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<p>We sought to accurately and validly model emissions generating and activities, including changes in traveler behavior and thus GHG emissions in the wake of bikeway projects. We wanted the results to be applicable to practice and policy in California. We created a life cycle assessment model for GHG emissions resulting from bikeway construction and use by those who formerly used cars, used transit, cycled on other routes, walked, or did not make trips. We conducted intercept surveys at 20 new bikeway facilities across Los Angeles County to understand the changes in travel induced by the bikeway. We also aggregated before and after count data from across the country to understand the range of observed changes in annual cycling volumes that result from a new or upgraded bikeway, and perform statistical tests on the correlation between Census variables and bikeway volume outcomes. Though far less GHG emissions are attributable to cycling than driving, not all bikeways reduce life cycle GHG emissions. But many do. We specify the conditions under which a bikeway is more likely to reduce GHG emissions. We also make recommendations to the Air Resources Board and Strategic Growth Council to adjust an existing method used to estimate reductions in GHG emissions from bikeway projects. This research can play a key role to support future decisions to use revenues from the Greenhouse Gas Reduction Fund for expenditures on high performing individual bikeway, bikeway networks, and bike related programs.</p>		
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Toward Accurate and Valid Estimates of Greenhouse Gas Reductions from Bikeway Projects

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Introduction

Problem

Transportation projects that can demonstrate cost-effective greenhouse gas (GHG) emissions reductions are eligible for targeted funding from growing revenue sources. Chief among these funding sources is California's Greenhouse Gas Reduction Fund, established under AB 32. A growing body of evidence indicates that the provision of bikeway infrastructure is effective in increasing bicycle ridership¹. The increasing availability performance-based funding for GHG reductions bolsters the importance of providing a method for validly and accurately quantifying GHG emissions impacts of bicycle infrastructure investment.

Calculating GHG emissions reductions for transportation projects is both difficult and increasingly imperative for policy. The state of existing scholarship reflects three problems with quantifying GHG for transportation projects: 1) the inherent complexity of transportation systems and travel behavior, 2) the lack of fine-grained data to support emissions calculations, 3) the inability to apply existing academic models to policy implementation.

Objectives

We seek to model changes in traveler behavior and thus GHG emissions in the wake of bikeway projects. Previous research has estimated reductions in GHG emissions from specific bikeway improvements, but there has been little work that has produced generalizable parameters

¹ Dill, Jennifer, and Theresa Carr. "Bicycle commuting and facilities in major US cities: if you build them, commuters will use them." *Transportation Research Record: Journal of the Transportation Research Board* 1828 (2003): 116-123; Buehler, Ralph, and John Pucher. "Cycling to work in 90 large American cities: new evidence on the role of bike paths and lanes." *Transportation* 39, no. 2 (2012): 409-432.

for estimating GHG emissions reductions from a range of bicycle transportation projects. Concomitantly, there has been little work on how demographics and neighborhood characteristics determine the GHG implications of transportation projects. To hypothesize a few examples: shifting trips from private vehicles to biking has greater reductions in GHG emissions when the local vehicle fleet has lower fuel economy; low-volume bikeways that require substantial infrastructure may not recoup the GHG emissions invested in their construction; and bikeways that connect to high-quality transit may result in larger shifts from private vehicles.

This research advances the state of knowledge by drawing upon fine-grained empirical data for a variety of bicycle projects. It also advances the state of practice: travel demand models that incorporate bicycling are uncommon, and where they do exist around the state, they are in their nascent stages. Our research methods deliberately include counts and surveys in disadvantaged communities, and we seek to discern whether there may be greater propensity to shift modes to bicycling and where such shifts may result in greater reductions of GHGs and criteria pollutants if available vehicles are older or less fuel efficient. We did not find many of the dynamics we hypothesized specific to disadvantaged communities, primarily due to small sample size.

Our research discerns among bikeway projects based on readily available inputs such as Census sociodemographic data, proposed bikeway type, connectivity to bikeway networks and transit, and topography. This project produces data and analysis to support the development and validation of models that incorporate demographic data and changes in travel behavior when estimating GHG reductions. These models can form the basis decision-support tools for state agencies allocating bikeway funds, for state decision-makers programming cap and trade funds, and for local agencies who may be implementing climate action plans or simply prioritizing local transportation projects.

Scope

We seek a replicable, defensible method for estimating GHG emissions reductions from proposed bicycle projects that considers varying types of projects and their future use. As such, we use a life-cycle assessment (LCA) approach that compares the construction, operation, and use of bikeway facilities versus other transportation modes that would be used in place of the bikeway. We do not consider the effects of proposed programs, such as expanding a regional bikeway network or a bike share system.

To understand the determinants of GHG emissions, we seek data to describe the proposed project and forecast future volumes and attraction from other modes. This data includes (1) information that would be readily available in a planning document or on an application for funding, (2) data from the United States Census Bureau, (3) before and after data on cycling volumes at sites where bikeway improvements were made, and (4) responses to a cyclist intercept survey. The before/after data (3) is data from around the United States: Austin, Chicago, Denver, Honolulu, Los Angeles, Portland (OR), San Francisco, and Washington (DC). The cyclist intercept survey data (4) is from Los Angeles County. Thus, the transferability of our results is limited to urban areas in the United States.

A much larger and more diverse set of observations would be needed to specify a robust model for reductions in GHG emissions from bicycle facilities. Drawing opportunistically on existing data, however, we can identify some of the key parameters that drive GHG emissions reductions and specify a useful, if imperfect model. We also clearly indicate the process by which the model would be improved with additional data.

Literature Review

Studies Linking Bicycling and GHG Emissions

Increasing the share of trips made by bicycle is frequently cited as a method to reduce GHG emissions, but there is scant literature that demonstrates the magnitude of these effects. The most common empirical attempts to quantify the attempts are made in emerging literature on the “co-benefits” of bicycling on both GHG emissions reduction and the health benefits of active transportation.²

Ideally, the literature would provide a framework for evaluating the GHG reductions on a per-project basis. Unfortunately, only a small portion of this research demonstrate these reductions based on real-world studies on infrastructure interventions. An analysis of installation of upgraded bicycle parking facilities at a university in Serbia and found a bicycling increase of 143% of 39 from 16 bikers per day led to a reduction of 1845.9 kg/CO₂ per year. In a study of a bike path adjoining a BRT corridor in Los Angeles, using a combination of post-intervention count data and survey, researchers found that biking increases may be saving between 371 and 602 metric tons (MT) of CO₂ per year.³

² Mrkajic, Vladimir, Djordje Vukelic, and Andjelka Mihajlov. "Reduction of CO 2 emission and non-environmental co-benefits of bicycle infrastructure provision: the case of the University of Novi Sad, Serbia." *Renewable and Sustainable Energy Reviews* 49 (2015): 232-242; Bearman, Nick, and Alex D. Singleton. "Modelling the potential impact on CO 2 emissions of an increased uptake of active travel for the home to school commute using individual level data." *Journal of Transport & Health* 1, no. 4 (2014): 295-304; Blondel, Benoît, Chloé Mispelon, Julian Ferguson. "Cycle more Often 2 cool down the planet!" European Cyclists' Federation. (2011). Retrieved at <https://ecf.com/sites/ecf.com/files/co2%20study.pdf>.

³ ICF International. *Metro Orange Line Mode Shift Study and Greenhouse Gas Emissions Analysis*. (2011). Retrieved from http://media.metro.net/projects_studies/bikeway_planning/images/Metro_Orange_Line_Study_March_2011.pdf. "Modelling the potential impact on CO 2 emissions of an increased uptake of active travel for the home to school commute using individual level data." *Journal of Transport & Health* 1, no. 4 (2014): 295-304; Blondel, Benoît, Chloé Mispelon, Julian Ferguson. "Cycle more Often 2 cool down the planet!" European Cyclists' Federation. (2011). Retrieved at <https://ecf.com/sites/ecf.com/files/co2%20study.pdf>.

In a longitudinal study of three important biking network linkages found no significant reduction in CO₂ emissions, reasoning that increased usage of the links may have the result of route changes or new trips but were not a substitute for motorized travel.⁴ Conversely, a study modeling complete street design proposals in Chicago, found that including bicycle lanes may increase GHG emissions by increasing automobile congestion.⁵

Others studies use stated preference methods to determine the increase in bicycling due to facility interventions. A stated preference survey of 231 people in Vancouver, Canada, found that a public bike share program would result in a decrease of between 0.07% to 0.14% of total annual transportation emissions.⁶ A study in Puebla, Mexico modeled the increased mode share of bicycling based on survey responses to hypothetical implementation of bicycle friendly policies and infrastructure, including bike paths, lanes and a bike share program. Based on the responses, they modeled an increase of bike mode share from 1.5% in 2005 to 4% in 2020, taking into account policies that increase intermodality usage, and found that the increase in cycling led to a 1% reduction of CO₂ during the week and 2.4% on the weekends.⁷ An intercept survey in 14 central European cities and found that the installation of bike lanes along regular commute routes in combination with secure bike parking facilities would lead to an average reduction of 3.56% GHG emissions across all the cities.⁸

⁴ Brand, Christian, Anna Goodman, David Ogilvie, and iConnect consortium. "Evaluating the impacts of new walking and cycling infrastructure on carbon dioxide emissions from motorized travel: a controlled longitudinal study." *Applied Energy* 128 (2014): 284-295.

⁵ Peiravian, Farideddin, and Sybil Derrible. "Complete Streets Designs: A Comparative Emission Impact Analysis." In *Transportation Research Board 93rd Annual Meeting*, no. 14-1814. 2014.

⁶ Lane, Erin, Julie Elsliger, Chelsea Enslow, WK Connie Lam, Nur Shodjai, Zolzaya Tuguldur, and Vincent Yeh. "Modelling Reductions of Carbon Emissions Under Various Scenarios of a Public Bicycle Share System Within Vancouver, BC." (2012).

⁷ Bussière, Y., Jean-Luc Collomb, Emmanuel Ravalet, Lyon CERTU, and France Emmanuel. "Cycling in the city and reduction of greenhouse gas emissions: the case of Mexico." In *World Bank Fifth Urban Research Symposium, Marseille*. (2009).

⁸ Meggs, J., and J. Schweizer. "Effects of Bicycle Facility Provision on Mortality Prevention and GHG Reduction: Cost-Benefit Analyses within the BICY Project." Retrieved from <http://www.bicy.it/docs/129/HEAT-Scenario-CBA-FINAL-DRAFT-for-WHO.pdf>.

Research employed a systems dynamics model – modeling the various transportation network scenarios over many years – to simulate the result of different policy interventions in Auckland, New Zealand, finding a range from a 3 megaton reduction over 40 years with the existing regional strategy to develop a partial network of mixed cycling infrastructure, to a high of 26 million metric tons reduction over 40 years with the implementation using a mix of segregated lanes on arterials combined updating roads gradually updated with best practice traffic calming features.⁹ A study of bicycling in Washington, DC, found that a 0.02% reduction in CO₂ emissions with the implementation of short term biking and pedestrian measures (bike stations and bike sharing) and a cumulative 0.3% reduction in transportation emissions due to the long-term implementation of a regional biking infrastructure plan by 2030.¹⁰

Gaps in the Literature

Currently the literature linking bike infrastructure improvements to changes in GHG emissions is ripe with notable gaps. Perhaps the best guide for local planners it to understand the project-level impact on GHG emissions, but there are only a handful of studies that approach this issue in that way. Multiple reviews have noted the lack of studies based on data gathered before and after an improvement to biking infrastructure, and the literature largely relies on stated preference surveys and systems modeling techniques.¹¹

⁹ Macmillan, Alexandra, Jennie Connor, Karen Witten, Robin Kearns, David Rees, and Alistair Woodward. "The societal costs and benefits of commuter bicycling: simulating the effects of specific policies using system dynamics modeling." *Environmental Health Perspectives* 122, no. 4 (2014): 335.

¹⁰ Bansal, Monica, and Erin Morrow. "Meeting Transportation Goals to Reduce Greenhouse Gases in the National Capital Region: " What Would It Take?" Scenario." *Transportation Research Record: Journal of the Transportation Research Board* 2252 (2011): 135-143.

¹¹ Handy, Susan, Gil Tal, and Marlon G. Boarnet. "Impacts of Bicycling Strategies on Passenger Vehicle Use and Greenhouse Gas Emissions." (2014). Retrieved from http://www.arb.ca.gov/cc/sb375/policies/bicycling/bicycling_brief.pdf; Larouche, Richard. "The environmental and population health benefits of active transport: A review." (2012).

There is also a lack of research on facility-level intervention, as much of the literature models bicycling growth at the regional level. As bicycle usage is based on many regional factors (transit access, network strength, weather, perception and safety, helmet laws, biking culture), regional studies provide little use for application in other locations compared to facility-level studies.¹² While there have been multiple studies that look at bicycle usage, mode split, and route choice as a result of a facility-level intervention,¹³ that literature has yet to be linked to the question of GHG impacts.

Some studies have approached the linkage between bicycling and GHG emissions impact by asking what bicycling mode share would be necessary to meet state GHG emissions reduction goals, divorcing the analysis from an evaluation of which interventions would be necessary to encourage mode switch.¹⁴ These and other longer-term studies also incorporate theoretical technological improvements to vehicles, minimizing the contribution of bicycling to GHG reduction in the short term, though its cost-effectiveness has been acknowledged.¹⁵

As the literature on this issue has developed, there have been numerous improvements in modeling methodology, though rarely, if ever, have they been employed by the same study.

Lastly, the vast majority of these studies are not in the United States.

¹² Bearman, Nick, and Alex D. Singleton. "Modelling the potential impact on CO₂ emissions of an increased uptake of active travel for the home to school commute using individual level data." *Journal of Transport & Health* 1, no. 4 (2014): 295-304.

¹³ Broach, Joseph, Jennifer Dill, and John Gliebe. "Where do cyclists ride? A route choice model developed with revealed preference GPS data." *Transportation Research Part A: Policy and Practice* 46.10 (2012): 1730-1740; Dill, Jennifer, and Theresa Carr. "Bicycle commuting and facilities in major US cities: if you build them, commuters will use them." *Transportation Research Record: Journal of the Transportation Research Board* 1828 (2003): 116-123; Pucher, John, Jennifer Dill, and Susan Handy. "Infrastructure, programs, and policies to increase bicycling: an international review." *Preventive Medicine*. 50 (2010): S106-S125.

¹⁴ Woodcock, James, Phil Edwards, Cathryn Tonne, Ben G. Armstrong, Olu Ashiru, David Banister, Sean Beevers et al. "Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport." *The Lancet* 374, no. 9705 (2009): 1930-1943. Grabow, M., Hahn, M., Whited, M., & Black, S. (2010) estimated that if cycling increased to a 20% mode share in Madison, WI would lead to a 4.2% reduction in CO₂ emissions. Grabow, Maggie, Micah Hahn, Melissa Whited, and Spencer Black. *Valuing Bicycling's Economic and Health Impacts in Wisconsin*. Nelson Institute for Environmental Studies, University of Wisconsin–Madison, 2010.

¹⁵ Larouche, Richard. "The environmental and population health benefits of active transport: A review." (2012).

Non-environmental Co-benefits of Cycling

In addition to valuing the environmental contributions of increased cycling, emerging “cobenefits” literature explores the link between cycling and health and economic outcomes. Cycling increases have also been linked to health benefits through increasing physical activity, including weight loss and improved cardiovascular fitness.¹⁶ Studies find health increases of varying degrees, and it is important to note that health benefits are largest when cycling substitutes for non-active transportation or other sedentary activities.¹⁷ Studies have also found that increased cycling is associated with improved general well-being, typically through interviews and other qualitative analysis.¹⁸ There are only a small number of studies in this area, and further research is needed to determine the direction of causality. Results linking increases in cycling and health are hampered by questions of the direction of causality.¹⁹

Increases in cycling can also lead to economic benefits, both directly and indirectly through improved health conditions. Bicycling may improve access to jobs, lead to transport cost savings for bicycle commuters, and increase economic activity in areas in close proximity to bike paths and lanes.²⁰

¹⁶Pucher, J., Buehler, R., Bassett, D. R., & Dannenberg, A. L. (2010). Walking and cycling to health: a comparative analysis of city, state, and international data. *American journal of public health*, 100(10), 1986-1992.

