspects of the other reviews, we (1) included cycling for all trip purposes, (2) focused on the relationship between bicycle networks and cycling levels, (3) limited our analysis to peer-reviewed journal articles, books, or reports, and (4) extended the time period to include publications that appeared between 1990 and mid-2014. As documented below, over 45% of the more than 84 studies reviewed here were published in 2010 or later.

To identify sources, we used the Web of Science — including both social sciences and sciences records — and the TRID database (http://trid.trb.org/). TRID is a combination of the Transportation Research Information Services database maintained by the Transportation Research Board and the Joint Transport Research Centre's International Transport Research Documentation (ITRD) database maintained by the OECD. Searches included the following terms coupled with bicycle, bicycling, and/or bike: facilities, lanes, paths, cycle tracks, network, boxes, planning, network planning, and intersection. We also used citation searches to identify newer literature. We limited our review to research that examined the effects of networks and their attributes on levels of bicycling. This includes direct evidence (e.g. higher counts or rates of bicycling) and indirect (e.g. stated preferences or perceptions that influence decisions to bicycle). We do not include research that only looks at effects on safety (e.g. crash rates) or operations. Another article in this *Special Issue* covers the safety literature. Finally, we included publications in English language only.

This literature review includes a total of 84 peer-reviewed studies on links, nodes, and bicycle networks published since 1990. The number of peer-reviewed publications increased sharply since 1990 and particularly since 2010. Our search identified only one peer-reviewed study for the period 1990–94, 11 studies between 1995 and 1999, 10 publications between 2000 and 2004, 23 peer-reviewed studies between 2005 and 2009, and 39 peer-reviewed publications between 2010 and mid-2014. Over time, research on bicycle infrastructure evolved from studies focusing on links of the network, to including the nodes (intersections), and finally to attempts to capture characteristics of entire networks.

Our review of the research is organized in three sections that reflect this evolution in research. We first cover evidence regarding links of the bicycle network, ranging from cycling on roadways with motorized traffic to separate paths. This is followed by research on intersections — the nodes of the bicycle network — and the types of facilities used there, such as bike boxes and signals. The third section reviews emerging research that examines bicycle infrastructure as a network, measuring a range of types of links and/or nodes of the bicycle network. After this three-part review of research findings, we analyze the methods used in the research, followed by conclusions identifying research gaps and suggestions for future research.

Links of the Bicycling Network

The 67 peer-reviewed studies about links of the bikeway network reviewed here analyze cycling on roadways shared with motorized traffic and on facilities separated from motor vehicles, including bike lanes or shoulders on roadways, shared sidewalks, physically separated cycle tracks next to general traffic lanes, and separated paths away from motorized traffic — often in parks.

Cycling on Shared Roadways

Accommodations to facilitate cycling with motorized traffic include signed bike routes with directional signs for cyclists, extra-wide car travel lanes or shoulders, cyclist markings on roadways (so-called 'sharrows'), bicycle streets that give priority to bicycles over cars, and traffic calming to reduce vehicle travel speed and volume (AASHTO, 2012; CROW, 2007; FGSV, 2010; Furth, 2012; NACTO, 2014). Mainly implemented in North America, bicycle boulevards or neighborhood greenways are neighborhood streets with traffic-calming features to discourage motorized traffic. Stop signs, that are typical for most intersections in North American neighborhoods, are removed in the direction of the bicycle travel along these routes to facilitate continuous travel without dismounting at every intersection (Dill, McNeil, Broach, & Ma, 2014).

In spite of a preference for separate cycling facilities reported in most stated-preference surveys, revealed-preference studies from the USA and Canada indicate that roadways without separate cycling facilities accounted for 50–90% of kilometers cycled and that most cyclists rode on roadways without separate facilities at least for parts of their trips (Aultman-Hall, Hall, & Baetz, 1998; Broach, Dill, & Gliebe, 2012; Dill, 2009; Howard & Burns, 2001; Moritz, 1998; Sener, Eluru, & Bhat, 2009b). This is partially explained by the limited and often fragmented supply of dedicated bicycle infrastructure in most North American cities and the planning practice to only provide bike paths and lanes along roadways with higher motorized traffic volumes or speeds, but to mix cyclists with other traffic on traffic-calmed roads (Pucher & Buehler, 2008, 2012; Pucher et al., 2010). A recent study from Portland, Oregon — arguably one of the most bike-friendly large cities in the USA — tracked cyclists' routes with GPS devices and found that about 50% of kilometers cycled occurred on roadways. The other half was attributed to bicycle facilities — even though these facilities only accounted for 8% of the bikeable road network (Broach et al., 2012; Dill, 2009).

Other revealed-preference studies attribute about half of the on-road cycling kilometers in North America to local or neighborhood streets (Aultman-Hall et al., 1998; Howard & Burns, 2001; Moritz, 1998). In fact, most revealed- and stated-preference studies agree that cyclists who ride on roadways prefer streets with fewer travel lanes, lower volumes of motorized traffic, slower speeds, and without car parking (Abraham, McMillan, Brownlee, & Hunt, 2002; Akar & Clifton, 2009; Caulfield, 2014; Chataway, Kaplan, Nielsen, & Prato, 2014; Dill, 2009; Dill, Mohr, & Ma, 2014; Dill & Voros, 2007; Heinen et al., 2010; Pucher & Buehler, 2008; Sener, Eluru, & Bhat, 2009a; Sener et al., 2009b; Winters, Davidson, Kao, & Teschke, 2011). For example, Broach et al. (2012) found that for non-commute trips, cyclists in Portland, Oregon would only use streets with over 20 000 vehicles per day if alternative on-road routes with less motorized traffic required detours that were twice as long as the high-traffic-volume route or included very steep hills. A 2008 survey of 74 cyclists in Vancouver, Canada showed that cyclists deviated from the most direct route between trip origin and destination to ride on streets with traffic-calming features (Winters, Teschke, Grant, Setton, & Brauer, 2010). Few studies capture the quality of roadway surfaces for cycling, but some indicate that cyclist prefer higher quality, smooth, and hard surfaces (Kang & Fricker, 2013; Sener et al., 2009b; Stinson & Bhat, 2003).

Several studies indicate that the dislike and fear of cycling with motorized traffic is greater among inexperienced cyclists, risk-averse individuals, women, and younger cyclists (Garrard, Rose, & Lo, 2008; Heinen et al., 2010; Jackson & Ruehr, 1998; Krizek & Roland, 2005; Stinson & Bhat, 2003, 2004). By contrast some studies find that car traffic volume and speed are not significant predictors of cycling levels (Vernez-Moudon et al., 2005), that some experienced cyclists preferred riding on streets and disliked separate paths and lanes (Abraham et al., 2002; Antonakos, 1994; Kang & Fricker, 2013), and that bike commuters were less sensitive to car travel volume and speeds than those who cycled for other trip purposes (Broach et al., 2012; Sener et al., 2009a). Two studies indicate that cyclists in Copenhagen, Denmark — one of the most bike-friendly cities in Western Europe — preferred separate bikeways, but did not report an increased likelihood for a negative riding experience when cycling on roadways (Chataway et al., 2014; Snizek, Nielsen, & Skov-Petersen, 2013).

Bike boulevards are one way to address concerns about cycling with motorized traffic. One stated-preference survey (Winters & Teschke, 2010) and one revealed-preference study using GPS (Broach et al, 2012) found a stronger preference for bike boulevards over striped bike lanes, though below separated paths. However, Dill, McNeil, et al. (2014) found no effect within one year of the installation of bike boulevards in Portland, Oregon on cycling levels for residents living adjacent to a bike boulevard.

