Transportation Research Interdisciplinary Perspectives 14 (2022) 100604

Contents lists available at ScienceDirect

Transportation Research Interdisciplinary Perspectives

journal homepage: www.sciencedirect.com/journal/transportation-research-interdisciplinary-perspectives

Active transportation pilot program evaluation: A longitudinal assessment of bicycle facility density changes on use in Minneapolis

Billy Fields [a,*], Angie L. Cradock [b], Jessica L. Barrett [b], Tony Hull [c], Steven J. Melly [d]

[a] Department of Political Science, Texas State University, San Marcos, TX, United States
[b] Department of Social and Behavioral Sciences, Harvard T.H. Chan School of Public Health, Boston, MA, United States
[c] Active Transportation Consultant Minneapolis, MN, United States
[d] Urban Health Collaborative, Dornsife School of Public Health, Drexel University, Philadelphia, PA, United States

ARTICLE INFO

Keywords:
Active transportation
Bicycling
Physical activity
Nonmotorized Transportation Pilot Program

ABSTRACT

Cities around the world are adding bicycle facilities to enhance physically active travel to improve sustainable transport and public health outcomes. One of the most promising policy interventions is the use of targeted pilot programs that aim to build connected networks of bicycle facilities to increase bicycle use. In the United States, the federal Nonmotorized Transportation Pilot Program (NTPP) provided approximately $25 million to four communities (Columbia, MO, Marin County, CA, Minneapolis, MN, and Sheboygan County, WI) to test the impact of building a full network of bicycle facilities. This study examines the impact of the NTPP in Minneapolis to determine whether the addition of bicycle facilities and increased density of bicycle facilities are related to increased bicycle ridership over time. Secondarily, the study examines the impact of differing facility types (protected facilities like trails vs. non-protected facilities like on-street bike lanes) on bicycle use. The study finds that both the presence of and density of bicycle facilities emerged as significant independent predictors of bicycle counts and growth in counts over time. Compared to locations with no facility, sites with protected facilities had 113 more cyclists during the evening peak 2-hour count period (95% CI 16.19, 209.99; $p = 0.02$) and a greater rate of increase in cyclist counts over time. Over the study period, counts increased by 69% at locations with protected bikeways, by 26% at locations with on-street bike lanes, and by 10% at locations with no on-site facility.

Introduction

Cities around the world are adding bicycle facilities to streets to enhance physically active travel to improve sustainable transport and public health outcomes. Physical inactivity is a major public health concern due to its association with disease and premature mortality (Lee et al., 2012). International recommendations from the World Health Organization call for creating active environments with improved walking and bicycling infrastructure as part of a global action plan on physical activity (World Health Organization, 2018). From the transportation perspective, bicycle infrastructure can help to expand low-carbon transportation options (Replogle and Fulton, 2014, Tayarani et al., 2018), improve safety outcomes (Pucher and Buehler 2016, Pedroso et al., 2016), and link communities to local jobs and services (C40 Cities 2020).

To promote bicycle transportation options, cities have undertaken policy interventions designed to improve the network of dedicated cycling facilities including on-street bicycle lanes and protected trails and cycle tracks. Cross-sectional studies suggest that higher concentrations of bicycling facilities linked to a community bicycle transportation network are associated with increased numbers of bicyclists (Aldred et al., 2019, Mertens et al., 2017, Pedroso et al., 2016, Pucher et al., 2010). However, few longitudinal evaluations of the impact of bicycle infrastructure and networks on bicycling have been conducted at a community level (Winters et al., 2018, Krizek et al., 2009, Parker et al., 2013, Goodman et al., 2014, Fields et al., 2014). Schoner and Levinson (2014) analyze the impact of bicycle network factors on Census derived bicycle mode shares. The study finds that bicycle connectivity and facility density are key factors in spurring increased bicycle mode shares. While close proximity to new walking and cycling facilities appears to

* Corresponding author at: Department of Political Science, Texas State University, 601 University Drive, Undergraduate Academic Center 355, San Marcos, TX 78666-4684, United States.
E-mail address: wf16@txstate.edu (B. Fields).

https://doi.org/10.1016/j.trip.2022.100604
Received 14 January 2022; Received in revised form 8 April 2022; Accepted 13 April 2022
Available online 5 May 2022

increase overall physical activity levels (Aldred et al., 2019, Kärmeniemi et al., 2018, Fields et al., 2014), there is limited longitudinal research on the impact of connecting networks of facilities on increased ridership or whether change over time in bicycling use varies according to specific facility type.

This case study uses a longitudinal, repeated measures natural experimental design to examine the impact of local improvements in bicycle facilities on changes in bicycle counts over time in Minneapolis from 2007 to 2013. The growth of the bicycle network in Minneapolis was sparked by significant investments in the Nonmotorized Transportation Pilot Program (NTPP) which provided approximately $25 million of federal funding for active transportation infrastructure (FHWA 2012). The infrastructure investments of the NTPP provide a unique opportunity to study the impact of a community-level investment in active transportation over a relatively short time (2007–2013) and provide lessons on the potential of transportation pilot programs to connect bicycle facilities and stimulate physically active transport. This paper begins with an overview of active transport pilot programs and situates the NTPP and the Minneapolis case within this context. This is followed by a detailed analysis of the impact of bicycle facility changes on bicycle use patterns in Minneapolis. The study takes advantage of one of the largest bicycle count programs in North America to link infrastructure changes to bicycle use patterns via systematic longitudinal counts of cyclists. The paper concludes with a discussion on the potential of urban transportation pilot programs to enhance bicycle facility systems and physically active travel.