¹⁷ Handy, S., Van Wee, B., & Kroesen, M. (2014). Promoting cycling for transport: research needs and challenges. *Transport reviews*, 34(1), 4-24.

¹⁸ Barton, H. (2009). Land use planning and health and well-being. *Land Use Policy*, 26, S115-S123. Pretty, J., Peacock, J., Hine, R., Sellens, M., South, N., & Griffin, M. (2007). Green exercise in the UK countryside: Effects on health and psychological well-being, and implications for policy and planning. *Journal of environmental planning and management*, 50(2), 211-231.

¹⁹ Handy, S., Van Wee, B., & Kroesen, M. (2014).

²⁰ Krizec, K. J. (2007). Estimating the economic benefits of bicycling and bicycle facilities: An interpretive review and proposed methods. In *Essays on transport economics* (pp. 219-248). Physica-Verlag HD.

Review of California-Specific Bikeway GHG Emissions Estimation Methods

Current California Air Resources Board methodology

The California Air Resources Board (CARB) has published a methodology to evaluate GHG emissions for bikeway projects that apply for funds from the Strategic Growth Council's Affordable Housing and Sustainable Communities Program. The methodology is used to evaluate and compare GHG effects of prospective investments in bikeway projects. The CARB methodology primarily evaluates GHG savings of bikeways as a mitigation measure for development or as a connector to high quality transit hub. The CARB methodology asks for the facility type (class) and length and calculates predicted volumes based on the type of city, proximity to activity centers, and traffic on parallel road.²¹

A review of the CARB methodology in light of the literature shows that there are a number of areas in which the methodology could be improved to more accurately account for the GHG savings of bikeways. We argue that bikeways reduce GHG emissions independently, and that methodology for independent evaluation is necessary to support investment in bikeways independent of land use development. We secondly propose improvements to CARB's methodology for calculating GHG emissions in light of advances present in both the academic literature and similar studies conducted in other locations.

²¹ California Strategic Growth Council (2015). Affordable Housing and Sustainable Communities Program: 2015-16 Program Guidelines. Available at http://sgc.ca.gov/pdf/ADOPTED_FINAL_15-16_AHSC_Guidelines_with_QM.pdf

Improving Spatial Accuracy of GHG Estimates Using California Vehicle Registration Data

Emissions reductions from avoided vehicle trips are calculated based on an average for Los Angeles County in CARB's EMFAC model. Acknowledging different fleet emissions characteristics is a methodological improvement over many studies, but ignores important variations in average automobile GHG emissions within the county.²² The GHG emissions reduction potential of bikeways in neighborhoods is increased if it substitutes for car trips with higher GHG emissions, and therefore the neighborhood level provides a more accurate estimate of emissions savings.²³ Averaging the first and final year fleet emissions profile from EMFAC improves upon studies that rely only on current emissions profiles, but other studies have shown that the reduction in vehicle emissions over time is not linear, and may change at different rates in different neighborhoods.²⁴

Thomas, et al.²⁵ used a database of California Department of Motor Vehicle records for Los Angeles County to estimate GHG emissions per VMT for each bicycling facility based on the fleet characteristics of the surrounding area. The database has a record for every vehicle registered in Los Angeles County and includes the registrant's address and the make and model year of the car.

²² Grabow, M., Hahn, M., Whited, M., & Black, S. (2010). *Valuing Bicycling's Economic and Health Impacts in Wisconsin*. Nelson Institute for Environmental Studies, University of Wisconsin—Madison uses a national emissions average from the EPA for the current year only. Lane, Erin, Julie Elsliger, Chelsea Enslow, WK Connie Lam, Nur Shodjai, Zolzaya Tuguldur, and Vincent Yeh. "Modelling Reductions of Carbon Emissions Under Various Scenarios of a Public Bicycle Share System Within Vancouver, BC." (2012) uses city average. Gotschi, Thomas, and Kevin Mills. "Active transportation for America: The case for increased federal investment in bicycling and walking." (2008).

²³ Bearman, Nick, and Alex D. Singleton. "Modelling the potential impact on CO₂ emissions of an increased uptake of active travel for the home to school commute using individual level data." *Journal of Transport & Health* 1, no. 4 (2014).

²⁴ Bansal, Monica, and Erin Morrow. "Meeting Transportation Goals to Reduce Greenhouse Gases in the National Capital Region: "What Would It Take?" Scenario." *Transportation Research Record: Journal of the Transportation Research Board* 2252 (2011): 135-143.

²⁵ Thomas, T., Blumenberg, E., & Salon, D. (2015). Travel Adaptations and the Great Recession: Evidence from Los Angeles County. In Transportation Research Board 94th Annual Meeting (No. 15-6027).

However, Thomas et al., found no evidence in the 2005 - 2009 to support the argument that vehicles available in lower-income communities had below-average fuel economy.

The Impact of New Facilities on Bicycle Ridership

Determining the potential GHG reductions from the installation or upgrade of biking infrastructure requires estimating the avoided motorized vehicle travel. We calculate this as a fraction of the change in ridership. The literature on cycling behavior identifies two groups of variables that impact bike ridership; demographic variables and variables related to cycling infrastructure and travel behavior. We use factors the literature has identified as being significant predictors of cycling behavior to inform variable selection for our model.

Bicycling infrastructure improvements, such as a bike lane or path, are the most common cycling interventions. There are many studies that attempt to quantify the increase in ridership due to cycling infrastructure interventions, though few have used longitudinal data. Aggregate-level studies found an increase in ridership resulting from infrastructure investment, but studies of facility-level improvements have mixed findings.²⁶

Studies have shown that multiple aspects of the cycling network and environment in a given city influence ridership. For example, multiple studies find that bicycle commuting at the regional level is correlated with the density of the bike lane network.²⁷ Studies have repeatedly found bike sharing programs increase ridership, though note that bike share programs are typically accompanied by biking infrastructure improvements.²⁸ Bike racks on buses lead to an increase in

²⁶ Pucher, John, Jennifer Dill, and Susan Handy. "Infrastructure, programs, and policies to increase bicycling: an international review." *Preventive Medicine* 50 (2010): S106-S125.

²⁷ Dill, Jennifer, and Theresa Carr. "Bicycle commuting and facilities in major US cities: if you build them, commuters will use them." *Transportation Research Record: Journal of the Transportation Research Board* 1828 (2003): 116-123. Buehler, Ralph, and John Pucher. "Cycling to work in 90 large American cities: new evidence on the role of bike paths and lanes." *Transportation* 39.2 (2012): 409-432.

²⁸ Pucher, John, et al. "Walking and cycling to health: a comparative analysis of city, state, and international data." *American Journal of Public Health* 100.10 (2010): 1986-1992.

bike commuting.²⁹ Mandatory helmet laws were found to negatively impact ridership in Australia,³⁰ but did not impact recreational ridership in Canada.³¹

A number of studies have found that certain demographic factors are highly correlated with cycling, including income, age, gender, and race or ethnicity.³² A study using the National Household Travel Survey to examine socio-economic factors finding that gender, ethnicity, and availability of a vehicle were the largest determinant daily cycling.³³ Dill and Voros (2007) found that 27% of people ages 16 or younger had used a bicycle for transportation in the past 30 days. They also find that Hispanics were most likely of all races/ethnicities to cycle.³⁴ Pucher et. al (1999) further find that public attitudes, cultural differences, climate, safety impact the likelihood of cycling as a mode of transport.³⁵

Motivated by the goal of providing a more accurate measure of GHG emissions changes from bicycling facility improvements, our research models ridership changes and travel choices made at the facility level. Previous studies on this topic have more often looked at aggregate cycling rates across a city, and frequently employ a stated-preference methodology. Therefore, we compiled an original data to provide facility-level, longitudinal observations.

²⁹ Hagelin, Christopher A. *A return on investment analysis of bikes-on-bus programs*. No. NCTR 576-05. 2005.

³⁰ Clarke, Colin F. "Evaluation of New Zealand's bicycle helmet law." *The New Zealand Medical Journal (Online)* 125, no. 1349 (2012).

³¹ Dennis, Jessica, Beth Potter, Tim Ramsay, and Ryan Zarychanski. "The effects of provincial bicycle helmet legislation on helmet use and bicycle ridership in Canada." *Injury Prevention* 16, no. 4 (2010): 219-224.

³² Dill, Jennifer, and Kim Voros. "Factors affecting bicycling demand: initial survey findings from the Portland, Oregon, region." *Transportation Research Record: Journal of the Transportation Research Board* 2031 (2007): 9-17.

³³ Pucher, John, Ralph Buehler, Dafna Merom, and Adrian Bauman. "Walking and cycling in the United States, 2001–2009: evidence from the National Household Travel Surveys." *American Journal of Public Health* 101, no. S1 (2011): S310-S317; Pucher, John, et al. "Walking and cycling to health: a comparative analysis of city, state, and international data." *American Journal of Public Health* 100.10 (2010): 1986-1992.

³⁴ Dill, Jennifer, and Kim Voros. "Factors affecting bicycling demand: initial survey findings from the Portland, Oregon, region." *Transportation Research Record: Journal of the Transportation Research Board* 2031 (2007): 9-17.

³⁵ Pucher, John, Charles Komanoff, and Paul Schimek. "Bicycling renaissance in North America?: Recent trends and alternative policies to promote bicycling." *Transportation Research Part A: Policy and Practice* 33, no. 7 (1999): 625-654.

Estimating Changes in GHG Due to Bicycle Facilities

In order to estimate changes in GHG emissions from bicycle facilities, there are three distinct analytical tasks. The first is a life-cycle assessment (LCA) of the infrastructure project and its use. LCA is a defined practice for assessing GHG emissions, with accounting rules for allocating emissions changes to a given change in some system. Our task is to choose the appropriate accounting rules, and to identify changes that are significant enough to be included in the analysis. We generate a candidate list of all activities that may result from the installation and use of the bikeway.

The second and third analytical tasks both feed into the LCA but are sufficiently complex that they merit a separate discussion. The second task is forecasting ridership on the new bicycle facility. To do this, we draw opportunistically on existing bicycle count data, where before/after data exists at sites where bicycle facilities were installed. The third task is estimating what share of bicycle ridership on a facility represents a reduction in vehicle and transit travel. To do this, we collect original survey data, asking riders on relatively new bicycle facilities in Los Angeles how they used to take the trip before the bikeway was constructed.

We intended to also account for the fuel efficiency of the vehicles that would carry the avoided vehicle trips, assuming that this would be correlated with income, and that we could estimate it using neighborhood income data from the US Census. But a recent study³⁶ of registered vehicles in California found no evidence of such a correlation, so we abandoned this parameter.

³⁶ Thomas, T., Blumenberg, E., & Salon, D. (2015). Travel Adaptations and the Great Recession: Evidence from Los Angeles County. In Transportation Research Board 94th Annual Meeting (No. 15-6027).

Life-Cycle Assessment

Accounting frames

Researchers can employ one of two accounting frames for life-cycle assessment of transportation projects. The choice of frame determines which emissions-generating activities are included within the assessment and how these activities are allocated to the bicycle facility.

Attributional LCA: average historical frame

Attributional LCA approaches assess the change in GHG emissions that has resulted from some observable change. Such approaches are retrospective, seeking to allocate average historic GHG emissions to a common functional unit, such as the number of trips or the number of kilometers travelled on a bicycle facility.

Changes in GHG emissions due to transportation projects are assessed versus a direct counterfactual trip, which is most accurately measured with an intercept survey similar to the one used in this project. Future changes in bicycle facility use are not considered, nor are any changes in future vehicle purchase decisions or the deployment of new roadway infrastructure.

Most previous transportation infrastructure life-cycle assessment studies use an attributional approach, the exceptions being Chester, et. al,³⁷ and subsequent studies employ both an attributional and a consequential approach in order to incorporate future expected mode shift from transportation projects and associated land use developments that affect travel choices over the long term.

³⁷ Chester, Mikhail, Stephanie Pincetl, Zoe Elizabeth, William Eisenstein, and Juan Matute. "Infrastructure and automobile shifts: positioning transit to reduce life-cycle environmental impacts for urban sustainability goals." *Environmental Research Letters* 8, no. 1 (2013): 015041.

Consequential LCA: marginal future frame

Consequential LCA approaches assess the change in GHG emissions that would result from a prospective change, such as the government's decision to deploy a new bikeway facility, and how that change affects other actions. A consequential LCA of an urban bikeway considers how the urban system changes as a result of the bikeway, and how this change directly or indirectly influences future effects.

While an attributional LCA is retrospective, considering only current and past use of the bikeway facility, consequential LCA considers future use, requiring a forecast of future changes in travel behavior. Thus, included in the consequential frame but not the attributional frame are future network effects: the future use of a planned bicycle network expansion is greater than the sum of the use of individual future bicycle facilities in isolation.

Also included are indirect changes in infrastructure that may result from an individual bicycle facility or network. For instance, if someone in the future decides to forego the purchase of a vehicle because of the network of bikeway facilities, this avoided vehicle manufacture would be included in the consequential frame but not the attributional frame. Also within scope are if presence of a bicycle facility makes someone more likely to replace unlinked driving trips with trips by another mode, such as transit.

Table 1 introduces the substantial differences between the attributional and consequential assessment for bikeway projects

Table 1: Substantial differences between an attributional and consequential assessment

	Attributional	Consequential
Cyclist Volumes	All observed volumes	Change in cyclist volumes resulting from the new or upgraded facility (after count minus before count)
Treatment of Forecasts	Observed historical trends	Includes predicted future changes in volumes, due to network or system effects
Trip attraction	Observed rates of trip attraction from other modes	Forecast change in trip attraction from other modes
Unlinked Travel Behavior	Excluded	Included (e.g. reduction in mid-day car trips for a would-be-motorist who now bikes to work on a new facility)

Because of the need to forecast future travel behavior and indirect effects such as avoided vehicle manufacture, consequential LCA is far more uncertain than attributional LCA. Previous research has noted that with decisions that have profound upstream impacts, attributional LCA can be misleading but consequential LCA approaches can be hampered by uncertainty.³⁸ Biofuels LCA studies use a consequential LCA approach because historic average life-cycle GHG emissions of biofuels in limited production are not an accurate predictor of future life-cycle GHG emissions from the same biofuel produced at a large scale.

³⁸ Suh, S., & Yang, Y. (2014). On the uncanny capabilities of consequential LCA. *The International Journal of Life Cycle Assessment*, 19(6), 1179-1184.

Should consequential or attributional LCA be used in the California policy environment?