Separate Facilities: Bike Lanes, Cycle Tracks, and Bike Paths

Respondents to stated-preference surveys typically indicate a greater likelihood of cycling on various types of separate facilities compared to cycling with motorized traffic (Akar & Clifton, 2009; Gossling, 2013).

Bike lanes. Some studies focused exclusively on bike lanes, which provide a dedicated space for cyclists to ride on roadways. Typically bike lanes are separated from motorized travel by white lines painted on the roadway and situated between motorized travel lanes and car parking or the sidewalk. However, width, design, coloring, location on the roadway, and quality of bike lanes vary widely within and between cities and countries. Individual- and aggregate-level studies found a positive empirical relationship between cycling levels and bike lane supply (Barnes, Thompson, & Krizek, 2006; Buehler & Pucher, 2012; Dill & Carr, 2003; Goodno, McNeil, Parks, & Dock, 2013). For example, an aggregate-level study of 42 large US cities found that each additional linear mile of bike lanes per square mile land area was associated with a roughly 1% increase in share of bike commuters (Dill & Carr, 2003).

Some studies did not find a relationship between bike lanes and cycling (Cervero, Sarmiento, Jacoby, Gomez, & Neiman, 2009; de Geus, de Bourdeaudhuij, Jannes, & Meeusen, 2008; Sener et al., 2009a; Taylor & Mahmassani, 1996). For example, in a survey of 800 individuals from Belgium, de Geus et al. (2008) found that in areas with 'adequate' bike lane supply, individual-level characteristics were more important determinants of cycling than variations in bike lane supply. Similarly, Cervero et al (2009) concluded that bike-lane kilometers per land area did not significantly influence utilitarian cycling among 830 adults in Bogota, Colombia. Two studies concluded that striped bike lanes helped offset negative aspects of adjacent high-volume and fast-moving car travel, but were insufficient to overcome other negative aspects of the built environment (Broach et al., 2012; Dill, Mohr, et al., 2014). One study identified cyclist safety concerns about turning car traffic crossing a buffered bike lane (Monsere, McNeil, & Dill, 2012).

In spite of the few inconclusive studies cited in the paragraph above, stated-preference surveys of cyclists and non-cyclists typically showed that cyclists preferred and felt safer on bike lanes compared to cycling in traffic (Akar & Clifton, 2009; Antonakos, 1994; Fishman, Washington, Haworth, & Watson, 2015; Landis, Vattikuti, & Brannick, 1998; Sanders & Cooper, 2013; Sener et al., 2009a). Several studies describe other types of bike lanes, such as colored bike lanes, shared bus and bike lanes, advisory bike lanes using dashed lines on roadways to dedicate space for bicycles, extra-wide lanes to accommodate cyclist's lateral movement when cycling uphill, or contra-flow bike lanes on one-way roads for cars (Buehler & Handy, 2008; Furth, 2012; Pucher & Buehler, 2008), but they did not isolate the impact of these facilities on cycling levels or cyclist perceptions.

Few studies distinguished between location, design, and quality of bike lanes. For example, Krizek and Roland (2005) instructed 28 volunteer cyclists to ride on predetermined routes with discontinuous bike lanes in Minneapolis, MN. Results indicated less comfort on bike lanes that were discontinuous. In other studies cyclists also reported greater comfort on wide or buffered bike lanes due to greater separation from traffic and opening car doors from parked cars (Li, Wang, Liu, Schneider, & Ragland, 2012; Monsere et al., 2012). An intercept survey of cyclists at a buffered bike lane in Washington, DC found a perception of greater safety and reduced concern about being hit by an opening car door (Monsere et al., 2012). Another Washington, DC study on the buffered two-way bike lane in the center of Pennsylvania Avenue found a 250% increase in cycling levels during peak commute hours two years after the installation of the facility, though it is unclear what share of that increase is from new riders or riders diverted from other routes (Goodno et al., 2013). However, one study did not find any difference in cyclist preference between narrow and wide bike lanes (Sener et al., 2009a).

Cycle tracks. Cycle tracks (also known as protected or separated bike lanes) are on or adjacent to roadways, but physically separated from motorized traffic by a curb, concrete barriers, or by a space buffer with bollards — and thus often provide direct connections along roadways and protection from traffic (Furth, 2012). Copenhagen, Denmark has a long history of building cycle tracks separated from roadways and pedestrians with a curb on either side of the cycle track, but many other cities have begun building cycle tracks as well (Furth, 2012;

Pucher & Buehler, 2008). Three separate revealed-preference studies from Copenhagen, Washington, DC, and five US cities found positive riding experiences on cycle tracks and increases in cycling levels after the installation of cycle tracks (Goodno et al., 2013; Monsere et al., 2014; Snizek et al., 2013). A survey of cycle tracks in North America (Lusk et al., 2011) found increased cyclist safety on cycle tracks when compared to cycling along 'comparable' corridors. Pucher and Buehler (2006, 2008) imply that cycle tracks helped boost cycling levels in Copenhagen, Denmark and Montreal, Canada. There is limited research on the diversion of cyclists from other routes onto newly constructed cycle tracks. Monsere et al. (2014) conducted intercept surveys along cycle tracks in 5 US cities and asked cyclists about hypothetical alternative route choices — without the newly constructed cycle track. They found that 65% (range across cities 17–83%) of cyclists would have used the same route, 24% (range 11–60%) diverted from another route, and 10% (range 6–21%) would have used another mode of transport.

Bike paths. Bicycle paths are physically separated from roadways and typically run through parks or along waterfronts — often not following the road network. Several before-and-after studies showed that the construction of bike paths increased the number of bike trips or share of trips by bicycle (Barnes et al., 2006; Heinen et al., 2010). Individual-level studies indicated that those living or moving closer to bike paths were more likely to cycle (Beenackers et al., 2012; Vernez-Moudon et al., 2005). Studies from the USA and the UK found bike paths to be an integral part of bicycling networks (Dill & Voros, 2007; Parkin, Wardman, & Page, 2008; Shafizadeh & Niemeier, 1997). Tilahun, Levinson, and Krizek (2007) found that respondents were willing to commute 20 minutes longer if they could switch from cycling in the roadway to an off-street bike path. In a comparison of 8800 wards in the UK, Parkin et al. (2008) found that a higher proportion of off-road paths in the bike network was associated with more bike commuting — but that demand for cycling on paths was inelastic ($e = |0.049|$). Studies report higher cycling levels and a more positive perception for bike paths that were wider and better connected to other cycling facilities (Aultman-Hall et al., 1998; Li et al., 2012; Wendel-Vos, Droomers, Kremers, Brug, & van Lenthe, 2007). Three studies showed that urban vs. suburban location, as well as race and income of societal groups living adjacent to paths moderated the impact of paths on cycling levels (Cohen, Sehgal, & Williamson, 2008; Deka & Connelly, 2011; Merom, Bauman, Vita, & Close, 2003). One study did not find an increase in cycling after the construction of a trail (Evenson, Herring, & Houston, 2005) and another study reported that experienced cyclists disliked bike paths (Antonakos, 1994).

Comparing the impact of bike lanes and paths. Some studies attempted to measure the differential impact of paths and lanes. However, findings diverge. Using linear and binary regressions to predict aggregate bike commute rates for 90 large US cities, Buehler and Pucher (2012) concluded that both bike paths and lanes had a statistically similar positive impact on bike commute levels. Several studies found a preference of bike paths over lanes among cyclists and non-cyclists (Broach et al., 2012; Kang & Fricker, 2013; Taylor & Mahmassani, 1996; Winters & Teschke, 2010) — particularly among women and inexperienced cyclists (Garrard et al., 2008; Jackson & Ruehr, 1998). Additionally, a study of 969 UK work commuters found that cyclists were willing to trade off longer travel times for cycling on paths instead of lanes (Wardman, Tight, & Page, 2007). By contrast, two studies from Minnesota and Texas found that cyclists — in particular bike commuters — preferred bike lanes over bike paths (Stinson & Bhat, 2003; Tilahun et al., 2007). Finally, two studies from the USA found that neither supply nor proximity to off-street trails or bike lanes was associated with higher levels of cycling (Dill & Voros, 2007; Vernez-Moudon et al., 2005).