Transportation pilot programs: Mainstreaming transformation

Transportation pilot programs and temporary "pop-up" projects have become increasingly utilized policy tools to accelerate the growth of walking and bicycling networks (NACTO 2013, Sadik-Khan and Solomonow 2017). In the immediate months following the onset of the COVID-19 pandemic, for example, over 100 cities around the world constructed experimental bicycle and pedestrian networks to help address the need for safe transportation options (NACTO 2020). Buehler and Pucher (2021) track the continued development of bicycle facilities during the pandemic and find that 32 of 42 large European cities and 102 of 200 US surveyed cities expanded bicycling facilities during the pandemic. Combs and Pardo (2021) created and examined an open-source database of interventions from 524 cities around the world. Analysis of the database finds that the most commonly used intervention strategy by cities around the world was reallocation of street space for walking and cycling. This was used by 13% of cities that implemented street change policies during the pandemic. Kraus and Koch analyzed the impact of pop-up lanes in 106 European cities and find an increase of cycling of 41.6% in treatment corridors (Kraus and Koch 2021). While this current wave of interventions shows the urgency of responding to the present crisis, a lengthy history of innovative active transportation pilot programs dates back to the 1970s.

The first significant active transportation pilot program was in the Netherlands in the late 1970s. The Netherlands program with targeted demonstration projects in Tilburg and Den Haag and a network bicycle plan for Delft represented "a paradigm shift in thinking about traffic" (van Goeverden and Godefrooij 2011, p. 1) with a movement away from purely auto-oriented planning and a renewed focus on active transportation safety. Van Goeverden and Godefrooij (2011, p. 85) point out that the key principles of Dutch bicycle planning that are now seen as best practice standards of bicycle networks, "coherence, directness, attractiveness, safety, and comfort," were piloted through the Delft bicycle planning process and are now embedded in the Dutch transportation planning systems. This suggests that pilots are often a way to build new administrative processes that can change underlying transportation practices.

While the Dutch pilot projects helped to build new standards for bicycle planning, the impact on overall bicycle use in Delft in the short-term varied with the geographic scale of analysis utilized to evaluate the policy. In a synthesis of research on the Delft pilot, van Goeverden et. al. (2015, p. 408) find that the growth in cyclists is "large along the improved route, is at the most moderate in the corridor, and is only small in the whole city." This finding suggests that even in successful pilot projects initial research is unlikely to identify population-wide change in the short-term and more likely to identify changes in use along the route and network level where physical infrastructure changes are taking place.

The emerging best practices generated through the Dutch pilot experience and a similar pilot program in Denmark (van Goeverden et. al. 2015, p. 404) have influenced a new wave of active transportation pilot programs. Canada, for example, created the Urban Transportation Showcase pilot program in 2006 (Buehler and Pucher 2012). In the U.K., London experimented with the mini-Holland program where three outlying boroughs (Enfield, Kingston, and Waltham Forest) shared £90 million to make "these boroughs as cycle-friendly as their Dutch equivalents – where more than 50% of journeys are made by cycle in some cities" (Department for Transport UK 2020). This program has since been wrapped into the larger London Healthy Streets Approach (Balderson, 2018).

In an analysis of the impact of the initial mini-Holland program during the first year of the program, Aldred et al. (2019) found that residents of "high dose" areas that received significant infrastructure investment participated in an additional 41 min of physically active travel per week and were 24% more likely to have cycled during the week than residents outside of the mini-Hollands area. Overall, Aldred et al. (2019) echo the findings of van Goeverden et al. (2015) about the importance of improved infrastructure and connection to bicycle networks. Aldred et. al. (2019, p. 158) point out that, "Area-based interventions incorporating cycle routes and neighbourhood traffic reduction may be particularly good at encouraging active travel more broadly, compared to cycle routes alone.".

The Nonmotorized Transportation Pilot Program (NTPP) in the United States fits within this lineage of active transportation pilot programs. The NTPP was established through the 2005 U.S. federal transportation bill SAFETEA-LU (FHWA 2012).· The purpose of the program laid out in the authorizing legislation was "to demonstrate the extent to which bicycling and walking can carry a significant part of the transportation load, and represent a major portion of the transportation solution, within selected communities" (FHWA 2012). To accomplish this task, funding was allocated to create "a network of nonmotorized transportation infrastructure facilities, including sidewalks, bicycle lanes, and pedestrian and bicycle trails, that connect directly with transit stations, schools, residences, businesses, recreation areas, and other community activity centers" (FHWA 2012).The NTPP provided approximately $25 million to four cities/counties (Columbia, MO, Marin County, CA, Minneapolis, MN, and Sheboygan County, WI) to help build this connected active transportation system.

In a systematic review of the pilot communities, Götschi et al. (2011) conducted before and after community wide surveys and did not find statistically significant change in walking and bicycling rates. The authors point out the relatively short time span of the interventions, complexities of community level surveys, and the targeted nature of the infrastructure interventions as key methodological hurdles. Overall, community-level measurement is a difficult means of detecting changes that may be occurring around the more localized, neighborhood infrastructure treatments. Götschi et. al. (2011, p. 16) conclude that "effects of the local projects become diluted across the population samples, which makes them difficult to detect." These results match previous research findings of pilot programs in the Netherlands (van Goeverden et al., 2015).

While the community level surveys were unable to detect changing rates of walking and cycling in the pilot communities, Lyons et al. (2014) analyzed more targeted outcome measurements of the NTPP. The authors found that the walking mode share increased by 15.8% and the bicycling mode share increased by 44% over the pilot period. In terms of access to bicycling networks, Lyons et. al. (2014, p. v) found that the NTPP "expanded 1/4-mile bicycle network access to approximately 240,000 people, 106,000 housing units, and 102,000 jobs." In Minneapolis specifically, Lyons et al. (2014) found that 1/4-mile access to the bicycle network increased from 32% to 48% for the entire city population.

While Lyons et al. (2014) was able to quantify changes to access to the network, the research did not analyze potential increases in overall connectivity and density of the bicycle network. This is a potentially important area of research as Lyons et. al. (2014, p. 52) note that a more systematic analysis of "connectivity benefits would create a fuller understanding of the program's achievements.".