Figure 1: Attributional (Retrospective) LCA versus Consequential (Prospective) LCA

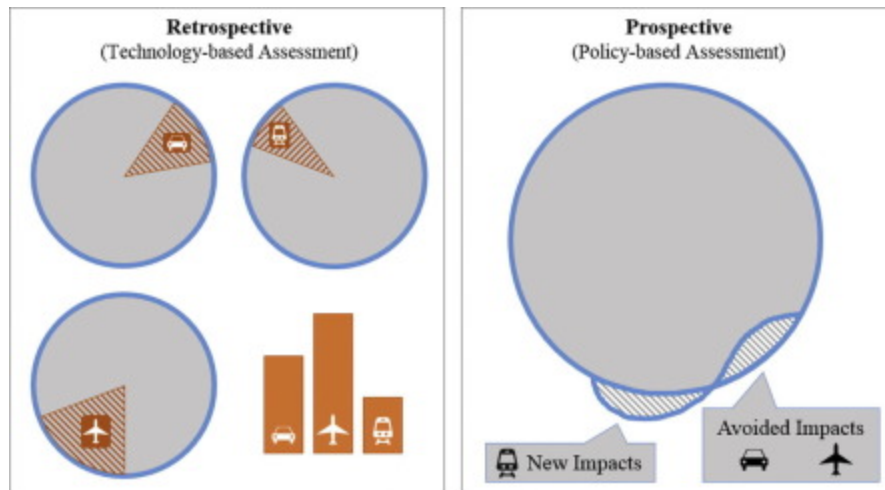


Figure from Chester and Ryerson³⁹ depicting included activities of attributional LCA (Retrospective) versus consequential LCA (Prospective)

The question asked in a consequential LCA – the prospective net life-cycle GHG effects of a decision to deploy a bicycle facility – most closely mirrors the *ex ante* decision to fund or construct a bikeway facility, as in State’s current application of bikeway GHG assessment within the Affordable Housing and Sustainable Communities program application. *Ex post* analysis of a bicycle facility that has been installed and is in use can employ an attributional approach to life-cycle assessment, which can inform future LCAs that use a consequential approach, as in this study. Because the bicycle facility does not yet exist at the time of the decision to construct a bikeway, and each facility is unique, it is not possible to conduct a true attributional LCA. Thus, any attributional LCA would instead be an estimate based on historical average values for comparable facilities. Thus we recommend a consequential LCA approach for planning and funding evaluation.

³⁹ Chester, Mikhail V., and Megan S. Ryerson. "Grand challenges for high-speed rail environmental assessment in the United States." *Transportation Research Part A: Policy and Practice* 61 (2014): 15-26.

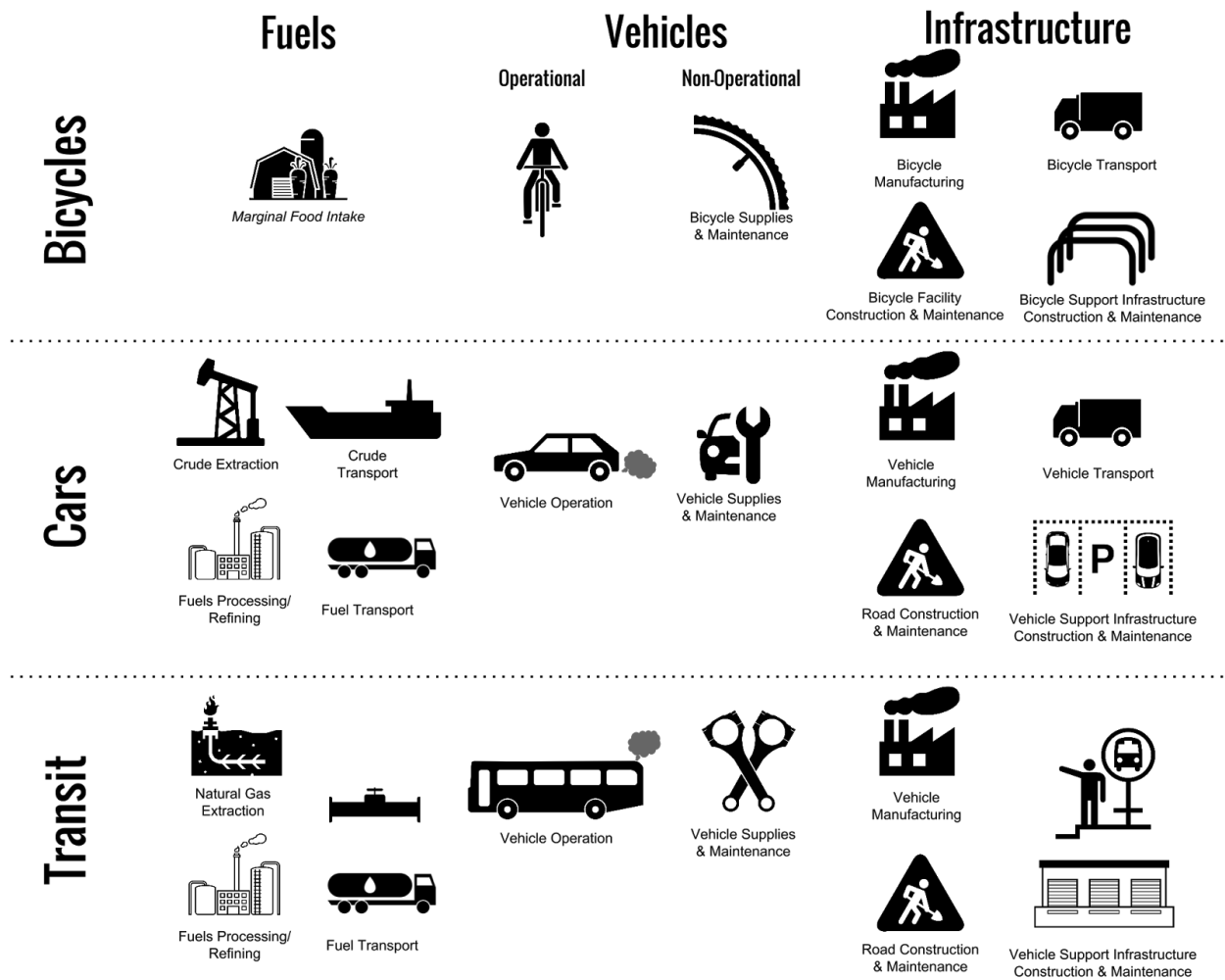
Several aspects included in a consequential LCA were beyond the scope of our analysis. We did not explore changes in unlinked travel behavior, for example someone who does not use their car for a mid-day lunch trip because they are now biking to work. We also did not explore the prediction of how network or system effects would affect future volumes. The literature suggests that network effects are significant. A 10% greater supply of bike lanes is associated with a 3.1% greater number of bike commuters per 10,000 population. Similarly, a 10% greater supply of bike paths is associated with a 2.5% higher level of bike commuting. As in our previous correlation analysis, a t-test comparison shows that the coefficients for bike lanes and paths are not significantly different from each other at the 95% confidence level.⁴⁰

Measuring Life-Cycle GHG Emissions: Activity Phases

GHG emissions-generating activities associated with bikeway use and counterfactual trips are divided into four phases: energy production, vehicle operational, vehicle non-operational, and infrastructure.

⁴⁰ 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.

Figure 2: The various emissions-generating activities and phases for bicycles, cars, and bus transit



. Icons source: TheNounProject.com

Bicycle

Fuels

Cycling requires additional human energy expenditure compared to driving or using transit.

A report by the European Cyclists Federation calculated 16 g CO₂e/km of life-cycle emissions from

the required caloric intake to replenish the cyclist's additional energy expenditure versus sedentary activity.⁴¹ We used a different approach with a revised estimate for energy premium for 10-12 MPH cycling versus sitting (342 kcal/hour), accounting for the greater average weights of Americans (78.7 kg versus 70 kg for Europeans)⁴² and the greater carbon intensity of the United States food system⁴³ (2.21 g versus 1.44 g CO₂e/kcal) to calculate 42.6 g CO₂e/km in life-cycle emissions.

In this study, we assume that calories expended on cycling activity are replaced at a one-to-one ratio. However, how cycling activity affects an individual's marginal caloric intake depends on a number of factors, including pre-existing excess caloric intake. Out of scope for this study are any energy to treat any increase in defecation from increase in food consumption and upstream extraction, transport, and refining activities for fuels used by energy-assisted bicycles.

Vehicle operational

Conventional bicycles are zero-emissions vehicles in the operating phase. Energy-assisted bicycles such as mopeds and electric bicycles have direct or indirect emissions associated with the operating phase, but are beyond the scope of this study.

Vehicle non-operational

Vehicle non-operational activities include manufacturing, transporting, and end-of-life activities associated with bicycle supplies and maintenance, such as expendable parts (e.g. tires, tube, brake pads). An LCA of bicycle manufacturing and maintenance using SimaPro 8.0.3 calculated

⁴¹ Blondel, Benoît, Chloé Mispelon, Julian Ferguson. "Cycle more Often 2 cool down the planet!" European Cyclists' Federation. (2011). Retrieved at <https://ecf.com/sites/ecf.com/files/co2%20study.pdf>.

⁴² Fryar CD, Gu Q, Ogden CL. Anthropometric reference data for children and adults: United States, 2007–2010. National Center for Health Statistics. Vital Health Stat 11(252). 2012.

⁴³ Weber, C. L., & Matthews, H. S. (2008). Food-miles and the relative climate impacts of food choices in the United States. *Environmental Science & Technology*, 42(10), 3508-3513.

life-cycle emissions of 22.4 kg CO₂-e for maintenance activities over the bicycle's lifetime of 5,000 km (3107 miles).⁴⁴

The disposal of bicycle tires can produce net emissions if the material is combusted or landfilled. The California Department of Resources Recycling and Recovery (CalRecycle) maintains an active tire recycling program. The United States EPA's WARM model estimates recycling each kg of tire leads to a 432 g reduction in CO₂e versus the emissions that would be generated from the use of virgin materials.⁴⁵

Infrastructure

We examine three types of bikeway infrastructure for this project: A class 1 dedicated bicycle path, a class 2 striped bike lane, and a class 4 cycle track or protected bike lane. We assume a class 1 dedicated facility is a 4.26-meter wide path constructed with graded and compacted soil, a rock aggregate subbase, an asphalt or concrete base and surface layer, topped by slurry sealant. We assume a class 2 on-street bicycle lane utilizes existing roadway with new epoxy-based durable liquid pavement marking (DLPM) striping. We assume a class 4 protected bikeway is a 3.6-meter wide facility resurfaced with on-site recycled aggregate and asphalt binding and slurry sealant, with HDPE plastic and steel delineators placed at an average of 20-foot intervals. Because the aggregate material is recycled-in-place for this facility, there are far less emissions associated with the extraction, processing, and transport of raw materials. We assume the years of useful life and total infrastructure emissions shown in Table 2.

⁴⁴ PRé Sustainability. SimaPro Software. (2013).

⁴⁵United States Environmental Protection Agency. Waste Reduction Model. (2015).

Table 2 Bikeway infrastructure lifespan and emissions per kilometer

Bikeway Type	Infrastructure lifespan	kg CO₂e/km/year
Class 1 Path	20	2,496.6
Class 2 Lane (Restripe)	10	55.0
Class 4 Protected/Cycle track	15	271.1

Bikeways without slurry or sealant (for example, rural greenways paved with decomposed granite) would have reduced emissions associated with the infrastructure. Our model is not sensitive to this.

In the case of a class 2 on-street bicycle facility repurposed from an existing automobile right-of-way (e.g. road diet), a pure attributional approach would consider the fractional historic infrastructure being repurposed, with an amortized deduction for previous use as an automobile facility. A pure consequential approach would not consider the fractional historic infrastructure being repurposed. Because the timeframe for a class 2 facility's previous use for automobiles is unknown and varies between facilities, and because automobiles continue to wear class 2 facilities, we exclude the fractional historic infrastructure from our analysis.

Because we perform a consequential assessment of the decision to fund bikeway infrastructure, we allocate 100% of the in-scope facility infrastructure to the bikeway project. This is in contrast to Matute and Chester⁴⁶, which allocated a portion of the infrastructure to walking and recreational cycling purposes.

⁴⁶ Matute, J. M., & Chester, M. V. (2015). Cost-effectiveness of reductions in greenhouse gas emissions from High-Speed Rail and urban transportation projects in California. *Transportation Research Part D: Transport and Environment*, 40, 104-113.

Bicycle manufacture

The results of an LCA of bicycle manufacturing and maintenance differs depending upon assumptions of where the bicycle is manufactured. Assuming an aluminum frame bicycle manufactured in China and sold in California, an LCA of bicycle manufacturing and maintenance using SimaPro 8.0.3 calculated 110 kg CO₂-e emissions associated with manufacturing.⁴⁷

Car

Fuels

Energy production and vehicle operational

Life-cycle emissions from fuel extraction, transport, and refining activities can be significant. California has adopted the Argonne National Laboratory's GREET model to create state-specific well-to-tank values for a variety of fuels for use in the administration of the Low Carbon Fuel Standard program.⁴⁸ For this study, we used two values for energy production emissions, based on the marginal car studied by Chester et. al (2013): a 35 mile per gallon (MPG) vehicle operating in Los Angeles traffic conditions, and an average Los Angeles County vehicle: a 21.6 MPG vehicle with fuel efficiency derived from the California Air Resources Board's EMFAC 2014 model,⁴⁹ which accounts for vehicle registration and average congestion levels in the county. We assumed the 1.7 average occupancy of Chester's Los Angeles sedan for both prototypical vehicles. We assume vehicles use California Air Resources Board Oxygenated Blend Gasoline. We do not account for facility or corridor-level variations in system operations efficiency (e.g. congestion).

⁴⁷ (PRé Consultants, 2013). PRé Sustainability. SimaPro Software. (2013).

⁴⁸ California Air Resources Board, 2015.

⁴⁹ California Air Resources Board. EMFAC2014 Web Database. Retrieved at <http://www.arb.ca.gov/emfac/2014/>

Vehicle non-operational

The disposal of vehicle tires can produce net emissions if the material is combusted or landfilled. The California Department of Resources Recycling and Recovery (CalRecycle) maintains an active tire recycling program. The United States EPA's WARM model estimates recycling each kg of tire leads to a 432 g reduction in CO₂e versus the emissions that would be generated from the use of virgin materials.⁵⁰

Infrastructure

A roadway is constructed with a compacted soil, a rock aggregate subbase, an asphalt or concrete base and surface layer, and a slurry or seal. Additional materials such as curbs, lane markings, and signage are also needed. Regular operation of a roadway includes street lighting and traffic control systems. Frequent maintenance includes street sweeping. Occasional maintenance includes salting, herbicide spraying, resurfacing, and reconstruction. Support infrastructure includes the roadway shoulder and parking facilities. Previous work by Chester, et. al, (2013) for Los Angeles County, California yielded an estimate of 9.4 g CO₂e per vehicle kilometer traveled for roadway and parking infrastructure construction and operation.

Motor vehicle manufacture

The extraction of raw materials, parts logistics to support manufacture, and transport of vehicle from point of manufacture to point of sale produces significant levels of GHG emissions. Previous work by Chester, et. al (2013) for Los Angeles County, California yielded an estimate of 28.6 g CO₂-e per kilometer traveled for vehicle manufacture and maintenance.

⁵⁰ (United States Environmental Protection Agency, 2015. Waste Reduction Model. Available at <https://www3.epa.gov/warm>

Transit

Many models to estimate greenhouse gas reductions from bikeway projects, including the CARB methodology, ignore the GHG emissions impact of mode switching from transit to bike.⁵¹ This is problematic for a number of reasons. Studies have shown that a large portion of new bikers switch from transit, or chain biking with a transit trip,⁵² with one study concluding that transit and biking compete more for mode share than do biking and driving.⁵³

The European Cyclist Federation life-cycle assessment of bus transit, which uses European averages, attributes GHG emissions per passenger kilometer based on an average bus occupancy rate of 10, and find 6 g GHG emissions for production and maintenance, and 95 g per passenger kilometer for operations (mainly fuel).⁵⁴ The European Cyclist Federation operations estimate is based on an assumption that 70% of bus trips are urban while 30% are regional, a split that is likely specific to the locations studied. Accounting for mode shift from transit to bicycles is necessary since calculating GHG emissions for bus trips involves many of the same activities.⁵⁵

We calculate Los Angeles specific values for transit trips based on the North American Bus Industries 60-foot BRT articulated buses operating on the Los Angeles Metropolitan Transportation

⁵¹ E.g. Brand, C., Goodman, A., Ogilvie, D., & iConnect consortium. (2014). Evaluating the impacts of new walking and cycling infrastructure on carbon dioxide emissions from motorized travel: A controlled longitudinal study. *Applied energy*, 128, 284-295.