Other facilities: cycling on shared sidewalks and bridges. Even though cycling is often allowed on sidewalks, only a few studies mentioned cycling on shared sidewalks as explicit city policy to increase cycling (Pucher & Buehler, 2007). Two studies indicated that cycling on sidewalks was rare and that cyclists preferred bikeways to riding on shared sidewalks with pedestrians (Aultman-Hall & Adams, 1998; Srisurapanon et al., 2003). Several studies indicated that cyclists in general and inexperienced cyclists in particular preferred bridges with low traffic volumes and/or greater separation of cyclists from motorized traffic (Barnes et al., 2006; Broach et al., 2012; Heinen et al., 2010; Melson, Duthie, & Boyles, 2013; Pucher et al., 2010; Stinson & Bhat, 2003). By contrast one study found no difference in cyclist preferences for riding on either pedestrian only bridges or bridges with motorized traffic (Aultman-Hall & Adams, 1998; Heinen et al., 2010).

Nodes of the Bicycling Network

Nearly all bicycle travel involves traversing intersections, where the number of potential conflict points with motor vehicles increases compared with links, due to turning movements. As a result, intersection design, including traffic control devices, will affect decisions on whether, when, and where to ride. The intersection characteristics that likely affect these decisions include those not specific to bicycles (e.g. number of lanes, volume of motor vehicle traffic, stop signs, and traffic signals) and devices aimed at bicyclists.

There are several traffic control devices aimed specifically at improving the movement and safety of bicyclists through intersections. Bicycle-specific traffic signals can provide a separate signal phase (Monsere, Figliozzi, Thompson, & Paulsen, 2013). Bike boxes, also known as advanced stop lines, are areas at the front of the general traffic lane, in front of the stop line for cars, but behind the pedestrian crosswalk, where bicyclists can wait during the red signal phase. The placement of the box is intended to increase the visibility of bicyclists to motor vehicle drivers, particularly those turning across a bike lane (Dill, Monsere, & McNeil, 2012; Loskorn, Mills, Brady, Duthie, & Machemehl, 2013). Sometimes they are coupled with signal phasing that allows bicycles a head start. Another treatment used to handle through bicycles and turning motor vehicles is a combined bike lane/motor vehicle turn lane (NACTO, 2014). These are sometimes used in conjunction with cycle tracks. Bike signals and bike boxes are more common in Europe, though adoption in the USA is increasing. Another intersection treatment is a crossing marking, which guides the bicyclist on a specific path through the intersection, usually from a bike lane. Such marking might be with dashed stripes, sharrows, and/or colored pavement (NACTO, 2014). Two-stage turn queue boxes provide bicyclists a way to make a left turn (or right turn in some countries) on a multi-lane road without crossing from a right-side bike lane to a motor vehicle left-turn lane. Raised crossings for bicycles are used in several European cities, though less common for bicyclists at intersections in North America.

None of the studies reviewed focused on making a direct link between intersection characteristics or treatments and ridership. Instead, the research focuses on the effect of designs on real or perceived safety or revealed or stated route choice. Intersection treatments that improve perceptions of safety are likely to affect ridership. And, route choice is one way such perceptions and preferences are revealed, for example, by avoiding dangerous intersections and traveling further to reach intersections that are perceived to be safer. However, the route choice modeling provides an estimate of a rider's value, usually in time or distance, of the intersection features, not a direct estimate of how it might affect ridership volume.

Intersection Characteristics

All intersections can be a source of conflict and delay for cyclists and are usually perceived as negative or problematic parts of cyclists' routes (Heinen et al., 2010). Several studies have shown that cyclists prefer to avoid intersections with stop signs or traffic signals (Caulfield, Brick, & McCarthy, 2012; Menghini, Carrasco, Schussler, & Axhausen, 2010; Rietveld & Daniel, 2004; Sener et al., 2009a; Snizek et al., 2013; Stinson & Bhat, 2003). However, these studies do not consider specific intersection characteristics, such as traffic volumes. The studies that do consider such characteristics reveal a more nuanced relationship. Using GPS data, a study in Portland, OR found that cyclists generally avoided traffic signals (not bicycle-specific) and unsignalized intersection crossings (though the effect was less or non-existent when turning right) and stop signs. However, when motorized traffic volumes at an intersection increased to over 5000 or 10 000 vehicles per day, this overcame the negative effect of the traffic signal. The authors could not determine if the signal provided increased perceptions of safety and/or a time saving. The effects were stronger for non-commute trips than commute trips (Broach et al., 2012). Similarly, Aultman-Hall et al. (1998) found that cyclists' routes had more traffic signals than the shortest route and that these were more likely to be used to make a turn and to travel between major and minor streets. Laws that allow bicyclists to not stop at stop signs (known in the USA as 'Idaho stop' laws) are one way to offset the negative effects of minor intersections, though we found no research on relationships to ridership.

Bicycle-specific Intersection Treatments

Very few studies look at the effects of bicycle-specific treatments at intersections on cycling levels or preferences. Comparing reported routes to shortest path routes, a study in Vancouver, BC, Canada found that cyclists went out of their way to use bicycle-activated signal crossings (Winters et al., 2010). One study found that over three-quarters of bicyclists riding through intersections with bike boxes felt that the treatment improved safety (Dill et al., 2012). Other bike box studies assessed operations, such as compliance and conflicts, and did not measure perceptions of safety or effects on use. A study of cycle tracks in five US cities asked cyclists how safe they felt in the different intersection designs which were aimed at reducing conflicts with turning motor vehicles. Cyclists riding through intersections with separate bicycle signal phases felt the safest

(Monsere et al., 2014). This was the only study we found that examined the effect of bicycle traffic signals on use or perceptions. Other studies of bicycle signals focus on compliance and safety issues (Monsere et al., 2013). A study in Sweden found increases in bicycle volumes after the installation of raised crossings (Garder, Leden, & Pulkkinen, 1998). We did not find any peer-reviewed studies on the effects of other intersection treatments, such as two-stage turn queue boxes.

Toward Studying the Whole Bicycling Network

If individual characteristics of a network's links and nodes contribute to cycling levels, it logically follows that a network of such features would as well, and several of the studies cited above draw this conclusion based upon findings on individual network characteristics (e.g. Akar & Clifton, 2009; Aultman-Hall et al., 1998). Several studies report that countries and cities with high cycling levels in Western Europe and North America had extensive networks of separate bicycle facilities and traffic-calmed streets (Fraser & Lock, 2011; Furth, 2012; Pucher et al., 2010; Pucher, Komanoff, & Schimek, 1999). This was confirmed by several individual- and aggregate-level studies that found a positive relationship between cycling levels and overall bikeway supply — a category that often combines bike lanes, cycle tracks, or bike paths (Buehler, 2012; Buehler & Pucher, 2012; Dill & Carr, 2003; Nelson & Allen, 1997).

Studies have found a stated preference specifically for continuous or connected bicycle facilities, as opposed to bicycle facilities generally (Caulfield et al., 2012; Stinson & Bhat, 2003), and a predictive model based upon stated preferences found that a dense network of bike facilities could help increase bicycle trips (Ortuzar, Iacobelli, & Valeze, 2000). One study linked cycling levels to self-reported measures of the bicycling environment, including being able to take shortcuts on a bicycle compared to routes available to cars. This measure of connectivity was found to be significant (Titze, Stronegger, Janschitz, & Oja, 2008). However, a study in Bogota, Colombia found that stated levels of bicycling were not associated with bike-lane density of completeness; overall street density was important (Cervero et al., 2009). Other studies have also found significant positive associations between street connectivity and bicycling, regardless of bicycle-specific infrastructure (Beenackers et al., 2012; Dill, Mohr, et al., 2014; Dill & Voros, 2007).