The Minneapolis pilot provides a unique opportunity to estimate the longitudinal impact of changes in bicycling attributed to the development and implementation of a network of bicycle facilities. The Minneapolis pilot focused on linking the extensive pre-existing set of protected trails with new on-road connections to create a connected network of bicycle facilities (Lyons et al., 2014, Fields and Hull 2013). Over 76 miles of new facilities were added between 2007 and 2013 via NTPP and other funding sources. The result was a 59% increase in the overall bicycle facility length. Just under 10% of these new facilities (7 miles) were protected facilities with a buffer between cyclists and road traffic. In addition, dedicated resources were also provided for planning and program projects.

Overall, the literature on pilot measurement suggests bicycle use change at the community level will be difficult to quantify in a short-term evaluation (van Goeverden et al., 2015, Aldred et al., 2019, Götschi et al., 2011). This research suggests that proximity to and density of new bicycle facilities and how these facilities may help to create networks (Lyons et al., 2014) are the driving forces behind bicycle use change. With this research in mind, the primary objective of this study is to identify whether the addition of bicycle facilities and increased density of bicycle facilities surrounding count locations in Minneapolis during the pilot program are related to increased bicycle ridership over time. Secondarily, we examined whether potential growth in ridership differed by facility type (protected facilities like trails vs. non-protected facilities like on-street bike lanes).

Study design and sample

Count data on the number of observed bicycle riders were collected annually at multiple locations in the city of Minneapolis between 2007 and 2013 by BikeWalk Twin Cities (the program name of the Minneapolis pilot program operated by the non-profit Transit for Livable Communities). The time period analyzed (2007 to 2013) represents the core period of pilot program facility expansion and roughly corresponds to the period under review by the US Congress. The final report to Congress evaluating the impact of the Pilot program was released in 2012 (Lyons et al., 2012). Based on established protocols (Alta Planning and Design and Institute of Transportation Engineers 2010), trained data collectors conducted manual screen-line bicycle counts between 4 and 6 pm on weekdays in September (BikeWalk Twin Cities 2011). To measure change over time, the present study utilized the BikeWalk Twin Cities count database and focused on core area locations where at least 3 years of data were available during the years 2007 to 2013. In total, 39 locations across the city with 254 unique observations were included in the study dataset. Of these locations, 22 had seven years of annual count observation, 15 had six years of count observation, and 2 had five years of count observation during the study period.

Measures

The primary outcome measure is the number of bicyclists observed during the evening commute period via manual counts at each location. While robust and extensive electronic count data would be optimal, manual peak count data provide a useful platform for analysis of overall patterns of daily active transportation use and can provide a foundation for understanding active transportation traffic patterns over time (Hankey et al., 2012). Studies suggest that manual peak count data taken during rush hour provide a reliable measure of corridor-level bicycling behavior (Parker et al., 2013, Ryan et. al. 2014), with noted variations in manual count data due to weather and other micro-level site characteristics (Nordback et al., 2013).

We hypothesized that both the presence of a bicycle facility at the count location *and* the density of bicycle facilities around the count location would contribute to the amount of bicycle travel documented at a given location over time. We used available programmatic data and Geographic Information Systems (GIS) data to document the presence, type, and location of bicycle facilities existing at the count site and within a one-half mile radius of count locations annually between 2007 and 2013. Facilities at the count site and facility improvements in buffers were categorized as protected bikeways (trails or other facilities that are physically separated from motor vehicle traffic) or on-street bicycle facilities like bike lanes. Cycle-tracks, a growing form of protected bicycle facility, were not widely implemented during the study period. The local bicycle facility density was characterized by the length (in linear miles) of bicycle facilities added since 2007 (the start of the study data) within a half-mile circular buffer of each count location. Similarly, we calculated residential road length within the buffer at each location to approximate the street network density, based on 2013 TIGER/Line geographic data from the U.S. Census Bureau (U.S. Census Bureau 2013).

Because daily variations in weather have documented impact on ridership (Hankey et al., 2012), other model covariates including the average daily temperature (degrees Fahrenheit) and precipitation (inches of rainfall on the day of and the day before a count) which were obtained from the National Oceanic and Atmospheric Administration (2015).

Statistical analysis

Capitalizing on the annual repeated assessments of rush hour peak counts collected longitudinally within sites over time, we estimated linear individual growth models to examine whether several factors were associated with different levels or rates of change in bicycle counts during the study period. Individual growth models allow the investigator to estimate the impact of variables that are associated with the growth in ridership (or lack of growth), over time, at a given count location and to estimate the impact on growth that may be attributable to observed changes that happened during the study period (Singer et al., 2003). The approach also allows researchers to estimate impacts of the intervention that is variable over time. Individual growth model analysis is a powerful technique for this application because it minimizes the potential for bias due to unobserved time-stable characteristics of count locations (Singer et al., 2003) that are often associated with bicycling patterns in cross-sectional studies (Hankey et al., 2012, Buehler and Pucher 2012, Krizek and Johnson 2006).

Using a minimum of three years of observed counts per location, we examined differences in the rate of change over time (i.e., growth) in counts between locations, both with and without adjustment for other variables. We then estimated subsequent models to examine any differential trends in growth of cycling over time by the category of bicycle facility type controlling for daily temperature and precipitation.

Model 1 was a growth model adjusting for temperature and precipitation only. Model 2 added indicator variables for two count-location on-site bicycle facility type categories (i.e., protected bikeway, on-street bike lane; vs. no facility) and their interaction with time, and a variable (i.e., time after improvement) to estimate how changing the count location on-site facility may change the rate of growth over time in cycling. Model 3 also included a variable to estimate the impact of the total length of bicycle facility density added controlling for the length of residential road (miles) within the buffer as an indicator of the potential length along which a bicyclist could ride using bicycle-specific facilities accounting for the length of all the streets in the buffers. Model 4 separated the length of added bicycle facilities (miles) in the buffer by type (protected bikeway, on-street bike lane or shared lane) to look at whether the added facility density length's impact on the growth of cycling at a count location varied by the types of facilities added within the local system. Model fit statistics were assessed to determine the additional variation in the peak count outcome explained by variables of interest added over the previous model. A statistical significance level of $p < 0.05$ was used and all analyses were performed using SAS version 9.4 (SAS Institute, Inc., Cary, NC).