⁵² ICF International. *Metro Orange Line Mode Shift Study and Greenhouse Gas Emissions Analysis*. (2011). Retrieved from

http://media.metro.net/projects_studies/bikeway_planning/images/Metro_Orange_Line_Study_March_2011.pdf.

Larouche, Richard. "The environmental and population health benefits of active transport: A review." (2012).

Blondel, Benoît, Chloé Mispelon, Julian Ferguson. "Cycle more Often 2 cool down the planet!" European Cyclists' Federation. (2011). Retrieved at <https://ecf.com/sites/ecf.com/files/co2%20study.pdf>.

⁵³ Meggs, J., & Schweizer, J. (n.d.). Effects of Bicycle Facility Provision on Mortality Prevention and GHG Reduction : Cost-Benefit Analyses within the BICY Project, 1–18.

⁵⁴ Blondel, Benoît, Chloé Mispelon, Julian Ferguson. "Cycle more Often 2 cool down the planet!" European Cyclists' Federation. (2011). Retrieved at <https://ecf.com/sites/ecf.com/files/co2%20study.pdf>.

⁵⁵ Glover, Leigh. "What Could Increased Cycling Contribute to Reducing Australia's Transport Greenhouse Gas Emissions?." *GAMUT* (2010): 1.

Authority Orange Line studied by Chester, et. al., (2013). We use two values based on the average vehicle occupancy of a high-productivity line (66.7 g CO₂e/passenger km, based on 37 passengers as on the Orange Line) and the average occupancy of Los Angeles Metro buses (121.4 g CO₂e/passenger km, based on 16.6 passengers)⁵⁶.

Estimating Reductions in VMT and Transit Miles Traveled

For the purposes of estimating GHG reductions, we are primarily interested in avoided vehicle trips and avoided transit trips. Our model is relatively simple and, as we will find, quite conservative. We estimate avoided vehicle trips as a percentage of the cyclists using the facility, using data from an intercept survey that asked Los Angeles cyclists what mode they would have taken if the bike lane did not exist. We estimate trip length using data from that same survey.

For *ex ante* analysis of bikeways that have not yet been constructed, we estimate the cyclists that will use the facility as a function of the number of people currently cycling at site of the proposed facility, as measured by bicycle counts. For this, we draw on a data set of before/after counts for bicycle facilities installed in various cities in the US.

We estimate avoided VMT as

$$\text{VMT} = \# \text{ of avoided vehicle trips} * \text{average length } L \text{ of avoided trips}$$

And we estimate avoided vehicle trips as a percentage of observed bicycle ridership:

$$\text{Trips}_{\text{avoided}} = V_b * m_v \quad \text{and}$$

⁵⁶ Figure calculated using National Transit Database (2014) [Table 19: Service Supplied and Consumed](#). Passenger miles of travel / vehicle miles of travel for directly-operated motorbus service.

$$\text{Trips_avoided} = V_b * m_t$$

Where V_b is annualized bicycle volumes and m_v and m_t are percentages of all of the observed ridership, corresponding to the percent of riders that would have traveled in a private vehicle and the percent of riders who would have taken transit, respectively. We estimate trips_avoided in this fashion because V_b is straightforward to measure by conducting bicycle counts. We estimate m_v and m_t as a static parameter (the mean shifted trips mode share from our surveys). While m_v is more likely to depend on contextual factors like the demographics around the bikeway, bikeway design, the price of parking, and car ownership around the bikeway, our survey dataset is too small to estimate m_v as a function of any of these things. Future research should examine this. More survey data collection is needed to reveal the nature of such relationships.

Likewise, we estimate L as a static parameter based on the average trip length in our survey responses. As with m_v , the length of avoided trips probably depends on the context, particularly upon the density of urban development and bikeway network connectivity. It stands to reason that a longer new bicycle facility will enable for the substitution of longer trips than a shorter bicycle facility. As above, the specification of this estimate as a simple static parameter is driven by the small size of our survey data set, and future research should examine a more refined model for the length of avoided trips.

From intercept surveys, we find that average trip distance L is about 11.28 km (7 miles). We find that m_v ranges from a low of 1.9% in the poster responses to 10-25% (depending on trip purpose and facility type) in the dismounted survey responses. m_t is 12.6% in the poster responses and 9-30% (depending on trip purpose and facility type) in the dismounted responses. The average trip distance L is notably longer than that found in the two large datasets that have information on

bicycle trip length, the American Community Survey and the National Household Transportation Survey; both of these datasets show average trip lengths closer to 3.2 to 4.8 km (2 to 3 miles).⁵⁷⁵⁸ Further detail on these parameters and some checks on their external validity are in the following section on Data Collection and Analysis.

Estimating bicycle ridership

For *ex post* estimation of GHG impacts of an existing bikeway, V_b (volume of bicyclists) can simply be measured by conducting counts. For bicycle facilities that have not been built yet, e.g. in the context of infrastructure funding decisions, we find that V_b can be relatively well estimated by conducting bicycle counts before the facility is built.

Our approach uses opportunistically gathered before and after count data from bicycle lanes and cycle tracks installed in the cities of Los Angeles, San Francisco, Honolulu, Portland, Chicago, Denver, Austin, and the District of Columbia. Our dataset consists of 46 before and after bicycle counts at 44 locations where bicycle infrastructure was installed. We find that the volume before facility installation, along with the age of the bikeway, are the parameters most closely related to the current bicycle volume. Surprisingly, we do not find a clear relationship between facility type (cycle track vs. bicycle lane with striping only) and bicycle volumes.

We find that a 15-85 percentile range for increases in ridership is from 4% to 254%.

⁵⁷ ACS data from McKenzie, Brian (2014). "Modes Less Traveled - Bicycling and Walking to Work in the United States, 2008-2012." *American Community Survey Reports*. Accessed at <https://www.census.gov/prod/2014pubs/acs-25.pdf>. 19.3 minutes is the average time duration of a bicycle commute; assuming average speeds of roughly 6 minutes per mile, this is just over 3 miles.

⁵⁸ NHTS data from Dolati, Haleh (2014). "Biking Distance: Exploring Gender, Race, and Climate." Thesis, Graduate Program in City and Regional Planning, The Ohio State University. Accessed https://etd.ohiolink.edu/!etd.send_file%3Faccession%3Dosu1388725654%26disposition%3Dinline, p. 29.

Data Collection and Analysis

Intercept Surveys

In Los Angeles, we used original survey data to study whether cycling infrastructure improvement led to a change in travel behavior, and the nature of bike trips on relatively new facilities in Los Angeles County. While counts can tell us whether cycling has increased at study locations, surveys allow us to understand whether changes in ridership can be attributed to new trips, mode switching, or route change. Pairs of UCLA student researchers conducted surveys and counts simultaneously at each location. In an effort to maximize response rate, we constructed two surveys: a five-minute survey that required the rider to dismount, and a single multiple choice question displayed on a poster that could be answered without dismounting.

Surveys were conducted in January and February 2016. At each location, surveys were conducted for a total of 16 hours in the following time periods: 7-11 AM, 11 AM - 3 PM, and 4-8 PM. The survey instruments and procedures, including procedures to survey minors, were approved by UCLA's Institutional Review Board (IRB#15-000468).

The five-minute survey was administered orally in English and Spanish. In the five-minute survey, we asked riders about their decision-making regarding their current trip, trip purpose, their origin and destination, whether they had a vehicle available for the trip, as well as basic demographic information, detailed in Appendix B.

Location selection for intercept surveys and bicycle counts in Los Angeles

In order to ask respondents about changes in mode choice and trip-making due to biking infrastructure improvements, we specifically chose biking infrastructure in Los Angeles County that

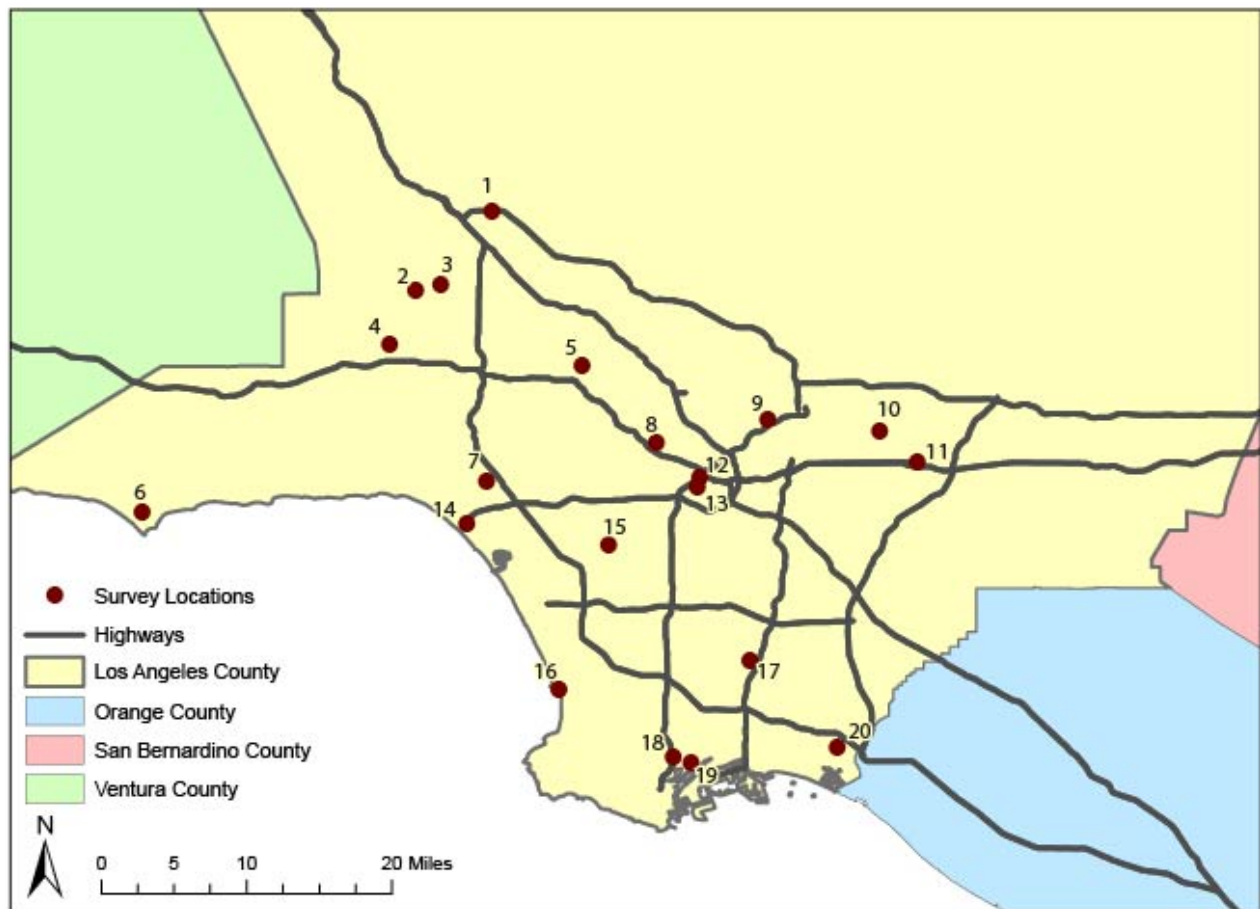
had recently been installed or upgraded. We selected locations in Los Angeles County that had cycling infrastructure improvements that occurred in the past 2 years and were at least 0.75 miles (1.2 km) long. We aimed to include as many very recent projects as possible, and included several that were less than six months old. Using recently upgraded infrastructure allowed us to ask survey respondents about how they traveled before the bicycle lane or path was installed. As described more fully below, it also allowed the opportunity for respondents to describe whether the infrastructure has influenced their travel decisions more generally. We compiled this list using current bike route maps, and determined the date of infrastructure improvement using either news stories or archived Google Maps Street View⁵⁹.

We also prioritized locations at which there were bike counts taken before the facility improvements, so that we could simultaneously conduct bicycle counts and thus augment our data set of before- and after- count data. We then prioritized the list to maximize the diversity of study locations according to type of cycling infrastructure, geographic location, and demographics of the immediate surrounding area.

The final 20 count/survey locations are as shown below and described in [Appendix A](#).

⁵⁹ Google. Google Maps Street View Feature. (2016). Available at <http://www.google.com/maps/streetview/>

Figure 3: Count and survey locations



Bike counts

Bike counts were conducted using a standard screenline methodology specified by the Southern California Association of Governments in 2012.⁶⁰ This records each person on a bicycle who is traveling along a segment or roadway (as opposed to an intersection). Bicycle counts allow us to understand the response rate of our surveys and tallies, and in some cases allow us to collect the “after” count and augment our before and after data set. Our counts also capture direction of

⁶⁰ Southern California Association of Governments. “Conducting Bicycle and Pedestrian Counts: A Manual for Jurisdictions in Los Angeles County and Beyond.” (2013). Available at http://media.metro.net/projects_studies/call_projects/images/metroscag_bikepedcounttrainingmanual.pdf

travel, sidewalk riding, gender, and wrong way riding. For more information on the methodology and a copy of the form used, see bikecounts.luskin.ucla.edu.

Survey Results

The poster survey received 463 responses. The five-minute oral survey received 155 responses.

Respondents

The responses to the poster and the oral survey differ markedly. Many fewer of the poster respondents said that the bike facility influenced their travel behavior, as described further below. The distribution of respondents across locations was also different for the two survey instruments, as shown in Table 3.

Table 3: Tier 1 and Tier 2 survey respondent locations

Location	Poster Responses	Oral Survey Responses	Poster %	Oral Survey %
Rosemead Blvd	2	1	0.4%	0.6%
Los Angeles River at Winnetka Ave	1	14	0.2%	9.0%
Foothill Blvd	0	1	0.0%	0.6%
Harbor Dr	300	50	64.8%	32.3%
Pico Blvd	11	12	2.4%	7.7%
Edgemont St	8	8	1.7%	5.2%
Reseda Blvd	10	3	2.2%	1.9%
2nd St	11	7	2.4%	4.5%
Figuerroa Blvd	4	4	0.9%	2.6%
7th St	63	9	13.6%	5.8%
York Ave	7	6	1.5%	3.9%
Vineland Ave	4	2	0.9%	1.3%
San Vicente Blvd	14	18	3.0%	11.6%
Tyler Ave	6	6	1.3%	3.9%
Louise Ave	1	2	0.2%	1.3%
E Atherton St	6	6	1.3%	3.9%
E Artesia Blvd	10	3	2.2%	1.9%
Pacific Coast Highway	0	1	0.0%	0.6%
Avalon Blvd	2	2	0.4%	1.3%
Slauson Ave	3	0	0.6%	0.0%

Notably, the Harbor Drive class 4 cycle track was the source of nearly $\frac{2}{3}$ of the poster responses, while this location did not dominate the oral survey to nearly the same degree. This facility upgraded (from class 2 to class 4) a 1.11 km gap in the 35.4 km beachside class 1 Marvin Braude Bike Trail, commonly used for recreation. Because this facility closes a short gap in a popular class 1 facility that was constructed over 30 years ago, cyclists who previously traveled on the class 2 gap may have reported they would have used a bicycle anyway if the facility had not been upgraded.

Table 3 also shows that despite our efforts to obtain responses from a variety of locations throughout the County, we had very few responses from some locations. Possible factors causing people not to respond include low ridership, language barriers, and the percentage of riders that are on time-sensitive utilitarian trips.