Our review of the research revealed that studies linking characteristics specific to a bicycle network to levels of cycling were less common than those examining individual features of the network. One exception is a recent paper using aggregate bicycle commuting data from 74 US cities (Schoner & Levinson, 2014). The authors develop several different measures that represent the size, connectivity, density, fragmentation, and directness of the bicycle network. The density of the bikeway network (all types of facilities combined) had the largest elasticity value, larger than connectivity, fragmentation, and directness combined. This finding suggested that densifying a city's network of bike facilities would have a greater effect on bicycle commuting than expanding the breadth of the network (Schoner & Levinson, 2014).

Four additional studies develop new, more complex measures of a bicycle network. However, at the time of this review, there were no published papers using the measures to link to outcomes of ridership. These studies all use a combination of a level of service or quality measure of the links in the network and a distribution of hypothetical trips within the network to develop an overall measure of the network. A tool developed by Klobucar and Fricker (2007) assumed that bicyclists make decisions based primarily on perceived safety and distance. They weighted each link's distance by a bicycle compatibility index (BCI) measure expected to capture perceived safety to get a 'safe length' for each link. The BCI captures the presence of a bike lane or paved shoulder, curb lane width and volume, other lane volumes, traffic speeds, parking, roadside development, truck volumes, and turn volumes (Harkey, Reinfurt, & Knuiman, 1998). They then developed theoretical origin–destination pairs between all intersections following an assumed trip length distribution and assigned the trips to the network based on the total safe length of the route. The overall measure of the network is a sum of the modeled number of bicyclists on each link multiplied by its safe length.

Lowry, Callister, Gresham, and Moore (2012) take this idea a step further by incorporating accessibility to specific destinations. Instead of the BCI, they use the link-level bicycle level of service (BLOS) measure from the *Highway Capacity Manual 2010 (HCM)*, which considers width of the bike lane, shoulder and outside lane, number of lanes, on-street parking, vehicle traffic volumes and speeds, pavement condition, percentage of heavy vehicles, and presence of a curb. A separate equation is used for off-street paths. The street or path characteristics are combined to assess BLOS for the link on an A–F scale. Lowry et al. (2012) use this link-level BLOS measure for the streets in a network in combination with accessibility to important destinations to create an overall measure of bikeability by zone. Generally, bikeability increases as more destinations can be reached along routes with better BLOS. A framework developed by Duthie and Unnikrishnan (2014) adds one more dimension — the cost of improving the network segment to an acceptable level (A, B, or C using the BCI). Using a set of theoretical origin–destination pairs, the method aims to optimize the set of paths between each pair at a minimal cost. The authors tested different scenarios and concluded that using a network approach could yield cost savings.

Mekuria, Furth, and Nixon (2012) developed a network measure based on the concept of minimizing cyclist stress during a bike trip. Every road segment is classified on a four-point scale (Level of Traffic Stress, LTS). LTS incorporates factors such as separation from motor vehicle traffic, number of lanes, width of the bike lane (with parking if applicable), speed limit, and bike lane blockage. LTS also incorporates intersection approaches (e.g. pocket bike lanes and right-turn lane characteristics) and the size and speed of signalized and unsignalized intersections. The method assumes that the stress of any route is determined by the worst, or most stressful, link of the entire route, and that some riders will not ride on links with higher levels of stress. This, therefore, limits the portion of a network available to a cyclist. Two measures of overall network connectivity are proposed: the percent of trips and the percent of nodes that are connected without exceeding a certain level of stress.

All four of these network measures allow planners to estimate the effects of making changes to the network (e.g. adding a bike lane) on overall bikeability. Limitations include difficulty in obtaining all of the data necessary (Callister & Lowry, 2013), though estimates or default assumptions can be used in some cases. Klobucar and Fricker (2007), Lowry et al. (2012), and Duthie and Unnikrishnan (2014) are all based upon a link-level measure that was developed using empirical data (BCI or BLOS), though the latter did not use empirical data to estimate costs. Intersection characteristics could be incorporated into these types of network measures if empirical data were available to estimate the value of intersection characteristics in a manner comparable to the link attributes. The BLOS from the HCM does have an intersection component, but it is not recommended for use at a network level (Lowry et al., 2012). While Mekuria et al. (2012) include intersection characteristics, the LTS measure was not developed using empirical data. It is loosely based upon a Dutch bicycle facility planning guide (CROW, 2007). Perhaps more importantly, we could not identify any peer-reviewed research that tests any of these four measures using empirical data, for example, linking the measures to actual levels of bicycling. Schoner and Levinson (2014) is the only study we found that uses a more complex measure of the bicycle network (multiple measures, in fact) to assess network effects on levels of cycling, though it uses aggregate data on commuting rather than individual-level data on all trip types.

Research Methods, Data Sources, Analysis Techniques, and Control Variables

The vast majority of peer-reviewed studies included here were from the USA, Canada, or Australia, where cycling levels are comparatively low. Only a few studies analyzed cities and countries with higher cycling levels in Western Europe (e.g. de Geus et al., 2008; Pucher & Buehler, 2008; Rietveld & Daniel, 2004; Snizek et al., 2013; Titze et al., 2008). This may reflect different stages of policy and infrastructure development. The need for empirical research to justify investment in new bicycle infrastructure appears to motivate some of the US research.

Most analyses relied on stated-preference surveys of cyclists and sometimes non-cyclists about their current cycling levels or their likelihood to cycle under various bicycle infrastructure scenario conditions (e.g. Akar & Clifton, 2009; Caulfield et al., 2012; Moritz, 1998; Stinson & Bhat, 2003; Winters & Teschke, 2010). An increasing number of studies employed revealed-preference techniques, often using GPS devices to track cyclists' routes, asking cyclists to indicate their routes on maps, or instructing cyclists to ride along predetermined routes to evaluate behavior (e.g. Broach et al., 2012; Dill, McNeil, et al., 2014; Menghini et al., 2010; Winters, et al., 2010).

Research on bikeways and networks relied on a mix of aggregate- and individual-level data. Aggregate-level analyses were either case studies of cities and countries or relied on (sub) samples of national data sources, such as travel surveys or censuses (e.g. Dill & Carr, 2003; Nelson & Allen, 1997; Pucher & Buehler, 2006; Schoner & Levinson, 2014). The majority of individual-level studies relied on statistically non-representative samples of avid cyclists, bike commuters, or members of university communities (e.g. Akar & Clifton, 2009; Broach et al., 2012; Stinson & Bhat, 2003; Tilahun et al., 2007). Participants were recruited via intercept surveys at bikeways or advertisements in newspapers, magazines, online, in bike shops, or during cycling events (e.g. Shafizadeh & Niemeier, 1997; Moritz, 1998). More recently, some studies employed random digit dialing and other techniques to recruit statistically representative samples (Dill, Mohr, et al., 2014; Vernez-Moudon et al., 2005). Most data for aggregate- and individual-level analyses were cross-sectional and evaluated cycling behavior or preferences at only one point in time. Only a few studies, often related to the installation of new bikeway facilities, tracked changes over time (e.g. Cohen et al., 2008; Dill, McNeil et al., 2014; Merom et al., 2003).