Results

Table 1 depicts descriptive characteristics of the count locations, including the average annual bicycle counts and bicycle facilities on-site and added in the adjacent half-mile buffer each year. In 2007, 23 (59%) locations had on-site facilities – 11 had protected bikeways and 12 had on-street bicycle lanes (not shown). Eleven of the 39 count locations received on-site facility improvements between 2008 and 2012. As noted previously, 76 total miles of bicycle facilities were added within the City of Minneapolis between 2007 and 2013. Seven of the miles added were protected bikeways (six miles of trails and one mile of on-street protected bikeway), while the remainder were on-street bike lanes or shared lanes. The mean number of bicyclists increased 53% from 2007 to 2013 during the evening commute period across the 39 count locations.

Table 2 shows the results from individual growth model analysis estimating differences in annual bicycle peak counts at 39 locations based on the set of relevant predictor variables. In 2007, the first year of the study period, the average bicycle count during the two-hour evening commuting period was 149.57 (95% CI 107.14, 192.00), at an average temperature 63.9°F and no precipitation (Model 1). Each year, bicycle counts increased from the baseline average during the two-hour evening commuting period at a rate of 5.5% (8.27 riders at 95% CI 1.87, 14.67; $p = 0.01$) from 2007 to 2013 (Model 1). The presence of a bicycle facility at the count location was associated with higher bicycle counts in 2007 – locations with a protected bikeway had 132% higher two-hour volumes (113.09 more riders at 95% CI 16.19, 209.99; $p = 0.02$) and locations with an on-street bike lane had 116% higher two-hour volumes (99.47 more riders at 95% CI 5.13, 193.81; $p = 0.04$) during the evening commuting period compared to locations with no on-site facility (Model 2).

Protected bikeways on-site were also associated with a faster rate of growth in ridership over time (21 more cyclists during the count period per year at 95% CI 7.51, 35.44; $p = 0.003$) where protected bikeways were initially present compared to locations with no on-site facility (1.4 more cyclists per year at 95% CI −7.88, 10.67; $p = 0.77$). Over the 6-year study period, counts increased by 69% (average 11% per year) at locations with protected bikeways, by 26% (average 4% per year) at locations with on-street bike lanes, and by 10% (average 2% per year) at locations with no on-site facility (Fig. 1). Time after improvement at an on-site facility was not significantly associated with difference in observed counts. Overall, total bicycle facility density length of combined facility types within a half mile buffer around a count location was not associated with a significant growth in ridership over time (Model 3: $b = 3.32$; 95% CI −2.59, 9.22; $p = 0.27$). However, for each mile of protected bikeway added within a count location buffer, ridership grew at a rate of 11.57 more cyclists per mile per year (95% CI 0.76, 22.38; $p = 0.04$), independent of temperature, precipitation and on-site facility type suggesting that protected facility density impacts overall ridership.

Discussion

These data suggest that on-site bicycle facilities (both protected bikeways and on-street bike lanes) were associated with higher baseline bicycle count levels at the start of the study, and that on-site protected bikeways were associated with greater growth in bicycle count levels over time from 2007 to 2013. Locations with an on-site protected bikeway facility were estimated to have 113 more cyclists during an individual evening peak 2-hour count period and to see an increased (faster) growth rate with 21 additional cyclists during the evening commute period each year compared to locations without facilities. While the growth rate change during each year was modest, the accumulated impact over the study period was more substantial – a growth rate in bicycle counts of 69% over the 6-year study period. Locations with an on-street bike lane, also showed growth though at a lower rate than protected bikeways. On average, these on-street bike lane locations saw 99 more cyclists on average during the peak period and a similar rate of increase in ridership over time compared to locations without facilities (26% increase over 6 years). Improvements to on-site bicycle facilities were not associated with an increased rate of growth in cyclists from 2007 to 2013, which may be due to impacts of the construction and lags in the necessary time to see impact of the intervention (Goodman et al., 2014, Fuller et. al. 2013).

Our findings suggest that the local bicycle facility density created by the installation of protected bicycle facilities in the half mile buffer area around a count location resulted in a faster rate of increase over time in bicycle counts in addition to growth associated with the immediate facility at the site of the count location. Each mile of protected bicycle facility length added to the half mile circular buffer around a count

Table 1
Annual Characteristics of 39 BikeWalk Twin Cities Count Locations between 2007 and 2013, Minneapolis, Minnesota.

Characteristic	2007 (N = 28)	2008 (N = 38)	2009 (N = 39)	2010 (N = 38)	2011 (N = 37)	2012 (N = 36)	2013 (N = 38)
	No. (%)	*No. (%)*	*No. (%)*	*No. (%)*	*No. (%)*	*No. (%)*	*No. (%)*
Improvement to On-Site Facility[a]	0 (0%)	1 (3%)	0 (0%)	6 (16%)	1 (3%)	3 (8%)	0 (0%)
	Mean (SD)	*Mean (SD)*	*Mean (SD)*	*Mean (SD)*	*Mean (SD)*	*Mean (SD)*	*Mean (SD)*
Bicycle Count[b]	138 (114)	172 (154)	161 (149)	151 (141)	188 (187)	185 (187)	211 (198)
Average Daily Temperature (°F)	55.0 (2.5)	59.1 (2.9)	70.3 (0.8)	59.7 (3.4)	58.7 (6.1)	67.2 (11.3)	75.3 (2.4)
Precipitation on Day of and Day Before Count (inches)	0.16 (0.46)	0.00 (0.00)	0.00 (0.00)	0.20 (0.37)	0.00 (0.01)	0.03 (0.05)	0.03 (0.02)
Added Bicycle Facility Length (miles) since 2007 in Buffer[c]	0 (n/a)	−0.01 (0.03)	0.17 (0.44)	0.41 (0.71)	2.09 (1.97)	2.19 (2.08)	2.85 (2.22)
Protected Bikeway	0 (n/a)	0 (0)	0.07 (0.19)	0.08 (0.22)	0.56 (1.37)	0.44 (1.27)	0.74 (1.46)
On-Street Bike Lane or Shared Lane	0 (n/a)	−0.01 (0.03)	0.10 (0.37)	0.33 (0.68)	1.53 (1.17)	1.75 (1.24)	2.12 (1.31)

Note: °F = degrees Fahrenheit; n/a = not applicable; SD = standard deviation. Statistics for each year represent the sample of count locations having annual counts for that particular year. Sample sizes varied by year, with all 39 counts represented in 2009.