62% of the respondents to the oral survey were recreational riders, and 65% of the respondents were riding on the Harbor Drive cycle track. Further, 28% of the oral survey respondents were recreational riders who were riding on Harbor Drive.

The respondents were relatively diverse in terms of sex, age, race, and income. 22% were female and 78% were male, a similar ratio to that found in field counts of cyclists in LA County. In terms of race, 46% were white, 20% were Latino, 14% were Asian, and fewer than 3% were black. In question 14, we asked respondents to choose their income range from the five income quintiles for households in Los Angeles County. Only 109 respondents chose to answer this question. The responses skewed to the top and bottom of the income distribution: 26% in the lowest quintile (1 of 5), 13% in quintile 2, 12% in quintile 3, 24% in quintile 4, and 25% in the top quintile. This is consistent with the National Household Travel Survey.

Mode Shift

Figure 4 displays the results from the poster survey. Most respondents (72%) said they would still ride at the survey location if the bike lane did not exist. The next most common response was that the respondent would shift their route if the bike lane did not exist (13%). Only 3.5% stated that they would take the bus and 1.9% stated that they would use a car.

The results from the longer, dismounted survey showed similar rates of respondents who said that the bike lane did not affect their decision to ride there, but within the respondents who

said it *did* affect their choices, the results were much different. Rates of mode shifting were much higher.

Figure 4: Stated mode shift from non-dismount survey

Results from non-dismount poster survey (N=463). "If this bike lane did not exist, I would:"

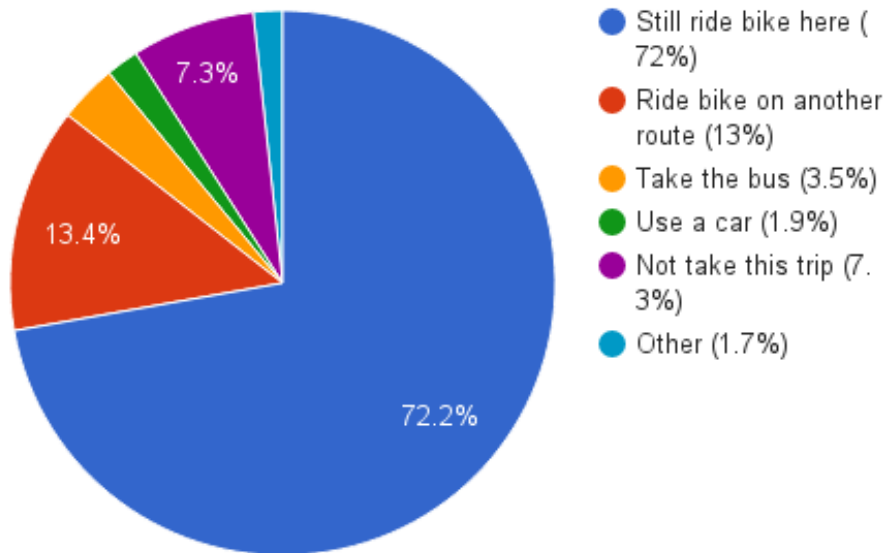


Table 4: Stated mode shift from oral surveys

	Non-dismount Poster Survey	Long Survey (All)	Long Survey (Class 2)	Long Survey (Class 4)
N	463	155	86	69
Ride bike this route	72.40%	29.82%	35.71%	24.79%
Ride bike other route	13.40%	37.16%	38.78%	35.54%
Take bus	3.50%	6.42%	11.22%	3.31%
Use car	1.90%	11.01%	7.14%	14.05%
No Trip	7.30%	11.47%	6.12%	15.70%
Other (e.g. walked)	1.70%	4.13%	1.02%	6.61%

Trip Purpose

63% of respondents stated that their trip purpose was recreational. 29% of respondents were cycling for utilitarian purposes, including 14% that they were commuting to or from work, 8% travelling family or personal purposes, and 7% said they were making a shopping trip. The other respondents were either travelling for other purposes, or a combination of the purposes.

As stated above, a majority of the trips were stated to be for recreational purposes. This is a significant finding, as many of the recreational riders did state that the bike lane influenced their choice to bike. This typically overlooked trip purpose is thus quite significant for determining whether bicycle facilities reduce GHG. Presumably, recreational riders who state that they would have driven if the bicycle facility did not exist would have driven their car to ride recreationally in a different location. Certainly we can expect that the share of recreational riders would vary from place to place, but more data would be needed to understand the typical ranges and how they are distributed. Still, this finding is a caution that data on utilitarian trips (such as Census American Community Survey data) misrepresent the spatial distribution of cycling, and that facilities with a potential to draw many new recreational riders may be quite competitive in their potential to reduce GHG.

Facility Catchment Zone

The origin and destination information allowed us to calculate the average distance someone would ride to use the facility, or the “catchment zone” for each facility. We treated each trip as two data points, using both the distance from trip origin to count location and count location to trip destination. The average trip distance was fairly high, 7 miles.

We used open-ended questions on the intercept survey to encourage a greater response rate from riders who may be uncomfortable giving an exact address, which resulted in origin and destination information varying in specificity. For example, a respondent might state their destination as “5th and Flower” or “downtown Los Angeles.” We had to make judgement calls about how to geocode their responses. Of 155 intercept survey respondents, and considering only the responses that produced a fairly specific location to which to geocode, 110 gave both origin and destination information, 132 gave only origin, and 117 gave only destination information.

We measured the distance from each origin and destination to the count location using bike route direction from google maps. We generally used the suggested route. For recreation trips on a bike path, we used the distance that maximized time on the bike path. We used exact addresses or specific landmarks if they were given. If a general location was given, for example a neighborhood or zip code, we used the central location given by Google Maps. For riders who gave a general landmark (for example, “the grocery store”), we used the nearest location depending on the direction of the rider. The mean total trip length was 7 miles, and the median total trip length was 5.3 miles.

We note that these trip lengths are longer than is generally observed in American Community Survey and National Household Travel Survey data, which find mean trip lengths of about 3 miles and about 2 miles respectively. . It may be the case that our geocoding procedure resulted in longer trip lengths. It may be the case that respondents overstate their trip distances. Or, it may also be due to our sample’s high proportion of recreational trips. Finally, it may be the case that average trip lengths in Los Angeles and at the sites we studied are longer than national average trip lengths.

Data Limitations and Sources of Bias

The poster survey was in English, and Los Angeles County has a significant population of people who do not speak English.

Willingness to dismount the bicycle and respond to the five-minute oral survey is a likely explanation for the large differences between the responses to the poster and the responses to the oral survey. In particular, the prevalence of mode switching vastly differed between these two response groups: only 2% of poster respondents stated that they would use a car if the bike lane did not exist, while over 14% of dismounted oral survey respondents said they would use a car. We suspect that the divide between the two groups may be along the lines of utilitarian / recreational. Over 60% of the oral survey respondents were riding for recreation.

Before and After Counts

The intercept surveys provide measures of stated preference -- stated previous mode, trip length, and others -- that are useful to evaluating the GHG impacts of bicycle facilities. Before and after bicycle counts complement those data with a measure of revealed preference: how much new ridership new facilities induce. The bicycle count data used in this project were painstakingly assembled from two types of sources: 1) professionals working in bicycle and pedestrian planning throughout the United States and Canada and 2) published reports and open-data websites. Many of these people were contacted directly or through the Association of Pedestrian and Bicycle Professionals. Data came back in many formats and with a varying degree of granularity. The process of bicycle counting has become generally more standardized through efforts such as the National Bicycle and Pedestrian Documentation Project, as well as UCLA's own Bicycle Count Data Clearinghouse⁶¹. However, because city planning departments have a wide range of resources and

⁶¹ Available at <http://bikecounts.luskin.ucla.edu>

expertise available, as well as a wide variety of purposes and reasons for counting, the collection and management of count data as well as the count methodology is very different from city to city.

Because we need to match count locations and data to facility changes, it was ideal when cities were able to provide updated GIS shapefiles of their bicycle route network. (We originally envisioned that we would calculate a network connectivity variable using bikeway network files, but it proved to be very difficult to find or create network files that would be historically accurate to the point in time when a given bikeway facility was constructed.) When cities did provide a bikeway network file, (San Francisco and Portland) we geocoded count locations using Google Earth and layered onto the network shapefile in GIS. A spatial proximity analysis was then used to isolate any count locations that were adjacent to any facility changes. In other cases, count spreadsheets provided to us included facility type data which we could then use to organize and filter the data for only count locations that were adjacent to bikeway facility changes.

Some cities and researchers have conducted ridership studies that analyze count data from before and after bikeway changes. Ridership change findings from these reports were collected and incorporated into our dataset. One of the most thorough reports of this kind is Portland University's Lessons from the Green Lanes study⁶² from which we used data, after communicating with primary authors of the report, Jennifer Dill and Nathan McNeil. We also include data from studies of installed facilities in Honolulu and Denver. The cities we collected data from and the respective number of facilities studied in each city are listed below.

To create facility project extents as GIS line features, we followed one of two procedures. In Portland and San Francisco, we had GIS files for the bikeway network with an attribute variable for the date installed. We identified contiguous sections of bikeway that were installed at the same

⁶² Chris Monsere, Jennifer Dill, Nathan McNeil, Kelly Clifton, Nick Foster, Tara Goddard, Matt Berkow, Joe Gilpin, Kim Voros, Drusilla van Hengel, Jamie Parks (2014). Lessons From The Green Lanes: Evaluating Protected Bike Lanes In The U.S. http://www.ssti.us/wp/wp-content/uploads/2014/07/ProtectedBikeLanes_NITC-June2014.pdf

time. In Los Angeles, the City provided a detailed table with a description of the bikeway project extents, and we drew custom line features to match. In Austin, Chicago, and Denver, the facilities were studied by the Green Lane Project and we referenced the facility extents described in that report.

Table 5: City count locations

City	Number of Bicycle Facilities Studied
District of Columbia	14
Portland	10
Los Angeles	9
San Francisco	4
Austin	3
Chicago	2
Denver	1
Honolulu	1
Total	44

Standardizing count data to calculate percent change in ridership

Each city in the dataset uses different count methodologies and durations. In some cases, count durations for the before time period were not equal to count durations for the after time period. For a given location, we standardized the before and after volumes so that they were in equivalent units, by normalizing the volumes to a common duration. For example: if we had a before count that found 20 cyclists over a 2 hour period, and an after count that found 10 cyclists over a 1 hour period, we would normalize them both to estimates of 10 cyclists per hour.

It is well known that bicycle volumes vary in somewhat systematic temporal patterns by time of day, day of week, weather, and season of the year.⁶³ What is less well known is the nature of

⁶³<http://njbikeped.org/wp-content/uploads/2013/02/5-Estimating-Annual-Average-Daily-Bicyclists-Error-and-Accuracy.pdf>

these variations and the extent to which they are locally specific. It could be possible to estimate annual volumes for each site in order to render the 44 locations comparable to one another, but we do not attempt this. Rather, we simply calculate the percent change in volume (*after - before / before*) for each site.

This method certainly has its drawbacks: it is not sensitive to volume changes that might be due to these systematic temporal patterns. On the other hand, in most cases cities attempted to eliminate the effect of these variations by counting at relatively consistent times: typically always during peak hours on week days, and in the case of annual counts, often during a similar month of the year. Further, it is not clear what the error around our annual estimate would be if we attempted to account for these temporal patterns without locally specific data for each city to support the calculation of localized hour-of-day, day-of-week, month-of-year, and weather factors, and such an effort would be quite arduous.

Demographic variables

Given that previous studies have found that certain demographics are correlated with increased cycling compared to the general population, we sought to examine whether facility improvements in neighborhood with these demographics will experience a larger number of new cyclists. But there is little research on how demographics that correlated with levels of cycling at the city, region, or state level impact changes in ridership at the facility level.

We used demographic variables that have been found to have a significant impact on bicycle ridership based on our literature review. These were age, gender, race, income, education level, current college enrollment, employment status, household type, population density⁶⁴ and employment density. In order to expedite the data assembly and processing, we were able to

⁶⁴ Dill, Jennifer, and Theresa Carr. "Bicycle commuting and facilities in major US cities: if you build them, commuters will use them." *Transportation Research Record: Journal of the Transportation Research Board* 1828 (2003): 116-123.

include most, but not all, of these. Not included were measures of education level, employment status, household type, and employment density.

We used demographic data from the 2014 American Community Survey (ACS) 5-year estimates at the block group level. Although the installation dates of the facilities vary, using a single ACS survey greatly facilitated the process. The median facility installation year was 2011, so this dataset is a relatively good measure of demographics at the time of facility installation.

Transportation variables

The choice to bicycle is determined by many interdependent variables that include accessibility to locations, the structure of the transportation network, and the relative attractiveness of other options. Understanding of the role that a given biking facility plays in a larger transportation network helps us better determine the impacts of a facility-level change on bicycle ridership,⁶⁵ and, through modeling of mode choice decisions, the overall impacts on GHG emissions. For example, does a bike lane in a connected bikeway network yield more new ridership than an isolated facility change? Such questions could be addressed with a set of variables related to local transportation conditions and options.

Using ACS data, we calculated the median commute time, the number and share of bike commuters, and the percentage of households without a vehicle for the catchment area around each count location. The advantage of these variables is that they are readily available. Further work could be done to compile other, salient variables, such as those related to public transportation service, bicycle access on public transportation (e.g. bikes on buses), bike sharing, parking and gas prices, or non-infrastructure variables such as bicycle helmet laws.

⁶⁵ Pucher, John, Jennifer Dill, and Susan Handy. "Infrastructure, programs, and policies to increase bicycling: an international review." *Preventive medicine*. 50 (2010): S106-S125.

Geoprocessing to associate variables with facilities

The Census demographic and transportation-related variables are associated with Census geographies, e.g. tracts, block groups, and blocks, while the bicycle facilities are stretches of roadway represented by line features in a GIS. Significant geoprocessing is thus necessary to associate the Census variables with facilities. We draw on our intercept survey results to assume a catchment zone of 2.4 miles. The median reported distance from respondents' origins to the count site was 2.3 miles, and the median reported distance to their destinations was 2.5 miles. One could argue for large catchment areas: median total trip length is 5.3 miles and mean trip length is 7.0 miles. But smaller catchment areas allow for greater discernment between facilities that are near one another. Future work could better test the predictive utility of calculating Census variables at varying catchment zones.

The geoprocessing steps proceed as follows:

1. Calculate a 2.4 mile planar buffer around the line feature representing a bicycle facility project
2. Determine the Census block groups that intersect with this buffer
3. Proportional allocation:
 - a. For those block groups that fall partially within the buffer, divide them so that the area that does fall within the buffer is a separate polygon feature. Calculate the area of this feature.
 - b. Proportionally allocate Census variables according to the area that falls within the buffer. For example, if 100 people live in a Census block, and 45% of the block's area is within the buffer, allocate a population of 45 people.

4. Calculate various sums and weighted averages, over all block groups and block group portions that intersect with the buffer, as follows:
 - a. Sum of population
 - b. Sum of Non-Hispanic White population
 - c. Sum of bicycle commuters
 - d. Sum of currently-enrolled university students
 - e. Sum of households without a vehicle
 - f. Weighted average of median income: sum of [*median income* * *households*], divided by the total households in block groups with a valid median income value
 - g. Weighted average of median age: sum of [*median age* * *households*], divided by the total households in block groups with a valid median age value
5. Formally associate these sums and weighted averages with the bicycle facility project line feature (known as *Join* in GIS).

As this process is lengthy and technical, we developed a geoprocessing model to automate the sequencing of steps and field calculations. [Appendix C](#) is a visual depiction of the model. Such a model allows this process to be run on any new bicycle facility project and could be of great value to agencies seeking to differentiate between potential bikeway projects.