There are several case studies and a few historical accounts or discourse analyses about the relationship of bikeway supply and cycling (e.g. Buehler & Handy, 2008; Gossling, 2013; Pucher & Buehler, 2012). Analysis techniques for quantitative studies included simple *t*-test comparisons, analysis of variance, ordinary least square regression, structural equation modeling, or some form of limited dependent analysis — such as logistic or multinomial logistic regression — to estimate the likelihood to cycle or have a positive experience cycling (e.g. Chataway et al., 2014; Cleaveland & Douma, 2009; Krizek & Roland, 2005).

Measures for cycling levels vary across the studies. Many aggregate analyses define cycling levels as the percentage of trips or number of trips by bicycle (e.g. Caulfield et al., 2012; Dill & Carr, 2003; Schoner & Levinson, 2014). Some studies focus just on the commute trip or the usual main mode commuting to work, while others include all trip purposes. Alternative measures of cycling levels include distance cycled, duration of cycling, positive or negative experiences while cycling, and the likelihood to cycle (e.g. Chataway et al., 2014; Dill, McNeil et al., 2014; Snizek et al., 2013). The studies of intersections relied either on surveys of riders' perceptions (Dill et al., 2012; Monsere et al., 2014; Winters et al., 2010) or route choice modeling (e.g. Aultman-Hall et al., 1998 Broach et al., 2012; Menghini et al., 2010; Sener et al., 2009a).

Measures for links of the bicycling network vary across studies from simple nominal indicators for the availability of bikeways to exact measurement of length of bikeway supply along each segment of a city's bikeway or roadway network. Aggregate studies typically standardize bikeway supply by population or land area (e.g. Nelson & Allen, 1997). Length of bikeway supply is often measured as centerline miles of bikeways, not accounting for the difference between one-way vs. two-directional bike lanes, cycle tracks, or paths (e.g. Buehler & Pucher, 2012). Most of the aggregate studies of networks used similar measures, for example, miles of lanes per square mile, with one exception (Schoner & Levinson, 2014).

Most studies control for demographic or socio-economic characteristics of respondents or the population. Typical control variables include age, gender, income, education, car ownership, or employment status. Several studies also control for psychological factors, attitudes of respondents, or perceptions of the built environment. Control variables for the built environment were often measured with Geographic Information Systems drawing distance buffers around bikeways to measure population density, mix of land uses, employment or retail intensity, street type, distance to traffic lights or bus stops, street connectivity, terrain, design elements, or access to parks. Some studies also controlled for temperature, rain, day of the week, season, light conditions, peak/off peak traffic, fatality rates, gasoline prices, transit supply, or government spending on bikeways. Even controlling for these factors, most studies find a positive relationship between bicycle networks and cycling levels. However, some studies showed that control variables can moderate the strength of the relationship between bikeway networks and cycling. Some studies also specifically examine differences in effects by demographic or behavioral characteristics, such as gender or cycling experience.

Conclusions and Research Gaps

Research linking bikeway networks and cycling levels has increased significantly over the last 20 years — with the strongest growth since 2010. The research has evolved from the study of lanes and paths, to include analyses of the role of intersection treatments, and finally to studies that attempt to measure whole bike network — including both links and nodes of bikeway networks. While some studies rely on descriptive case studies, historical analysis, or discourse analysis, the vast majority of studies in this area use quantitative techniques to investigate the relationship between bikeway networks and cycling levels.

Most studies suggest a positive relationship between bikeway networks or aspects of the network and cycling levels. Stated- and revealed-preference studies suggest a hierarchy of cyclist and non-cyclist preferences may exist, favoring separate paths and/or lanes over cycling in roadways with motorized traffic — particularly with high volumes of fast-moving motorized traffic. Among bike facilities, cyclists and non-cyclists seem to prefer physically separated bike paths or cycle tracks to bike lanes or wide shoulders on roadways. When riding on roadways with motorized traffic, cyclists seem to prefer traffic-calmed residential neighborhood streets, lower car traffic volumes, slower car traffic speeds, and roadways without car parking. While this hierarchy of preferences was confirmed in surveys of cyclists in general and inexperienced or more risk-averse cyclists in particular, some experienced cyclists reported a preference for riding in traffic with cars over cycling on separate facilities. Revealed- and stated-route-choice studies indicate that intersections have negative effects on the cycling experience, but that certain characteristics can offset this, such as having a signal when motorized traffic volumes are high. A handful of studies indicate that cyclists value bicycle-specific traffic control devices at intersections, such as bike boxes, bike traffic signals, and bicycle signal activation. The limited empirical research on networks indicates the value of measuring networks, rather than just individual link characteristics.

In spite of an increase in studies and general agreement among findings, several important research gaps remain. Most of our recommendations are geared toward quantitative analysis, because this seems to be the current thrust of the field. Descriptive case studies, historical accounts, and discourse analysis provide excellent descriptions of policy packages, historical developments, and political processes, but — by their nature — cannot isolate the exact role of bikeway networks as determinants of cycling levels.

First, individual-level studies often relied on samples of volunteers, members of university communities, or avid cyclists. There were only a few individual-level studies based on statistically representative samples. We do not know to what extent sample selection and self-selection of avid cyclists into these studies distorts findings of quantitative analysis to date. However, studies relying on statistically representative samples of cyclists and the population are needed to help overcome some of these shortcomings. This will likely have to entail statistical oversampling of cyclists, because riding a bicycle is a rare event in many cities and countries. It may also require oversampling of some population groups with known low cycling levels, such as women or older adults.

Second, a majority of studies was from the USA or Canada where cycling levels are low, motorized traffic volumes are high, and bikeway networks are typically fragmented. Within the US, most of the studies were from Texas, Florida, Minnesota, or Oregon. The need for empirical research to justify investment in new bicycle infrastructure appears to motivate some of the US research. However, more quantitative studies are needed from cities and regions with complete bikeway networks, likely in European countries, to identify the impact of various aspects of the bicycle network. There is some indication that the effect of supply of additional bikeways may be diminishing once a basic level of bikeway supply is reached.

Third, almost all quantitative analysis reviewed here used cross-sectional data, analyzing correlations between bikeway supply and cycling levels at one point in time. Studies tracking cycling levels and trends in bikeway networks over time could move research toward providing a causal link between bikeway networks and cycling levels — instead of establishing a mere correlation. Additionally, many of the longitudinal studies of new infrastructure lack control or comparison sites. Longitudinal research designs need to include controls or other methods to assess the possible explanations for changes in observed ridership — existing bicyclists changing routes, regular bicyclists cycling more often, or people starting to bicycle who had not before. Longitudinal designs must also address an outstanding question of how long it takes after a new facility is built for people to change behavior, particularly getting people to start cycling. The limited research reviewed here indicates that one year may not be long enough to detect this type of behavior change.

Fourth, while descriptive case study analysis and historical accounts point toward the importance of policy packages in promoting cycling, quantitative studies typically fail to control for many of these policies geared at promoting cycling. Ideal studies would investigate the role of bikeways as determinants of cycling levels while controlling for promotional programs, cycling training, safety training for cyclists and motorists, bike-transit integration, enforcement of traffic laws, and the other control variables listed in the methods section above. These analyses could also control for policies that restrict car use and make it more expensive. It remains unclear to what extent bikeways entice individuals to cycle and to what degree car restrictive policies 'push' people to consider cycling as an option.

Fifth, only a few studies analyze the role of specific types or features of bikeway facilities or intersection treatments. For example, for links of the bikeway networks, there is a lack of studies identifying the role of the quality of the facility (e.g. pavement), exact design (e.g. color, width or type of separation), or specific location (e.g. left- or right-side positioning on one-way streets). New research could also explore the use of bollards vs. curbs for cycle tracks, one-way vs. two-way cycle tracks, contra-flow bike lanes in one-way streets for cars, shared bus and bicycle lanes, or sharrows. For intersection treatments there is little knowledge about the role of green waves — giving cyclists consecutive green lights at intersections to speed up bike trips.