[a] On-Site Facility: bicycle facility (e.g., bike lane) existing at the count location.
[b] Bicycle counts conducted annually in September during the evening commuting period (4–6 pm).
[c] Half mile buffer adjacent to count location, created using geographic information system (GIS).

Table 2
Individual Linear Growth Models Predicting Trends in Bicycle Counts, 39 Count Locations, Minneapolis, Minnesota, 2007–2013.

	Unconditional Means Model,	Unconditional Growth Model,	Model 1,	Model 2,	Model 3,	Model 4,
	b (95% CI)	b (95% CI)	b (95% CI)	b (95% CI)	b (95% CI)	b (95% CI)
	p-value[a]	p-value[a]	p-value[a]	p-value[a]	p-value[a]	p-value[a]
Model Variables						
Intercept	172.55 (121.79, 223.31) **p < 0.001**	141.65 (99.83, 183.48) **p < 0.001**	149.57 (107.14, 192.00) **p < 0.001**	85.73 (23.63, 147.82) **p = 0.001**	90.51 (28.09, 152.94) **p = 0.01**	87.59 (24.96, 150.22) **p = 0.01**
Time (years)		9.85 (3.68, 16.02) **p = 0.002**	8.27 (1.87, 14.67) **p = 0.01**	1.39 (-7.88, 10.67) p = 0.77	−0.45 (-10.24, 9.34) p = 0.93	1.56 (-8.21, 11.34) p = 0.75
Average Daily Temperature (°F)[b]			0.47 (-0.19, 1.14) p = 0.16	0.53 (-0.14, 1.19) p = 0.12	0.55 (-0.12, 1.22) p = 0.11	0.47 (-0.20, 1.14) p = 0.17
Precipitation on Day of and Day Before Count (inches)			−57.8 (-82.01, –33.59) **p < 0.001**	−56.29 (-80.52, –32.05) **p < 0.001**	−54.77 (-79.10, −30.45) **p < 0.001**	−55.74 (-80.08, −31.40) **p < 0.001**
On-Site Bicycle Facility in 2007						
Protected Bikeway				113.09 (16.19, 209.99) **p = 0.02**	110.93 (13.97, 207.89) **p = 0.03**	112.86 (15.67, 210.04) **p = 0.02**
On-Street Bike Lane				99.47 (5.13, 193.81) **p = 0.04**	92.1 (-3.12, 187.32) p = 0.06	93.21 (-2.21, 188.64) p = 0.06
No Facility				Ref	Ref	Ref
On-Site Bicycle Facility in 2007 × Time						
Protected Bikeway				21.47 (7.51, 35.44) **p = 0.003**	21.26 (7.32, 35.20) **p = 0.003**	19.92 (6.35, 33.49) **p = 0.004**
On-Street Bike Lane				6.51 (-6.89, 19.90) p = 0.34	6.96 (-6.42, 20.34) p = 0.31	6.88 (-6.07, 19.82) p = 0.30
No Facility				Ref	Ref	Ref
Time after Improvement to On-Site Bicycle Facility				−10.08 (-24.56, 4.40) p = 0.17	−11.28 (-25.90, 3.34) p = 0.13	−10.2 (-24.69, 4.29) p = 0.17
Residential Road Length (miles) in Buffer in 2013[c]					−5.76 (-17.31, 5.79) p = 0.32	−6 (-17.57, 5.56) p = 0.30
Added Bicycle Facility Length (miles) since 2007 in Buffer[d]					3.32 (-2.59, 9.22) p = 0.27	
Protected Bikeway						11.57 (0.76, 22.38) **p = 0.04**
On-Street Bike Lane or Shared Lane						−3.12 (-12.34, 6.10) p = 0.51
Model Fit[e]						
(Restricted) Likelihood Distance	2917.1	2796.9	2765.3	2712.4	2700.8	2691.6
AIC	2921.1	2804.9	2773.3	2720.4	2708.8	2699.6
Residual Variance	3247.65	1488.84	1296.7	1291.42	1290.97	1292.83
Pseudo R-square		0.54	0.13	0.004	<0.001	

Note: °F = degrees Fahrenheit; 95% CI = 95% confidence interval; AIC = Akaike's Information Criteria; b = regression parameter estimate.

[a] Boldface indicates statistical significance ($p < 0.05$).

[b] Variable was grand mean-centered for model interpretation; intercept represents average estimated count at temperature 63.9 °F, adjusted for all other model variables.

[c] Variable was grand mean-centered for model interpretation; intercept represents average estimated count at residential road length 14.51 miles, adjusted for all other model variables.

[d] Half mile buffer adjacent to count location, created using geographic information system (GIS).

[e] Model Fit statistics: For the (Restricted) Likelihood Distance and AIC, a smaller number indicates better model fit. Residual Variance indicates the amount of variance not explained by model variables. Pseudo R-square indicates the proportion of the within-site variance explained by the variables added to the current model over the previous model (e.g., Model 2 compared with Model 1).