Results

Nearly all of the bikeways showed an increase in ridership. Five of 44 did show decreases in ridership. Recall that percent change in ridership = $(\text{after volume} - \text{before volume}) / \text{before volume}$.

Table 6: Descriptive statistics for percent change in ridership.

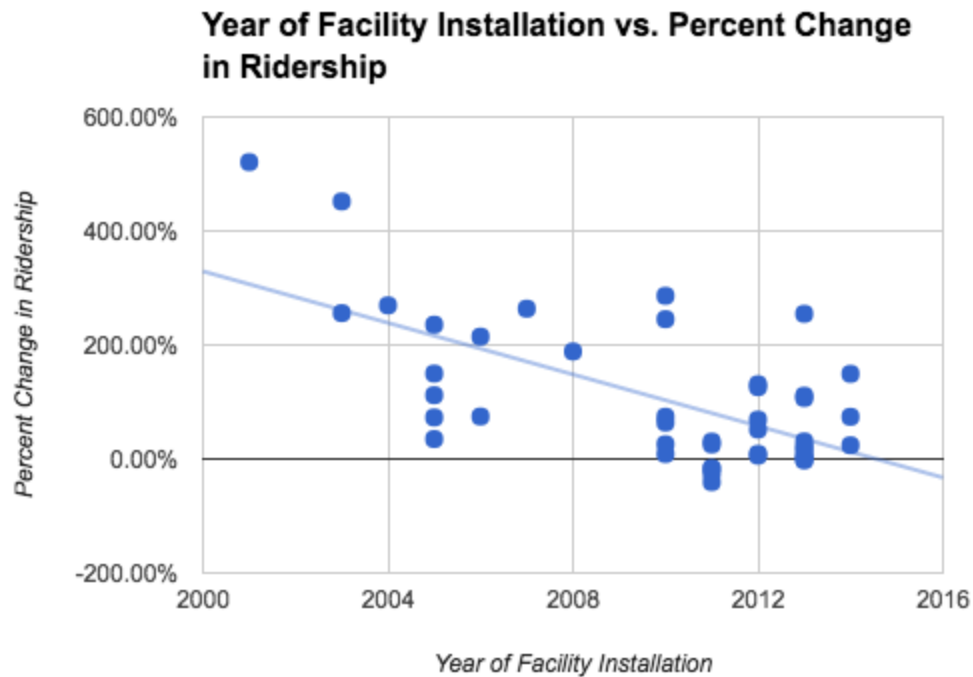
	Percent Change
minimum	-41%
15th percentile	4.0%
median	73%
mean	110%
85th percentile	250%
maximum	520%

We find that the mean percentage change is 110%, which means that on average, ridership more than doubled. Some outstanding sites had ridership increases of over 200%, and the maximum increase observed was over 500%.

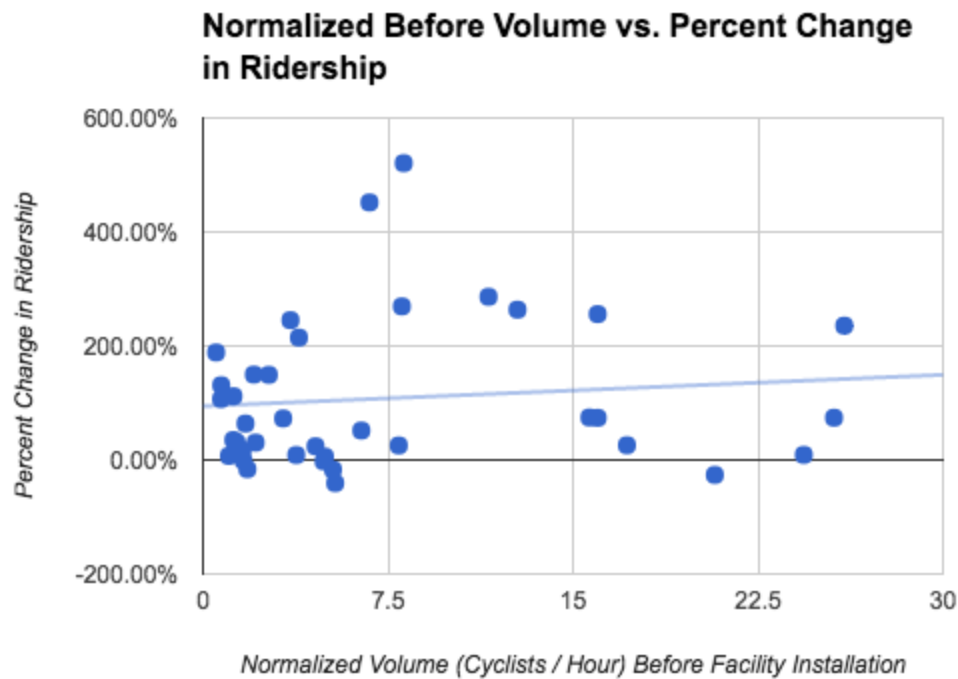
Surprisingly, we find that the ridership increases do not appear to be correlated with facility type. Of the 44 bicycle facility projects studied, 34 were bicycle lanes. These had a median and mean ridership percent change 73% and 113%, respectively. The remaining 10 facilities were 6 cycle tracks, 2 bicycle boulevards, and 2 bicycle paths. These had a median and mean ridership of 47% and 86% respectively. The low *N* should be a cause for caution when interpreting these results, but they are not what the literature on bicycle facility quality and facility types would suggest.

We find that facility installation year is correlated with ridership change, with older facilities having larger ridership changes. This is consistent with the hypothesis that bikeways have long-term effects on behavior that are difficult to observe in intercept surveys.

Figure 5. Year of Facility Installation vs. Percent Change in Ridership.



We find no relationship between volumes before facility installation and the percent change in ridership. This is notable because it implies that ridership change can be predicted reasonably reliably by volumes observed before facility installation. This is perhaps counterintuitive, as one could easily hypothesize that a) locations with high ridership have less potential to capture new riders, or b) locations with high ridership have *more* potential to capture new riders. We observe a few outliers that are exceptions to this, but our data show that ridership change is almost always 0-300% of volumes before facility installation.



Because of the difficulty involved in compiling this data set, we do not yet have results for the Census variables that required significant geoprocessing to associate with the bicycle facilities. This is a ripe area for future work.

Results

Consequential Versus Attributional Life-Cycle Approaches

For this project, we asked if a consequential versus attributional LCA approach would make a material difference in results. Our answer is yes. A consequential approach would recognize growth in the annual volume of facility's use and the proportion of cyclists attracted from higher-emitting motorized modes due to systemic and network effects not directly attributable to the individual facility. An attributional analysis would only consider average historical or first-year cyclist volumes and historical rates of attraction from other modes.

Attributional Assessment Results

We use a person-kilometer of travel as the functional unit for our attributional assessment results presented in Figure 6 and Table 7, which draw from volume estimates from bike counts conducted in Los Angeles County. Five of the six sample bikeways show small variations in results the all under 70 g CO₂e/pkm, well below the range of buses, light rail, and cars. One hypothetical bikeway, a low-utilization class 1 facility, shows a per-passenger-km value of CO₂e on par with an average occupancy new sedan.

Figure 6: Attributional comparison of bikeway facilities and other transportation modes, CO₂e per passenger km of travel

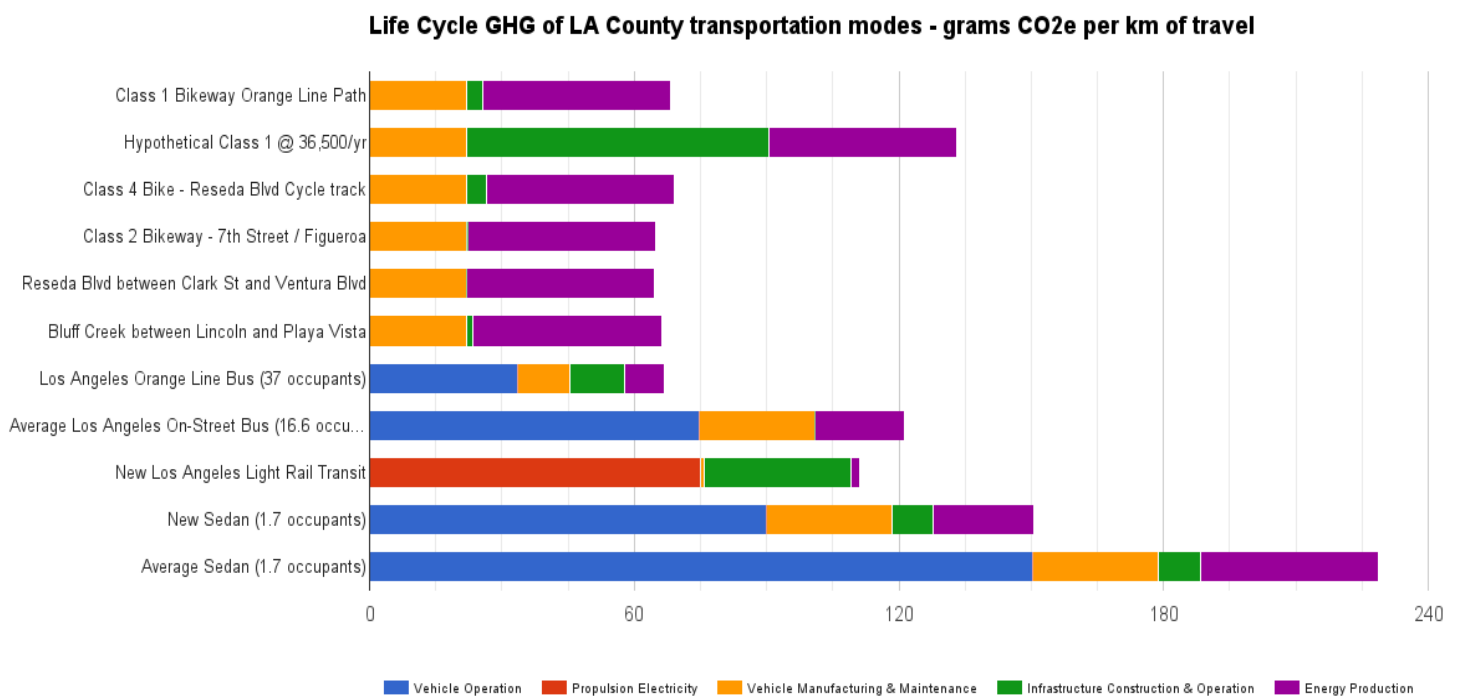


Table 7: Attributional comparison of bikeway facilities and other transportation modes, CO₂e per km of travel

	g CO ₂ e / pkm					
Mode / Project	Life-Cycle kg CO ₂ e	Vehicle Oper	Propulsion Electricity	Vehicle Mfctr & Maintenance	Infra Const & Operation	Energy Production
Class 1 Bikeway Orange Line Path	68.33	0.00	0.00	22.00	3.67	42.65
Class 4 Bike - Reseda Blvd Cycle track	69.15	0.00	0.00	22.00	4.50	42.65
Class 2 Bikeway - 7th Street / Figueroa	64.95	0.00	0.00	22.00	0.30	42.65
30th between Hoover & McClintock	64.69	0.00	0.00	22.00	0.04	42.65
Bluff Creek between Lincoln and Playa Vista	65.16	0.00	0.00	22.00	0.51	42.65
Los Angeles Orange Line Bus (37 occupants)	66.78	33.50	0.00	11.86	12.33	9.09
Average Los Angeles On-Street Bus (16.6 occupants)	121.36	74.67	0.00	26.43	0.00	20.26
New Los Angeles Light Rail Transit	111.25	0.00	75.02	0.81	33.38	2.04
New Sedan (1.7 occupants)	150.59	89.83	0.00	28.66	9.39	22.70
Average Sedan (1.7 occupants)	228.62	150.27	0.00	28.66	9.39	40.30

Consequential Assessment Results

Moving from the attributional assessment to a consequential assessment, we are only interested in changes in travel resulting from the construction of a new or upgraded bikeway. Thus, we adjust our survey results for the percentage of those who are new to cycling and/or new to the

facility (change in bikeway volume). For the fraction of those who would have ridden another route, we include infrastructure construction and operations but exclude bicycle manufacture and maintenance and energy production. For the fractional change in volume who are making a new bike trip, we include all bike-related activities, at the values specified in the attributional results. For the fractional change in volume who are switching from a car, we include all bike-related activities and subtract all car-related activities. For the fractional change in volume who are switching from a bus, we include all bike-related activities and subtract all bus-related activities.

In both the attributional and consequential case we allocate the full annual bikeway infrastructure construction and operations.

Sensitivity analysis

Our results are most sensitive to annual change in cyclist volumes and the change in rate of attraction from automobiles. To illustrate this sensitivity and the conditions under which a bikeway would reduce life-cycle emissions, we create hypothetical 3.76 km (2.3 mi) facilities which vary in their increase in annual volumes and change in attraction rate from cars to demonstrate the varying break-even points for each facility type. The scenario in Table 8 assumes an average trip length of 11.28 km (3.1 miles) on bikes, transit, and cars, with the specified percentages coming in cars.

Table 8: Tier 2 survey attraction rates for new cyclists for Consequential LCA

	All Classes	Class 2	Class 4
% New to route	52.9%	60.3%	47.3%
% Take Bus	9.2%	17.5%	4.4%
% Use Car	15.7%	11.1%	18.7%
% No trip (new to cycling)	22.2%	11.1%	29.7%

Table 9: Facility annual consequential GHG emissions sensitivity to annual change in volumes and motorist attraction

	Net change in life-cycle GHG as a consequence of the construction of hypothetical facilities, Sensitivity by annual change in volumes and mode shift from cars (MTCO2e/Year)				
Attraction rate from cars	50% of study results	75% of study results	90% of study results	Study Results (C1&C4: 18.7% from car, C2: 11.1% from car)	125% of study results
C1: Very Low Δ Volume (4,000)	9.2	8.7	8.4	8.2	7.7
C1: Low Δ Volume (40,000)	12.4	7.6	4.7	2.8	-2.1
C1: Mid-Low Δ Volume (80,000)	16.0	6.4	0.6	-3.3	-12.9
C1: Mid Δ Volume (275,000)	33.5	0.3	-19.5	-32.8	-65.9
C1: Very High Δ Volume (1,524,000)	145.4	-38.1	-148.2	-221.7	-405.2
C2: Low Δ Volume (4,000)	-0.1	-0.4	-0.5	-0.6	-0.9
C2: Mid Δ Volume (150,000)	-10.1	-20.9	-27.3	-31.6	-42.4
C2: Very High Δ Volume (400,000)	-27.4	-56.0	-73.2	-84.7	-113.4
C4: Very Low Δ Volume (4,000)	1.4	0.9	0.6	0.4	-0.1
C4: Low Δ Volume (8,000)	1.7	0.8	0.2	-0.2	-1.2
C4: Mid-Low Δ Volume (30,000)	3.7	0.1	-2.1	-3.5	-7.1
C4: Mid Δ Volume (137,500)	13.3	-3.2	-13.2	-19.8	-36.3
C4: Very High Δ Volume (762,000)	69.3	-22.4	-77.5	-114.2	-206.0

The result of this sensitivity analysis – that not all bikeway projects produce net reductions in GHG emissions on a consequential, life-cycle assessment basis – should give transportation and climate planners pause. Projects that require lower investment of GHG emissions into infrastructure construction and operation and projects that attract higher percentages of new cyclists from motorized modes are more likely to lead to life-cycle reductions in GHG emissions. For projects that attract high volumes of new cyclists in high proportions from driving, the GHG reductions can be significant.