Sixth, very few studies link ridership with newer (innovative) types of infrastructure, particularly intersection treatments. More research is needed on the effect of bicycle-specific treatments, including bike boxes, traffic signals, and two-stage queue boxes, and treatments where cycle tracks reach intersections (including the newly emerging concept of protected intersections), on perceptions and cycling levels. However, effects of these treatments on ridership likely need to be assessed in the context of the larger network. More studies are also needed on the effects of bicycle boulevards and other traffic-calming infrastructure.

Seventh, research measuring bikeway networks is still emerging, but shows promise. Using network measures can reveal whether the effect of the network is greater than the sum of its parts. Network measures need to incorporate features of both links and nodes. Several of the measures reviewed here are based on accessibility, which is a theoretically sound approach when considering bicycling for transportation. The research also revealed that one single measure might not capture all of a network's dimensions. Empirical research linking different measures of the network to cycling rates at the individual level are needed. Longitudinal studies, as networks evolve, would be particularly enlightening. Research on networks should also explore how the built environment moderates the effect of the bikeway network. This would include both the larger scale (e.g. land-use mix and access to destinations) and micro-scale (e.g. building scale and tree canopy).

Finally, research on bikeway networks would benefit from better and more systematic data collection on bikeway supply and cycling demand. Governments typically collect data about motorized traffic demand and roadway supply, but they rarely systematically gather data about cycling levels and the bikeway network. Standardization in the measurement and regular reporting of count and bikeway data (including standardized definitions of facilities) would help researchers track changes over time and compare across cities. Moreover, regular and systematic inclusion of bicycling in travel surveys and more systematic counts of cyclists would improve measurement of cycling demand.

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References

AASHTO. 2012. *Guide for the development of bicycle facilities* (4th ed.). Washington, DC: Association of State Highway and Transportation Officials.

Abraham, E., McMillan, S., Brownlee, A. T., & Hunt, D. (2002). *Investigation of cycling sensitivities*. Eighty-first transportation research board annual meeting, Washington, DC

Akar, G., & Clifton, K. J. (2009). Influence of individual perceptions and bicycle infrastructure on decision to bike. *Transportation Research Record: Journal of the Transportation Research Board, 2140*, 165–172. doi:10.3141/2140-18

Antonakos, C. (1994). Environmental and travel preferences of cyclists. *Transportation Research Record*, *1438*, 25–33.

Aultman-Hall, L., & Adams, M. F. (1998). Sidewalk bicycling safety issues. *Transportation Research Record: Bicycle and Pedestrian Research*, *1636*, 71–76.

Aultman-Hall, L., Hall, F. L., & Baetz, B. B. (1998). Analysis of bicycle commuter routes using geographic information systems: Implications for bicycle planning. *Transportation Research Record: Journal of the Transportation Research Board*, *1578*, 102–110. doi:10.3141/1578-13

Barnes, G., Thompson, K., & Krizek, K. J. (2006). *A longitudinal analysis of the effect of bicycle facilities on the commute share*. Eighty-fifth transportation research board annual meeting, Washington, DC.

Beenackers, M. A., Foster, S., Kamphuis, C. B. M., Titze, S., Divitini, M., Knuiman, M., Giles-Corti, B. (2012). Taking up cycling after residential relocation built environment factors. *American Journal of Preventive Medicine*, *42*(6), 610–615. doi:10.1016/j.amepre.2012.02.021

Broach, J., Dill, J., & Gliebe, J. (2012). Where do cyclists ride? A route choice model developed with revealed preference GPS data. *Transportation Research Part A: Policy and Practice*, *46*(10), 1730–1740. doi:10.1016/j.tra.2012.07.005

Buehler, R. (2012). Determinants of bicycle commuting in the Washington, DC region: The role of bicycle parking, cyclist showers, and free car parking at work. *Transportation Research Part D: Transport and Environment*, *17*(7), 525–531. doi:10.1016/j.trd.2012.06.003

Buehler, R., & Pucher, J. (2012). Cycling to work in 90 large American cities: New evidence on the role of bike paths and lanes. *Transportation*, *39*(2), 409–432. doi:10.1007/s11116-011-9355-8

Buehler, T., & Handy, S. (2008). Fifty years of bicycle policy in Davis, California. *Transportation Research Record*, *2074*, 52–57. doi:10.3141/2074-07

Callister, D., & Lowry, M. (2013). Tools and strategies for wide-Scale bicycle level-of-Service analysis. *Journal of Urban Planning and Development*, *139*(4), 250–257. doi:10.1061/(Asce)Up.1943-5444.0000159

Caulfield, B. (2014). Re-cycling a city - examining the growth of cycling in Dublin. *Transportation Research Part A: Policy and Practice*, *61*, 216–226. doi:10.1016/j.tra.2014.02.010

Caulfield, B., Brick, E., & McCarthy, O. T. (2012). Determining bicycle infrastructure preferences – A case study of Dublin. *Transportation Research Part D: Transport and Environment*, *17*(5), 413–417. doi:10.1016/j.trd.2012.04.001

Cervero, R., Sarmiento, O., Jacoby, E., Gomez, L., & Neiman, A. (2009). Influences of built environment on walking and cycling: Lessons from Bogota. *International Journal of Sustainable Transportation*, *3*(4), 203–226. doi:10.1080/15568310802178314

Chataway, E. S., Kaplan, S., Nielsen, T. A. S., & Prato, C. G. (2014). Safety perceptions and reported behavior related to cycling in mixed traffic: A comparison between Brisbane and Copenhagen. *Transportation Research Part F: Traffic Psychology and Behaviour*, *23*, 32–43. doi:10.1016/j.trf.2013.12.021

Cleaveland, F., & Douma, F. (2009). *The impact of bicycling facilities on commute mode share*. Eighty-eighth Transportation Research Board Annual Meeting. Washington, DC.

Cohen, D., Sehgal, A., & Williamson, S. (2008). Impact of new bicycle path on physical activity. *Preventive Medicine*, *46*, 80–81. doi:10.1016/j.ypmed.2007.07.022

CROW. (2007). *Design manual for bicycle traffic*. Utrecht: Author.

Deka, D., & Connelly, M. (2011). Does proximity to activity-inducing facilities explain lower rates of physical activity by low-income and minority populations? *Transportation Research Record*, *2264*, 83–91. doi:10.3141/2264-10

Dill, J. (2009). Bicycling for transportation and health: The role of infrastructure. *Journal of Public Health Policy*, *30*, S95–S110. doi:10.1057/jphp.2008.56

Dill, J., & Carr, T. (2003). Bicycle commuting and facilities in major U.S. cities: If you build them, commuters will use them. *Transportation Research Record: Journal of the Transportation Research Board*, *1828*, 116–123.

Dill, J., McNeil, N., Broach, J., & Ma, L. (2014). Bicycle boulevards and changes in physical activity and active transportation: Findings from a natural experiment. *Preventive Medicine*, *69*, S74–S78. doi:10.1016/j.ypmed.2014.10.006

Dill, J., Mohr, C., & Ma, L. (2014). How can psychological theory help cities increase walking and bicycling? *Journal of the American Planning Association*, *80*(1), 36–51. doi:10.1080/01944363.2014.934651

Dill, J., Monsere, C. M., & McNeil, N. (2012). Evaluation of bike boxes at signalized intersections. *Accident Analysis and Prevention*, *44*(1), 126–134. doi:10.1016/j.aap.2010.10.030

Dill, J., & Voros, K. (2007). Factors affecting bicycling demand: Initial survey findings from the Portland, Oregon Region. *Transportation Research Record: Journal of the Transportation Research Board*, *2031*, 9–17. doi:10.3141/2031-02

Duthie, J., & Unnikrishnan, A. (2014). Optimization framework for bicycle network design. *Journal of Transportation Engineering*, *140*(7). Retrieved from http://ascelibrary.org/doi/abs/10.1061/(ASCE)TE.1943-5436.0000690

Evenson, K. R., Herring, A. H., & Houston, S. L. (2005). Evaluating change in physical activity with the building of a multi-use trail. *American Journal of Preventive Medicine*, *28*, 177–185. doi:10.1016/j.amepre.2004.10.020

FGSV. (2010). *Design for bicycle infrastructure*. Cologne: German Association for Road and Transport Science.