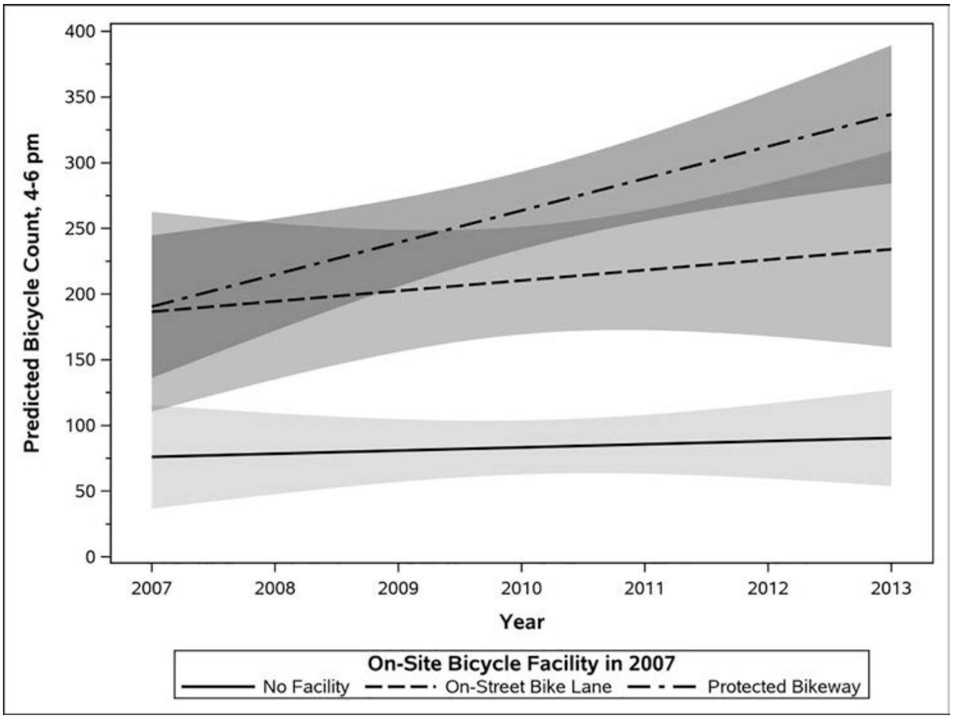

Fig. 1. Trends in Peak-Hour Bicycle Counts among 39 Count Locations in Minneapolis, Minnesota, 2007–2013, by On-Site Bicycle Facility in 2007, Estimated from Individual Linear Growth Models.

location was associated with an increase of 11.57 additional cyclists per year counted during the evening 2-hour commuting hours between 2007 and 2013. While this growth was small each year, the overall impact over the entire 6-year study period was substantial. These findings suggest that policy makers and transportation planners should consider the important additional impacts of the density of bicycle facilities and, in particular, the extent of protected bikeways in bicycle system planning. These findings corroborate previous works emphasizing the importance of bicycle systems and protected bikeways in spurring use (Pucher et al., 2010, Goodman et al., 2014, Schoner and Levinson 2014, Buehler and Dill 2016). Pilot programs that specifically focus on connecting bicycle networks utilizing protected facilities may see the largest improvements in key outcome measures.

These results suggest that comprehensive programs like the Minneapolis pilot program can increase bicycle use through both individual street-level facility projects and through the development of a bicycle network as part of a broader program. While more research is needed particularly on the interplay of on-street and off-street facilities, assessing and developing measures of network effects through facility density appears to be a promising area of future research.

Findings from this study indicate that protected bikeways both at the immediate count location and within the surrounding facility density buffer may contribute to increased bicycling over time in comparison with on-street bike lanes or shared lanes. This may be particularly relevant from a policy perspective as cities are beginning to add more cycle tracks and other protected bikeway facilities (Buehler and Dill 2016). While the preponderance of miles added to the system were on-road facilities, the analysis suggests that protected facilities tend to generate larger increases in bicycle usage than unprotected, on-street facilities. It was unclear how the on-road and off-road facilities connected (or did not connect) to create system impacts. More research is needed to evaluate these connections particularly as cities begin to add more cycle track mileage to their systems. While more detailed research is needed to understand the impact of specific system connections and to better understand how these systems may impact use in the global South (Castañeda, 2021), Nello-Deakin (2020) argues that the preponderance of research suggests that increasing the extent of cycling facilities, particularly the share of protected cycling infrastructure, positively impacts use. Our research adds more weight to this position. From a policy perspective, additional research on the political and administrative challenges of changing transportation systems may be a fruitful avenue of future research.

From a pilot research perspective, measuring more localized change patterns at the street corridor level and then measuring community change through the facility density extensions can be effective tools to evaluate bicycle transportation pilot programs.

Community transportation networks are large complex systems with inherited design characteristics from decades of previous infrastructure construction. These inherited designs in auto-centric countries like the United States have often emphasized low-density land uses along higher speed auto corridors. Overall mode share change at the community level resulting from targeted interventions in bicycle infrastructure is unlikely to be found in a short time span due to the predominance of these inherited designs. Change is likely to be seen at the more micro-level of street corridors where treatments change the infrastructure and then in adjacent corridors that are linked into a broader bicycle network. Data collection focused on treatment sites and measurements at the corridor levels can be an effective proxy for measuring community change through indicators of distance added and increased/decreased use. In addition, institutionalizing active transportation data collection over time can help to improve policy evaluations over the long-term.

Strengths and limitations

This study capitalizes on a natural experiment and uses a quasi-experimental design to address limitations of prior studies that have generally been of short duration or of small-scale improvements. We use objective assessments of behavior using community-wide counts of cyclists taken at 39 locations in the Twin Cities with at least three annual counts conducted during the evaluation period between 2007 and 2013. The modeling strategies employed reduce the potential for bias in estimates due to factors that are associated with bicycling rates in cross-sectional studies but that change minimally over time (e.g., geographic location, land use patterns), allowing for efficient study of change. Investigators were able to isolate the impact of the change in key variables that are associated with the growth in ridership (or lack of growth) over time at a given count location to better understand factors that contribute to changes in ridership (Singer et al., 2003, Wang et al., 2016, Fraser and Lock 2011).