Those who would not have made any trips before, either by cycling or another mode, represent new cyclists. Our model interprets only the GHG emissions impacts of these new cyclists,

and thus this induced cycling activity produces a net increase in GHG emissions. This induced cycling activity is likely to produce health-related benefits which are beyond the scope of this study. The economic and non-GHG environmental benefits of cycling are also beyond the scope of this study.

Upstream GHG Emissions for Food Consumption is Significant for Cycling

Although cycling does not produce tailpipe emissions in the operating phase, it requires human energy, which requires food calories. Food consumption is responsible for upstream GHG emissions associated with production, processing, transportation, and cooking. Other researchers have found that food-related emissions are significant, especially with meat-heavy diets.⁶⁶

We found that one kilometer of cycling fueled by the average American diet produces about 42 g in upstream food-related CO₂e. By contrast, one kilometer of travel in a 35 MPG vehicle produces about 153 g CO₂e in tailpipe emissions and 59 g CO₂e in upstream related to energy production. Food-related emissions account for roughly 29% of total life-cycle emissions in our most GHG-intensive bicycle facility scenario and roughly 66% of life-cycle emissions in our least GHG-intensive bicycle facility scenario.

Neighborhood Income and Vehicle Fuel Economy

We hypothesized that as new vehicles become more fuel efficient, there would be a growing gap in fuel efficiency between more-expensive late model vehicles and less-expensive 10+ year old vehicles. This growing gap would mean that investments to reduce vehicle use would have a greater effect on operating phase GHG emissions when the investments disproportionately

⁶⁶Thorpe, Daniel and David Keith. (2016). "Climate impacts of biking vs. driving." Harvard School of Engineering and Applied Sciences. Available at <http://www.keith.seas.harvard.edu/blog/climate-impacts-of-biking-vs-driving>

impacted communities with less-efficient vehicles. If disadvantaged communities had higher proportions of less fuel-efficient vehicles, then investments that targeted disadvantaged communities would produce higher reductions in operating phase GHG emissions.

Thomas, et. al. (2015) found no evidence in their 2005 - 2009 Los Angeles county vehicle Registrations dataset that vehicles available in lower-income communities had below-average fuel economy. This lack of evidence may be due to two decades of stagnant fuel economy standards captured by the sample. U.S. Federal fuel economy standards for cars remained fixed at 27.5 MPG between 1990 and 2010. Federal fuel economy standards were overhauled in 2011 and have since seen annual increases, to 44 MPG for small passenger cars and 33 MPG for larger passenger cars for the current 2017 model year. As Federal fuel economy standards continue to demand more efficiency from new vehicles, the gap in neighborhood average fuel economy may grow between wealthier neighborhoods with newer vehicles and lower-income neighborhoods with older vehicles. Any future research that finds such a trend would affect the relative effectiveness of investments that reduce vehicle use in lower-income neighborhoods.

Discussion

Future Improvements to GHG Emissions Estimation Methods

Varying trip lengths

Reductions in GHG emissions are directly linked to the length of an avoided trip. Most intervention-level studies use survey data to determine the length of an avoided vehicle trip. The iConnect longitudinal study of facility improvements in England used 7-day travel recall surveys of bikers (and pedestrians) using new infrastructure. Each survey participant was asked to recall the

purposes of trips they took, and the distance. The authors then calculated mean distance for each type of trip to model facility-based GHG reductions.⁶⁷ The study of the Metro Orange Line Bikeway similarly used trip length data from survey participants. They then calculated the relevant catchment area for each bus stop to figure out sample populations and apply to count data.⁶⁸ A study of campus biking facility improvements in Serbia used existing data on average commute distance to campus,⁶⁹ while another study used existing data on commute to school distances and willingness to bike to determine potential mode shift and bike commute distance.⁷⁰ The CARB study similarly uses an average trip distance (1.8 miles) for each bike trip, but does not explain how this figure was calculated.

It is also important to consider shared vehicle trips when modeling VMT reduction from bike count and survey data. Since multiple bikers could have taken the same trip in one car, GHG emissions reduction may be overestimated if this is not accounted for in the model.⁷¹

As previously noted, our trip length parameter $L = 7$ miles is longer than is generally observed in American Community Survey and National Household Travel Survey data, which find mean trip lengths of about 3 miles and about 2 miles respectively. It may be the case that our geocoding procedure resulted in longer trip lengths. It may be the case that respondents overstate their trip distances. Or, it may also be due to our sample's high proportion of recreational trips.

⁶⁷ Brand, C., Goodman, A., Ogilvie, D., & iConnect consortium. (2014). Evaluating the impacts of new walking and cycling infrastructure on carbon dioxide emissions from motorized travel: A controlled longitudinal study. *Applied energy*, 128, 284-295.

⁶⁸ ICF International. *Metro Orange Line Mode Shift Study and Greenhouse Gas Emissions Analysis*. (2011). Retrieved from

http://media.metro.net/projects_studies/bikeway_planning/images/Metro_Orange_Line_Study_March_2011.pdf.

⁶⁹ Mrkajic, Vladimir, Djordje Vukelic, and Andjelka Mihajlov. "Reduction of CO₂ emission and non-environmental co-benefits of bicycle infrastructure provision: the case of the University of Novi Sad, Serbia." *Renewable and Sustainable Energy Reviews* 49 (2015): 232-242.

⁷⁰ Bearman, Nick, and Alex D. Singleton. "Modelling the potential impact on CO₂ emissions of an increased uptake of active travel for the home to school commute using individual level data." *Journal of Transport & Health* 1, no. 4 (2014).

⁷¹ Glover, Leigh. "What Could Increased Cycling Contribute to Reducing Australia's Transport Greenhouse Gas Emissions?." *GAMUT* (2010): 1.

Finally, it may be the case that average trip lengths in Los Angeles and at the sites we studied are longer than national average trip lengths. More work is necessary to understand how trip lengths vary across urban regions and how to better estimate trip length for an individual bicycle facility project.

Modeling transit mode-switch as discrete function

One question that arises is how to account for mode switches from transit to biking when transit is on a fixed schedule that would have operated in either scenario. Studies that model network change over a period of many years assume that a large increase in biking over time city-wide will reduce the number of buses that are operated each day. These reductions are a step-function: each bus reduction corresponds to an increase of cyclists that previous took the bus that equals the number of bus passengers.⁷²

While we use average per-passenger-kilometer values in this study, we acknowledge that changes in transit service in response to ridership trends are a step function. When looking at long-term cycling increases, improvements to the cycling network is a key factor. An increase in the network is typically concomitant with other structural and societal changes that encourage cycling. For example, an increase in social acceptance of cycling, an increase in safety due to increased number and visibility of cyclists on the roads, longer routes with separated lanes or paths, and bike parking and showers at destinations. These changes impact the transportation network as a whole, and a large enough mode switch from bus travel to cycling on a given route may lead to a reduction in the number of buses required to serve the route in the long term.

Our study looks at short-term cycling increases at a facility-level, for which it is less reasonable to assume longer-term network changes, including a reduction in bus transit. Future

⁷² Lane, Erin, Julie Elsliger, Chelsea Enslow, WK Connie Lam, Nur Shodjai, Zolzaya Tuguldur, and Vincent Yeh. "Modelling Reductions of Carbon Emissions Under Various Scenarios of a Public Bicycle Share System Within Vancouver, BC." (2012).

studies that consider longer-term network changes should consider transit deployment as a step function.

Triple convergence and induced demand: effect on consequential LCA

Within the context of consequential life-cycle assessment, it is necessary to understand the GHG effects of latent travel demand and induced congestion. Because directly measuring these effects is beyond the scope of this project, a conceptual approach is necessary.

Congestion affects observable travel by triple convergence: drivers shift to or from other routes, other times, and other modes based on congested conditions.⁷³ Congestion also has unobservable effects on travel demand. Latent travel demand is unobservable, but exists when travel delay or some other cost causes an individual to forego a trip.⁷⁴ The presence of latent travel demand becomes observable when the travel delay or cost is reduced, and new or induced demand is observed as an increase over previously observed travel demand.

If use of a bicycle facility directly reduces vehicle use of a roadway segment during a congested period with latent travel demand, then the driver-come-cyclist's (Party A) vehicle will be replaced by another vehicle on that roadway segment, driven by Party B. The net effect on GHG emissions will depend on the total GHG emissions of the supplanted trip (Party A's trip) versus the change in GHG emissions of the replacement trip versus the predecessor trip driven by Party A. It can be assumed that Party B's replacement trip is either a shift from another route to exploit potential travel time savings (which would have a zero or potentially negative effect on GHG from Party B) or is the result of induced trip (which would increase GHG for Party B). Induced demand

⁷³ Downs, A. (1992). *Stuck in traffic*. Washington, DC: The Brookings Institution.

⁷⁴ Ben-Akiva, M., & Boccara, B. (1995). Discrete choice models with latent choice sets. *International Journal of Research in Marketing*, 12(1), 9-24.

would be more likely in cases where there are no viable alternate routes to the roadway segment at the congested period. Note that the congested roadway segment and the bicycle facility are not necessarily collocated, as Party A may shift travel routes as a result of the bicycle facility.

A bicycle facility may also reduce the capacity of a roadway by reducing the number of lanes or lane widths, as in a “road diet”. If the addition of a bicycle facility reduces capacity causes additional vehicle congestion on the collocated roadway segment, then there are three effects that will change GHG emissions. First, the forced flow of traffic in congested conditions will affect the vehicle operation cycle and increase GHG per mile traveled.⁷⁵ Second, the principle of triple convergence suggests that additional travel delay may cause some drivers to change routes to mitigate the increase in travel times, which would likely increase GHG, or modes of travel, which would likely decrease GHG for trips that had been made by car. Third, the additional travel delay may cause some would-be drivers to forego travel entirely so that their demand becomes latent, which would reduce GHG.

The latent travel demand and induced congestion factors that affect a consequential life-cycle assessment will vary on a case-by-case basis. As such, no universal rule would apply. Taken to their extreme, these factors would suggest that the greatest reductions in GHG emissions from bicycle facilities would come through capacity reductions on congested roadway segments for which there are no viable alternatives, which would have a strong social and economic impact.

Use of intercept surveys: short-term vs. long-term travel behavior

Intercept surveys allow us to observe a change in short-term travel behavior as stated by the respondents, while the before and after counts are an observation of revealed behavior changes, typically over a longer term. We surveyed people at facilities that were 0-2 years old,

⁷⁵ Barth, M., & Boriboonsomsin, K. (2008). Real-world carbon dioxide impacts of traffic congestion. Transportation Research Record: Journal of the Transportation Research Board, (2058), 163-171.

while the before and after counts concern facilities that are 1-10 years old. We find larger increases in ridership in the before and after counts than in the intercept surveys. The poster survey in particular seems to underestimate the percentage of riders whose decision to ride was influenced by the bicycle facility. In the poster survey, over 72% of riders said they would ride there regardless of the bicycle facility. In the longer-form survey, 36% of riders said they would ride there regardless. The before and after counts, which show a mean ridership increase of about 100% of before volumes, thus roughly match with the responses to the longer survey, but show much larger increases than those implied by the before and after counts.

This suggests that when intercept survey design may greatly influence whether or not respondents indicate that the bicycle facility affected their behavior, and the extent to which they indicate that they are substituting a bicycle trip for a car trip or a transit trip. When respondents were asked to consider all the ways in which the facility might have affected them in greater detail, their responses matched the ridership increases in the before and after data.

Bikeways have short- and long-term effect on behavior, and our poster survey probably biased respondents to think only of the short-term effects. The long-term effect of bikeways and their networks includes: people who move to a city or a neighborhood because it is bikeable, people who never buy a car because of the marginal effect of bikeways in combination w/ other modes available, and possible effects on parking and land use policy. The relationship between the age of bikeway and the increase in ridership observed in the before-and-after data set reinforces the importance of long-term changes in behavior. For the purposes of estimating GHG effects, we have focused on measurable short-term changes in behavior.

We believe that recreational riders are more likely to stop for survey versus non-recreational riders, who may be more time sensitive. We believe that time-sensitivity introduced bias for our tier 2 survey sample. Also, some recreational riders indicated that they were

avoiding car trips, and this outcome is not discussed in the literature. Whether a recreational cycling trip may be a substitute for driving to the gym (for spin class?) or other activities could be explored by future researchers.

Before/After counts and system and network effects

Because we are directly attributing the change in volumes observed in the before/after counts to the facility, we are unable to control for background increases or decreases in cycling due to other factors. These other factors are potentially numerous, the most prominent of which in our results was the length of time that had elapsed since the facility was installed. Others include regional network effects, the timing of the before/after counts with respect to the weather and seasons of the year, helmet requirements, cycling safety, the opening of a bike share system (which happened in Washington DC), and many others. Future research could control for these system and network variables in order to understand how they would affect cycling volume forecast. Such research would be predicated upon a relatively large dataset of methodologically consistent and extensive bicycle count data. This research program would help the state understand the extent to which an expanding regional network or the opening or expansion of a bike share system significantly increases cycling volumes and/or the attraction of new cyclists from other modes.

Thoughts for model refinement

Although we initially envisioned a more complex and interrelated model for reductions in VMT as a result of the installation of a bicycle facility, the empirical data were only robust enough to support a relatively simple model. We used a range of static parameters for: trip length, the percent of bicyclists who would have previously driven, and change in bicycle volumes. We did not model any of these three as a function of demographics and transportation network variables, as

originally imagined. Bigger empirical datasets would allow for the discernment of relationships between variables that we currently treat as independent. It's almost certainly the case that trip lengths, mode shift potential, bicycle volumes, demographics, and transportation network characteristics are interrelated. One could hypothesize about the nature of these relationships, but only robust count and survey data would allow for them to be described.

Policy Implications for the State of California

Caltrans is targeting a three-fold increase⁷⁶ in the proportion of statewide trips made by bicycles between a 2010-2012 baseline and 2020, from 1.5% to 4.5%.⁷⁷ Achieving this goal will require an all-hands-on-deck approach to funding infrastructure and programs aimed at increasing cycling. While the Caltrans Active Transportation Program is the primary source of state funding for costs associated with bikeways, bike-related infrastructure, and bike programs, the new Affordable Housing and Sustainable Communities program also funds these costs.

Implications for current and future Affordable Housing and Sustainable Communities project evaluation and selection

The Affordable Housing and Sustainable Communities program primarily funds costs associated with the production of affordable housing development. However, expenditures on bicycle facilities and supportive infrastructure are authorized in Public Resources Code §75212 and several listed as eligible costs listed in Appendix B of the Program Guidelines.⁷⁸ This project's

⁷⁶ California Department of Transportation (2015). Strategic Management Plan 2015-2020. Available at http://www.dot.ca.gov/perf/library/pdf/Caltrans_Strategic_Mgmt_Plan_033015.pdf

⁷⁷ California Department of Transportation (2013). 2012 California Household Travel Survey Final Report Appendix. Available at http://www.dot.ca.gov/hq/tpp/offices/omsp/statewide_travel_analysis/files/CHTS_Final_Report_June_2013.pdf

⁷⁸ California Strategic Growth Council (2015). Affordable Housing and Sustainable Communities Program: 2015-16 Program Guidelines. Available at http://sgc.ca.gov/pdf/ADOPTED_FINAL_15-16_AHSC_Guidelines_with_OM.pdf

findings can help program administrators decipher between bicycle projects that are likely to reduce GHG emissions on a life-cycle basis and projects that have significant infrastructure-related GHG that would need to produce higher levels of operating-phase reductions in GHG emissions reductions in order to reduce GHG emissions on a life-cycle basis (See Table 10).