Fishman, E., Washington, S., Haworth, N., & Watson, A. (2015). Factors influencing bike share membership: An analysis of Melbourne and Brisbane. *Transportation Research Part A*, *71*, 17–30.

Fraser, S. D. S., & Lock, K. (2011). Cycling for transport and public health: A systematic review of the effect of the environment on cycling. *The European Journal of Public Health*, *21*(6), 738–743. doi:10.1093/eurpub/ckq145

Furth, P. (2012). Bicycling infrastructure for mass cycling. In J. Pucher & R. Buehler (Eds.), *City cycling* (pp. 105–140). Cambridge, MA: MIT Press.

Garder, P., Leden, L., & Pulkkinen, U. (1998). Measuring the safety effect of raised bicycle crossings using a new research methodology. *Transportation Research Record: Journal of the Transportation Research Board*, *1636*, 64–70. doi:10.3141/1636-10

Garrard, J., Rose, G., & Lo, S. K. (2008). Promoting transportation cycling for women: The role of bicycle infrastructure. *Preventive Medicine*, *46*(1), 55–59. doi:10.1016/j.ypmed.2007.07.010

de Geus, B., de Bourdeaudhuij, I., Jannes, C., & Meeusen, R. (2008). Psychosocial and environmental factors associated with cycling for transport among a working population. *Health Education Research*, *23*, 697–708. doi:10.1093/her/cym055

Goodno, M., McNeil, N., Parks, J., & Dock, S. (2013). Evaluation of innovative bicycle facilities in Washington, DC Pennsylvania avenue median lanes and 15th street cycle track. *Transportation Research Record: Journal of the Transportation Research Board*, *2387*, 139–148. doi:10.3141/2387-16

Gossling, S. (2013). Urban transport transitions: Copenhagen, city of cyclists. *Journal of Transport Geography*, *33*, 196–206. doi:10.1016/j.jtrangeo.2013.10.013

Handy, S., van Wee, B., & Kroesen, M. (2014). Promoting cycling for transport: Research needs and challenges. *Transport Reviews*, *34*(1), 4–24. doi:10.1080/01441647.2013.860204

Harkey, D. L., Reinfurt, D. W., & Knuiman, M. (1998). Development of the bicycle compatibility index. *Transportation Research Record: Journal of the Transportation Research Board*, *1636*, 13–20. doi:10.3141/1636-03

Heinen, E., van Wee, B., & Maat, K. (2010). Commuting by bicycle: An overview of the literature. *Transport Reviews*, *30*(1), 59–96. doi:10.1080/01441640903187001

Howard, C., & Burns, E. K. (2001). *Cycling to work in phoenix – route choice, travel behavior, and commuter characteristics 2001 trb distinguished lecture, pt 1 – bicycle and pedestrian research, pt 2: safety and human performance*. pp. 39–46.

Jackson, M., & Ruehr, E. (1998). Let the people be heard: San Diego county bicycle use and attitude survey. *Transportation Research Record: Journal of the Transportation Research Board*, *1636*, 8–12. doi:10.3141/1636-02

Kang, L., & Fricker, J. D. (2013). Bicyclist commuters' choice of on-street versus off-street route segments. *Transportation*, *40*(5), 887–902. doi:10.1007/s11116-013-9453-x

Klobucar, M. S., & Fricker, J. D. (2007). Network evaluation tool to improve real and perceived bicycle safety. *Transportation Research Record: Journal of the Transportation Research Board*, *2031*, 25–33. doi:10.3141/2031-04

Krizek, K. J., & Roland, R. W. (2005). What is at the end of the road? – Understanding discontinuities of on-street bicycle lanes in urban settings. *Transportation Research Part D: Transport and Environment*, *10*(1), 55–68. doi:10.1016/j.trd.2004.09.005

Landis, B., Vattikuti, V., & Brannick, M. (1998). Real-Time human perceptions: Towards a bicycle level of service. *Transportation Research Record: Journal of the Transportation Research Board*, *1578*, 119–126. doi:10.3141/1578-15

Li, Z. B., Wang, W., Liu, P., Schneider, R., & Ragland, D. R. (2012). Investigating bicyclists' perception of comfort on physically separated bicycle paths in Nanjing, China. *Transportation Research Record*, *2317*, 76–84. doi:10.3141/2317-10

Loskorn, J., Mills, A. F., Brady, J. F., Duthie, J. C., & Machemehl, R. B. (2013). Effects of bicycle boxes on bicyclist and motorist behavior at intersections in Austin, Texas. *Journal of Transportation Engineering*, *139*(10), 1039–1046. doi:10.1061/(asce)te.1943-5436.0000584

Lowry, M. B., Callister, D., Gresham, M., & Moore, B. (2012). Assessment of communitywide bikeability with bicycle level of service. *Transportation Research Record: Journal of the Transportation Research Board*, *2314*, 41–48. doi:10.3141/2314-06

Lusk, A. C., Furth, P. G., Morency, P., Miranda-Moreno, L. F., Willett, W. C., & Dennerlein, J. T. (2011). Risk of injury for bicycling on cycle tracks versus in the street. *Injury Prevention, Brief Report*, *17*, 131–135. doi:10.1136/ip.2010.028696

Mekuria, M. C., Furth, P. G., & Nixon, H. (2012). *Low-Stress bicycling and network connectivity*. San Jose, CA: Mineta Transportation Institute.