There are several basic limitations to this study that should be noted. First, the study does not provide a full analysis of the Nonmotorized Pilot Program and its potential impacts (Lyons et al., 2014, Fields and Hull 2013). While our focus on counts provides some evidence of the program's impact, more detailed work is needed to fully assess program impacts particularly in terms of changing standards within transportation agencies that could impact policy over a longer time span. From a more technical perspective, the present study was not able to address potential spatial autocorrelation of the count observations due to preselection of the sites by the non-profit TLC (Cao et al., 2009). Finally, the present study of observed counts does not capture trip purpose or other demographic characteristics of users which limits extrapolation of some potential impacts (Krizek et al., 2009).

Conclusions

This research adds to the growing body of scholarship examining the impact of bicycle facilities on use and provides important evidence supporting strategies to increasing physically active transportation in communities through targeted investments in key infrastructure through pilot programs. We found that improvements in bicycle facilities and the facility density of bicycle infrastructure around those locations are significantly associated with the number of bicyclists and an increased rate of bicycling over time. The presence of bicycle facilities, particularly protected facilities like trails, and the density of these bicycle facilities impact their use. Policy makers and transportation planners looking to support increased bicycle ridership should consider investments that extend the local system of bicycle facilities and in particular, the density of protected bikeways in their bicycle transportation system.

Funding

This work is supported in part by Prevention Research Center cooperative agreement 1U48DP001946 with the Harvard Prevention Research Center (which includes the Nutrition and Obesity Policy Research and Evaluation Network and the Physical Activity Policy Research Network) from the National Center for Chronic Disease Prevention and Health Promotion of the Centers for Disease Control and Prevention. Additional funding came from the Gulf Coast Center for Evacuation and Transportation Resiliency through the University Transportation Center program (Project # 11–08). This work is solely the responsibility of the authors and does not represent official views of the Centers for Disease Control and Prevention, U.S. Department of Transportation, or any other funders. The study sponsors had no role in study design; collection, analysis, and interpretation of data; writing the report; and the decision to submit the report for publication.

CRediT authorship contribution statement

Billy Fields: Conceptualization, Writing – original draft, Writing – review & editing, Formal analysis, Supervision, Project administration. **Angie L. Cradock:** Conceptualization, Writing – original draft, Writing – review & editing, Formal analysis. **Jessica L. Barrett:** Conceptualization, Writing – original draft, Writing – review & editing, Formal analysis. **Tony Hull:** Writing – review & editing, Data curation. **Steven J. Melly:** Writing – review & editing, Software.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Aldred, R., Croft, J., Goodman, A., 2019. Impacts of an active travel intervention with a cycling focus in a suburban context: One-year findings from an evaluation of London's in-progress mini-Hollands programme. Transp. Res. Part A: Policy Pract. 123, 147–169.

Balderson, K., 2018. Lessons Learnt From Mini-Holland. in: Enjoy Waltham Forest Walking and Cycling Account 2017/18. Transport for London. Last accessed 6/21/20 from https://www.enjoywalthamforest.co.uk/wp-content/uploads/2019/01/Final-Walking-Cycling-Account-201718.pdf.

Buehler, R., Pucher, J., 2012. In: Pucher, J., Buehler, R. (Eds.), City Cycling. MIT Press, pp. 9–29.

Buehler, R., Pucher, J., 2021. COVID-19 impacts on cycling, 2019–2020. Transp. Rev. 41 (4), 393–400.

C40 Cities. 2020. C40 Mayors' Agenda for a Green and Just Recovery. July 15. Last accessed 7/28/20 from https://www.c40.org/other/agenda-for-a-green-and-just-recovery.

Cao, X., Mokhtarian, P.L., Handy, S.L., 2009. Examining the impacts of residential self-selection on travel behaviour: a focus on empirical findings. Transp. Rev. 29 (3), 359–395.

Castañeda, P., 2021. Cycling case closed? A situated response to Samuel Nello-Deakin's "Environmental determinants of cycling: not seeing the forest for the trees?". J. Transp. Geogr. 90, 102947.

Combs, T.S., Pardo, C.F., 2021. Shifting streets COVID-19 mobility data: findings from a global dataset and a research agenda for transport planning and policy. Transp. Res. Interdiscip. Perspect. 9, 100322.

Department for Transport UK. 2020. Case study: London Mini Hollands. Last accessed 9/16/20 from https://www.gov.uk/government/case-studies/london-mini-hollands.

Federal Highway Administration (FHWA). 2012. Report to the U.S. Congress on the Outcomes of the Nonmotorized Transportation Pilot Program SAFETEA-LU Section 1807. Washington, DC.

Fields, B., Cradock, A., Barrett, J., Melly, S., 2014. Assessing the Impact of Bicycle Facilities on Use: Evaluation of Minneapolis Nonmotorized Transportation Pilot Program. Presented at 93rd Annual Meeting of the Transportation Research Board, Washington, D.C..

Fields, B., Hull, T., 2013. Policy Implications of the Nonmotorized Transportation Pilot Program. In: Renne, J.L., Fields, B. (Eds.), Transport Beyond Oil. Island Press/Center for Resource Economics, Washington, DC, pp. 265–290.

Fraser, S.D., Lock, K., 2011. Cycling for transport and public health: a systematic review of the effect of the environment on cycling. Eur. J. Pub. Health 21 (6), 738–743.

Goodman, A., Sahlqvist, S., Ogilvie, D., 2014. New walking and cycling routes and increased physical activity: one-and 2-year findings from the UK iConnect Study. Am. J. Public Health 104 (9), e38–e46.

Götschi, T., Krizek, K. J., McGinnis, L., Lucke, J., & Barbeau, J., 2011. Nonmotorized transportation pilot program evaluation study, phase 2. Center for Transportation Studies University of Minnesota. Report Number CTS 11-13, 6 and 11.