Melson, C. L., Duthie, J. C., & Boyles, S. D. (2013). Influence of bridge facility attributes on bicycle travel behavior. *ITE Journal*, *83*(10), 36–41.
Menghini, G., Carrasco, N., Schussler, N., & Axhausen, K. W. (2010). Route choice of cyclists in Zurich. *Transportation Research Part A: Policy and Practice*, *44*(9), 754–765. doi:10.1016/j.tra.2010.07.008
Merom, D., Bauman, A., Vita, P., & Close, G. (2003). An environmental intervention to promote walking and cycling - The impact of a newly constructed rail trail in Western Sydney. *Preventive Medicine*, *36*(2), 235–242. doi:10.1016/S0091-7435(02)00025-7
Monsere, C., Dill, J., McNeil, N., Clifton, K., Foster, N., Goddard, T., Parks, J. (2014). *Lessons from the green lanes: Evaluating protected bike lanes in the U.S*. Retrieved from http://ppms.otrec.us/media/project_files/NITC-RR-583_ProtectedLanes_FinalReport.pdf
Monsere, C., Figliozzi, M., Thompson, S., & Paulsen, K. (2013). *Operational guidance for bicycle-specific traffic signals in the United States*. Portland, OR: Oregon department of transportation and Oregon transportation research and education consortium. Retrieved from http://ppms.otrec.us/media/project_files/Final_Report_Operational_Guidance_For_Bicycle_Specific_Traffic_Signals_1.pdf
Monsere, C. M., McNeil, N., & Dill, J. (2012). Multiuser perspectives on separated, on-Street bicycle infrastructure. *Transportation Research Record: Journal of the Transportation Research Board*, *2314*, 22–30. doi:10.3141/2314-04
Moritz, W. E. (1998). Adult bicyclists in the United States – Characteristics and riding experience in 1996. *Transportation Research Record: Bicycle and Pedestrian Research*, *1578*, 1–7.
NACTO. (2014). *Urban bikeway design guide* (2nd ed.). Washington, DC: National Association of City Transportation Officials.
Nelson, A., & Allen, D. (1997). If you build them, commuters will use them: Association between bicycle facilities and bicycle commuting. *Transportation Research Record*, *1578*, 79–83. doi:10.3141/1578-10
Ortuzar, J. D., Iacobelli, A., & Valeze, C. (2000). Estimating demand for a cycle-way network. *Transportation Research Part A: Policy and Practice*, *34*(5), 353–373. doi:10.1016/s0965-8564(99)00040-3
Parkin, J., Wardman, M., & Page, M. (2008). Estimation of the determinants of bicycle mode share for the journey to work using census data. *Transportation*, *35*, 93–109. doi:10.1007/s11116-007-9137-5
Pucher, J., & Buehler, R. (2006). Why Canadians cycle more than Americans: A comparative analysis of bicycling trends and policies. *Transport Policy*, *13*(1), 265–279.
Pucher, J., & Buehler, R. (2007). Sustainable transport in Canadian cities: Cycling trends and policies. *Berkeley Planning Journal*, *19*, 97–123.
Pucher, J., & Buehler, R. (2008). Making cycling irresistible: Lessons from the Netherlands, Denmark, and Germany. *Transport Reviews*, *28*(1), 495–528. doi:10.1080/01441640701806612
Pucher, J., & Buehler, R. (Eds.). (2012). *City cycling*. Cambridge, MA: MIT Press.
Pucher, J., Dill, J., & Handy, S. (2010). Infrastructure, programs, and policies to increase bicycling: An international review. *Preventive Medicine*, *50*(Suppl. 1), S106–125. doi:S0091-7435(09)00434-4 [pii] 10.1016/j.ypmed.2009.07.028
Pucher, J., Komanoff, C., & Schimek, P. (1999). Bicycling renaissance in North America? Recent trends and alternative policies to promote bicycling. *Transportation Research Part A: Policy and Practice*, *33*(7–8), 625–654. doi:10.1016/s0965-8564(99)00010-5
Rietveld, P., & Daniel, V. (2004). Determinants of bicycle use: Do municipal policies matter? *Transportation Research Part A: Policy and Practice*, *38*(7), 531–550.
Sanders, R. L., & Cooper, J. F. (2013). Do all roadway users want the same things? Results from roadway design survey of San Francisco bay area pedestrians, drivers, bicyclists, and transit users. *Transportation Research Record: Journal of the Transportation Research Board*, *2393*, 155–163. doi:10.3141/2393-18
Schoner, J. E., & Levinson, D. M. (2014). The missing link: Bicycle infrastructure networks and ridership in 74 US cities. *Transportation*, *41*(6), 1187–1204. doi:10.1007/s11116-014-9538-1
Sener, I. N., Eluru, N., & Bhat, C. R. (2009a). An analysis of bicycle route choice preferences in Texas, US. *Transportation*, *36*(5), 511–539. doi:10.1007/s11116-009-9201-4
Sener, I. N., Eluru, N., & Bhat, C. R. (2009b). Who are bicyclists? Why and how much are they bicycling? *Transportation Research Record: Journal of the Transportation Research Board*, *2134*, 63–72. doi:10.3141/2134-08
Shafizadeh, K., & Niemeier, D. (1997). Bicycle journey-to-work: Travel behavior characteristics and spatial analysis. *Transportation Research Record: Journal of the Transportation Research Record*, *1578*, 84–90. doi:10.3141/1578-11
Snizek, B., Nielsen, T. A. S., & Skov-Petersen, H. (2013). Mapping bicyclists' experiences in Copenhagen. *Journal of Transport Geography*, *30*, 227–233. doi:10.1016/j.jtrangeo.2013.02.001

Srisurapanon, V., Tangtrongchit, M. P., Ard-Onk, K., Limsuttiruch, P., Kiatpanachart, K., & Luengsirinapha, P. (2003). Potential network for the improvement of bikeway in Bangkok. In K. Satoh (Ed.), *Proceedings of the Eastern Asia Society for Transportation Studies,* (Vol. 4, Nos. 1 and 2, pp. 1797–1807). Tokyo: Eastern Asia Society for Transportation Studies. Retrieved from http://www.easts.info/2003proceedings/papers/1797.pdf

Stinson, M. A., & Bhat, C. R. (2003). Commuter bicyclist route choice analysis using a stated preference survey. *Transportation Research Record*, *1828*, 107–115. doi:10.3141/1828-13

Stinson, M. A., & Bhat, C. R. (2004). Frequency of bicycle commuting: Internet-Based survey analysis. *Transportation Research Record: Journal of the Transportation Research Board*, *1878*, 122–130. doi:10.3141/1878-15

Taylor, D., & Mahmassani, H. (1996). Analysis of state preferences for intermodal bicycle-Transit interfaces. *Transportation Research Record: Journal of the Transportation Research Board*, *1556*, 86–95. doi:10.3141/1556-11

Tilahun, N. Y., Levinson, D. M., & Krizek, K. J. (2007). Trails, lanes, or traffic: Valuing bicycle facilities with an adaptive stated preference survey. *Transportation Research Part A: Policy and Practice*, *41*(4), 287–301. doi:10.1016/j.tra.2006.09.007

Titze, S., Stronegger, W. J., Janschitz, S., & Oja, P. (2008). Association of built-environment, social-environment and personal factors with bicycling as a mode of transportation among Austrian city dwellers. *Preventive Medicine*, *47*(3), 252–259. doi:S0091-7435(08)00106-0 [pii] 10.1016/j.ypmed.2008.02.019

U.S. Department of Transportation. (2014). *Safer people, safer streets: Summary of U.S. department of transportation action plan to increase walking and biking and reduce pedestrian and bicyclist fatalities*. Retrieved November 11, 2014, from http://www.dot.gov/sites/dot.gov/files/docs/safer_people_safer_streets_summary_doc_acc_v1–11–9.pdf

Vernez-Moudon, A. V., Lee, C., Cheadle, A. D., Collier, C. W., Johnson, D., Schmid, T. L., & Weather, R. D. (2005). Cycling and the built environment, a US perspective. *Transportation Research Part D: Transport and Environment*, *10*(3), 245–261. doi:10.1016/j.trd.2005.04.001

Wardman, M., Tight, M., & Page, M. (2007). Factors influencing the propensity to cycle to work. *Transportation Research A*, *41*, 339–350.

Wendel-Vos, W., Droomers, M., Kremers, S., Brug, J., & van Lenthe, F. (2007). Potential environmental determinants of physical activity in adults: A systematic review. *Obesity Reviews*, *8*(5), 425–440. doi:10.1111/j.1467-789X.2007.00370.x

Winters, M., Davidson, G., Kao, D. N., & Teschke, K. (2011). Motivators and deterrents of bicycling: Comparing influences on decisions to ride. *Transportation*, *38*(1), 153–168. doi:10.1007/s11116-010-9284-y

Winters, M., & Teschke, K. (2010). Route preferences among adults in the near market for bicycling: Findings of the cycling in cities study. *American Journal of Health Promotion*, *25*(1), 40–47. doi:10.4278/ajhp.081006-QUAN-236

Winters, M., Teschke, K., Grant, M., Setton, E. M., & Brauer, M. (2010). How far out of the way will we travel? Built environment influences on route selection for bicycle and car travel. *Transportation Research Record: Journal of the Transportation Research Board*, *2190*, 1–10. doi:10.3141/2190-01