Hankey, S., Lindsey, G., Wang, X., Borah, J., Hoff, K., Utecht, B., Xu, Z., 2012. Estimating use of non-motorized infrastructure: Models of bicycle and pedestrian traffic in Minneapolis, MN. Landscape Urban Plann. 107 (3), 307–316.

Kärmeniemi, M., Lankila, T., Ikäheimo, T., Koivumaa-Honkanen, H., Korpelainen, R., 2018. The built environment as a determinant of physical activity: a systematic review of longitudinal studies and natural experiments. Ann. Behav. Med. 52 (3), 239–251.

Kraus, S., Koch, N., 2021. Provisional COVID-19 infrastructure induces large, rapid increases in cycling. PNAS 118 (15).

Krizek, K.J., Johnson, P.J., 2006. Proximity to trails and retail: effects on urban cycling and walking. J. Am. Plann. Assoc. 72 (1), 33–42.

Krizek, K.J., Barnes, G., Thompson, K., 2009. Analyzing the effect of bicycle facilities on commute mode share over time. J. Urban Plann. Dev. 135 (2), 66–73.

Lee, I.M., Shiroma, E.J., Lobelo, F., Puska, P., Blair, S.N., Katzmarzyk, P.T., Lancet Physical Activity Series Working Group, 2012. Effect of physical inactivity on major non-communicable diseases worldwide: an analysis of burden of disease and life expectancy. Lancet 380 (9838), 219–229.

Lyons, W., Rasmussen, B., Daddio, D., Fijalkowski, J., & Simmons, E., 2014. Nonmotorized transportation pilot program: Continued progress in developing walking and bicycling networks. Cambridge, MA; 2014. Report No.: DOT-VNTSC-FHWA-14-04.

Lyons, W., Rasmussen, B., Biton, A., Fijalkowski, J., Daddio, D., 2012. Report to the US Congress on the Outcomes of the Nonmotorized Transportation Pilot Program SAFETEA-LU Section 1807. Federal Highway Administration (FHWA), Washington, DC.

Mertens, L., Compernolle, S., Deforche, B., Mackenbach, J.D., Lakerveld, J., Brug, J., Roda, C., Feuillet, T., Oppert, J.-M., Glonti, K., Rutter, H., Bardos, H., De Bourdeaudhuij, I., Van Dyck, D., 2017. Built environmental correlates of cycling for transport across Europe. Health Place 44, 35–42.

NACTO. 2013. Urban street design guide. Washington, DC: Island Press/Center for Resource Economics.

NACTO. 2020. COVID-19: Transportation Response Center. Last accessed 4/25/20 from https://nacto.org/program/covid19/.
Nello-Deakin, S., 2020. Environmental determinants of cycling: not seeing the forest for the trees? J. Transp. Geogr. 85, 102704.
Nordback, K., Marshall, W.E., Janson, B.N., Stolz, E., 2013. Estimating annual average daily bicyclists: error and accuracy. Transp. Res. Rec. 2339 (1), 90–97.
Parker, K.M., Rice, J., Gustat, J., Ruley, J., Spriggs, A., Johnson, C., 2013. Effect of bike lane infrastructure improvements on ridership in one New Orleans neighborhood. Ann. Behav. Med. 45 (suppl_1), S101–S107.
Pedroso, F.E., Angriman, F., Bellows, A.L., Taylor, K., 2016. Bicycle use and cyclist safety following Boston's bicycle infrastructure expansion, 2009–2012. Am. J. Public Health 106 (12), 2171–2177.
Pucher, J., Buehler, R., 2016. Safer cycling through improved infrastructure. Am. J. Public Health 106 (12), 2089–2091.
Pucher, J., Dill, J., Handy, S., 2010. Infrastructure, programs, and policies to increase bicycling: an international review. Prev. Med. 50, S106–S125.
Replogle, M. A., & Fulton, L. M., 2014. A global high shift scenario: impacts and potential for more public transport, walking, and cycling with lower car use. Institute for Transportation and Development Policy and UC Davis. Last accessed 9/16/21 from https://itdpdotorg.wpengine.com/wp-content/uploads/2014/09/A-Global-High-Shift-Scenario_WEB.pdf.
Sadik-Khan, J., Solomonow, S., 2017. Streetfight: Handbook for an Urban Revolution. Penguin.
Schoner, J.E., Levinson, D.M., 2014. The missing link: bicycle infrastructure networks and ridership in 74 US cities. Transportation 41 (6), 1187–1204.
Singer, J.D., Willett, J.B., Willett, J.B., 2003. Applied Longitudinal Data Analysis: Modeling Change and Event Occurrence. Oxford University Press.
Tayarani, M., Poorfakhraei, A., Nadafianshahamabadi, R., Rowangould, G., 2018. Can regional transportation and land-use planning achieve deep reductions in GHG emissions from vehicles? Transp. Res. Part D: Transp. Environ. 63, 222–235.
van Goeverden, C. D., & Godefrooij, T., 2011. The Dutch Reference Study: Cases of interventions in bicycle infrastructure reviewed in the framework of Bikeability.
van Goeverden, K., Nielsen, T.S., Harder, H., van Nes, R., 2015. Interventions in bicycle infrastructure, lessons from Dutch and Danish cases. Transp. Res. Procedia 10, 403–412.
Wang, Y., Chau, C.K., Ng, W.Y., Leung, T.M., 2016. A review on the effects of physical built environment attributes on enhancing walking and cycling activity levels within residential neighborhoods. Cities 50, 1–15.
Winters, M., Branion-Calles, M., Therrien, S., Fuller, D., Gauvin, L., Whitehurst, D.G.T., Nelson, T., 2018. Impacts of Bicycle Infrastructure in Mid-Sized Cities (IBIMS): protocol for a natural experiment study in three Canadian cities. BMJ Open 8 (1), e019130.
World Health Organization. (2018). Global action plan on physical activity 2018-2030: more active people for a healthier world. Geneva.