Table 10 Eligible bike-related affordable Housing and Sustainable Communities program costs, by infrastructure GHGs

Eligible costs with low or no infrastructure GHGs	Eligible costs with higher infrastructure GHGs
<ul style="list-style-type: none"> • Non-capacity increasing streetscape improvements, including, but not limited to the installation of lighting, signage, or other related amenities for pedestrians, cyclists and transit riders • Installation of traffic control devices to improve safety of pedestrians and bicyclists • Bicycle carrying structures on public transit • Pedestrian and bicycle safety education programs • Publically accessible bicycle parking • Bike sharing program operations 	<ul style="list-style-type: none"> • Installation of new or improved bikeways that improve mobility and access of cyclists • Installation of new multi-use paths for active transportation users • Bike sharing infrastructure

For projects identified as having higher levels of infrastructure GHG, we recommend that that program administrators employ the strategies in Table 11 to reduce GHG emissions on a life-cycle basis.

Table 11 Strategies for reducing life-cycle GHGs for eligible costs with higher infrastructure GHGs

Eligible cost	Strategy for reducing life-cycle GHGs
Installation of new or improved bikeways that improve mobility and access of cyclists	Fund networks, or individual projects that cumulatively support the completion of planned networks of class 2 class 4 facilities, which do not produce substantial infrastructure-related GHGs
Installation of new multi-use paths for active transportation users	Choose class 1 facilities that will increase ridership by at least 125,000 annually and/or attract higher proportions of cyclists from motorized modes
Bike sharing infrastructure	Consider bikeshare systems that are a key part of a comprehensive plan to increase rates of cycling and reduce use of motorized modes

Expanding and densifying bikeway networks should increase the proportion of cyclists attracted from cars and transit, which in turn increases the annual reduction in GHG emissions attributable to the facility. The recommendation to fund networks requires the state to invest in multiple facilities that are planned as a network within single geographic area. This may run counter to a desire to spread limited funding among multiple geographic areas.

Our data produced additional insights on the types of bikeways that tend to have higher ridership and attract more people from cars. First, because ridership increase is roughly proportional to volumes before facility installation, sites where people are already bicycling are likely to have greater ridership increases. Bicycle counts at candidate bikeway sites would allow agencies to discern this. Second, we find that physically separated bikeways draw a greater proportion of trips from cars, relative to striped bicycle lanes. (14% vs. 7%) Third, we find that recreational trips tend to draw a greater proportion of trips from cars than utilitarian trips (18% vs. 10%). This finding is notable because bikeway infrastructure funding programs have often focused on utilitarian trips, or even specifically commute trips. The Bicycle Transportation Account, the precursor to the state's Active Transportation Program, was focused on funding bicycle

infrastructure projects that attracted bicycle commuters. The finding that facilities with high recreational use can shift car trips significantly implies that such facilities can compete for funding on the basis of GHG reduction.

Programs shown to increase rates of cycling or trip attraction from motorized modes can be an effective means of reducing GHG emissions, though they work through systemic factors that are often unobservable in mathematical models.

Methodological recommendations for the Affordable Housing and Sustainable Communities program

Life-cycle assessment, particularly the consequential approach, most accurately represents the net GHG effects of a decision to fund new, additional bikeway infrastructure. However, in practice, such an assessment is difficult to perform because of data needs and difficulty forecasting future facility volumes and trip attraction rates from motorized modes. As a practical matter, we do not recommend a full life-cycle assessment for individual bicycle projects that do not produce substantial changes in GHG emissions.

However, the Air Resources Board methodology⁷⁹ that the Strategic Growth Council uses to calculate potential reductions in GHG emissions from bikeway projects should be revised to be internally consistent. The existing bikeway methodology suggests that cycling is a zero-emissions mode, assuming no new emissions from a bikeway project. Cycling is a zero-emissions mode in the operating phase, just like a zero-emissions electric vehicle. However the energy production phase contains upstream emissions from food production, distribution, and preparation which we found to be significant.

⁷⁹ California Air Resources Board (2015). Greenhouse Gas Quantification Methodology for the Strategic Growth Council Affordable Housing and Sustainable Communities Program. Available at http://sgc.ca.gov/pdf/ADOPTED_FINAL_15-16_AHSC_Guidelines_with_OM.pdf#page=73

The Air Resources Board Methodology specifies a well-to-wheels carbon content factor (11,460.09 g CO₂e per gallon) for estimating emissions associated with avoided gasoline use (Appendix D, page D-4). The well-to-wheel accounting scope includes both the energy production phase (well-to-tank) and the operational phase (tank-to-wheel) of gasoline production and combustion to power a vehicle. However, in assuming that cycling is a zero-emissions mode, the Air Resources Board excludes energy production phase (food system) emissions for cycling, which this project found to be roughly proportional to energy production emissions for a 35-MPG vehicle. We recommend that the Air Resources Board revise their methodology to either include or exclude energy production phase emissions for both cycling and avoided motor vehicle fuel use.

Cost-effectiveness of GHG emissions reductions from bikeway projects

Because the Affordable Housing and Sustainable Communities program funds are generated by a market-based mechanism, the Cap-and-Trade Program, some stakeholders may wish to compare changes in GHG emissions against the market price of GHG emissions. Our analysis suggests that a bikeway that produces an 100 MT annual reduction in life-cycle CO₂e would be successful for a single facility. This annual reduction would translate into a reduction of 3,000 MTCO₂e over 30 years, or \$42,000 at \$14/MTCO₂e. The cost of a bikeway facility capital costs will likely exceed this amount, causing concerns about the cost-effectiveness using the Greenhouse Gas Reduction Fund of bikeway projects. Matute and Chester (2015) find that many public investments in transportation are more expensive than the market price for GHG emissions when only capital costs are considered. Only after considering user savings in transit fares and automobile costs do such projects appear to be economically viable uses of public Greenhouse Gas Reduction Fund revenues.

In California, there is no requirement that investments that receive these funds proceeds be cost-effective, only that they reduce GHG emissions. This allows the state to invest in projects and programs that have substantial co-benefits, such as bicycling. In addition, while bikeway infrastructure may not produce large reductions in GHG emissions in the short-term, it may be necessary to produce the long-term changes in travel behavior needed to reduce GHG emissions by 80% compared to 1990 levels.

The many co-benefits of cycling

The Caltrans Active Transportation Program has a broader set of goals that include increasing the proportion of trips accomplished by biking and walking, increasing safety and mobility for non-motorized users, and enhancing public health.⁸⁰ The literature review of this report further details the benefits of cycling beyond changes in GHG emissions.

⁸⁰ Available at California Department of Transportation (2015). ATP Purpose and Goals. Available at (<http://www.dot.ca.gov/hq/LocalPrograms/atp/documents/2015/Visio-ATP-Purpose-and-Goals-flowchart-3-3-15.pdf>)

Appendices

- A. Los Angeles County Intercept Survey Locations
- B. Intercept Survey Instruments
- C. Geoprocessing Model to Calculate Sociodemographic Variables in Facility Catchment Areas

Appendix A - Los Angeles County Survey Locations

Category	Location Number (Map Key)	Survey Street	Cross Streets	Count Location	City	Bikeway Type Now	Length	Installation Date (approximate)
Class 1 Bike Paths								
Seperated Facility	4	West San Fernando Valley LA River Bike Path		Between Tampa and Winnekta	Los Angeles	Bike Path	0.5 mi	8/28/2014
Class 4 Cycle tracks								
Seperated Facility	16	Harbor Dr	Herondo South to end of Harbor Drive	Beryl St.	Redondo Beach	Cycle track		6/13/2015
Seperated Facility	3	Reseda Blvd	B/W Prairie and Plummer	Plummer St.	Los Angeles	Cycle track	1 mi	4/15/2015
Seperated Facility	10	Rosemead Blvd	Calita Street to the railroad undercrossing near Lower Azusa Road	Las Tunas Dr.	Temple City	Cycle track	2 mi	5/1/2014
Seperated Facility	14	Pico Blvd	Between 6th and 7th	Between 6th and 7th	Santa Monica	cycletrack	1 block connec	8-2015 to 11-2015
Seperated Facility	12	2nd St	Glendale Blvd. to Spring St	2nd Street between Figueroa and 110 Freeway	Los Angeles - Downtown	Buffered Bike Lane / Cycle Track	1 mi	11/11/2013
Class 2 Bike Lanes								
Bike Lane	20	E Atherton St	Between Palo Verde Ave and N. Britton Dr.	Merriam Way	Long Beach	Bike Lane	1.3 mi	2014
Bike Lane	17	E Artesia Blvd	over the LA River and 710 Freeway. Between Atlantic and Long Beach Blvd.	Artesia and Long Beach Blvd.	Long Beach	Bike Lane	2.3 mi	2014
Bike Lane	13	7th St	Figueroa St. to Main St.	between Hill and Olive	Los Angeles - Downtown	Bike Lane	0.6 mi	10/31/2013
Bike Lane	5	Vineland Ave	Ventura to Chandler	@ Chandler	Los Angeles	Buffered Bike Lane	1.9 mi	8/15/2015
Bike Lane	6	Pacific Coast Highway	Zuma to Trancas	@Heathcliff	Malibu	Bike Lane	2 mi	4/15/2015
Bike Lane	15	Slauson Ave	B/W Alviso and Angeles Vista	@ Alviso	Windsor Hills(?)	Bike Lane	0.4 mi	after 10/1/2014
Bike Lane	7	San Vicente Blvd	Bundy Dr. to Bringham Ave.	@ Barrington	Los Angeles	Bike Lane	0.7 mi	5/1/2014
Bike Lane	9	York Blvd.	Figueroa St. to Arroyo Verde Rd.	between North Figueroa Street	Los Angeles	Bike Lane	0.7 mi	after 3/2014
Bike Lane	11	Tyler Ave	between Tony Arceo Memorial Park on the south and Valley Boulevard on the north	between Ramona Blvd. and Amador St.	El Monte	Bike Lane	0.6 mi	5/1/2015
Bike Lane	8	Edgemont St	Melrose and Santa Monica Blvd	@ Santa Monica	Los Angeles	Bike Lane	.5 mi	8/15/2015
Bike Lane	2	Louise Ave	Between Lassen and Plummer	@ Lassen	Los Angeles	Bike Lane	.5 mi	after 6-2015
Bike Lane	1	Foothill Blvd.	Balboa Blvd. to 1000' E/O Bledsoe S	@ Roxford	Los Angeles	Bike Lane	3.1 mi	6/9/2014
Bike Lane	19	Figueroa St	F St. to M St.	@ W. Anaheim	Wilmington	Bike Lane	.8 mi	Sept 2014
Bike Lane	18	Avalon Blvd	E st to Water St	@ C Street	Wilmington	Bike Lane	.6 mi	Sept 2014

Appendix B - Intercept Survey Instruments

Tier 1 (Poster) Survey Questions

If this bike lane did not exist, I would:

1. Still ride my bike here
2. Ride my bike on another route
3. Take the bus
4. Use a car
5. Not have taken this trip

Tier 2 (Dismount) Survey Questions

Trip-Specific Questions

1. What is the purpose of this trip?
 - a. Travel to or from Work
 - b. Travel for Work
 - c. Shopping
 - d. Family/Personal
 - e. Recreation
 - f. Other _____
2. Where did you begin your bicycle trip? [open ended, if possible, get an address, intersection, or zip code]
3. Where are you going? [open ended, if possible, get an address, intersection, or zip code]
4. Did the existence of this bike lane influence your travel decision today? [Yes / No]
 - a. Would you have taken this trip if this bike lane did not exist? [Yes / No]
 - b. Did the presence of this bike lane influence your decision to bike instead of use another mode of travel (car, bus, walk)? [Yes / No]
 - i. If yes, what other mode/modes would you have used? (drive/carpool/ bus/etc.)
 - c. If you would have ridden a bike regardless, did the presence of this bike facility influence the route of a bike trip? [Yes / No]
 - d. Other? _____
5. Did you have a vehicle available for this trip?
 - a. No
 - b. Yes, my personal vehicle
 - c. Yes, a family vehicle that I share with others
 - d. Yes, I can get a ride from a friend/ family
 - e. Yes, I can take a taxi or Uber/Lyft
6. Did you use another bike lane or path on this trip? [Yes / No]
7. Did you use transit on this trip? [Yes / No]
8. Does this bike lane make you feel safer in your journey [Yes/No]

General Questions

9. Think back to before this bike lane/path was installed. Has it changed how you get around? [Yes / No]
 - a. If Yes:
 - i. Are you more likely to travel by bike due to the existence of this bike path/lane? [Yes / No]
 - ii. Has it changed your route of travel? [Yes / No]
 - iii. Has it changed your mode of travel? That is, are you biking now when you previously were driving, carpooling, taking transit or walking? [Yes / No]

Appendix B - Intercept Survey Instruments

10. How often do you travel by bike? [Open-ended]
 - a. More than 3-6 times per week
 - b. 3-6 times per week
 - c. 1-3 times per week
 - d. Between 1 time per week and 1 time per month
 - e. Less than 1 time per month
11. What is your age? [numerical value]
12. What is your gender? [open ended]
13. What is your race or ethnicity? [Choose one or more]
 - a. White
 - b. Black/African American
 - c. Hispanic
 - d. American Indian/Alaska Native
 - e. Asian
 - f. Hawaiian/Pacific Islander
 - g. Other _____
14. What is your Household income? [multiple choice from ranges]
 - a. \$0 - \$29,000
 - b. \$29,000 - \$52,000
 - c. \$52,000 - \$82,000
 - d. \$82,000 - \$129,000
 - e. \$129,000+

Appendix C:
Geoprocessing Model to Calculate Socio-Demographic
Variables in Facility Catchment Areas

```

# -*- coding: utf-8 -*-
# -----
# LaneBufferModel.py
# Created on: 2016-07-31 16:37:05.00000
# (generated by ArcGIS/ModelBuilder)
# Usage: LaneBufferModel <Output_Lanes_w_SEC_joined> <Input_Bikeways>
<Dissolve_Field_s_by_Facility> <Dissolved_BGs_Output_Join_Field_FID_from_bikeway_file_>
<Bikeways_File_Input_Join_Field> <INTERMEDIATE_FILENAME_CITY_BIKEWAY DISSOLVED_FOR_JOIN>
# Description:
# -----

# Import arcpy module
import arcpy

# Script arguments
Output_Lanes_w_SEC_joined = arcpy.GetParameterAsText(0)
if Output_Lanes_w_SEC_joined == '#' or not Output_Lanes_w_SEC_joined:
    Output_Lanes_w_SEC_joined = "A:\\GHG Bikes\\Geodatabases\\AllCities.gdb\\CITY_OUTPUT_LANES"
# provide a default value if unspecified

Input_Bikeways = arcpy.GetParameterAsText(1)
if Input_Bikeways == '#' or not Input_Bikeways:
    Input_Bikeways = "AuBerChiDenHon_facility_changes_07222016P" # provide a default value if
unspecified

Dissolve_Field_s_by_Facility = arcpy.GetParameterAsText(2)
if Dissolve_Field_s_by_Facility == '#' or not Dissolve_Field_s_by_Facility:
    Dissolve_Field_s_by_Facility = "FID_INTERMED_Bikeways_Buffer" # provide a default value if
unspecified

Dissolved_BGs_Output_Join_Field_FID_from_bikeway_file_ = arcpy.GetParameterAsText(3)
if Dissolved_BGs_Output_Join_Field_FID_from_bikeway_file_ == '#' or not
Dissolved_BGs_Output_Join_Field_FID_from_bikeway_file_:
    Dissolved_BGs_Output_Join_Field_FID_from_bikeway_file_ = "FID_INTERMED_Bikeways_Buffer" #
provide a default value if unspecified

Bikeways_File_Input_Join_Field = arcpy.GetParameterAsText(4)
if Bikeways_File_Input_Join_Field == '#' or not Bikeways_File_Input_Join_Field:
    Bikeways_File_Input_Join_Field = "OBJECTID" # provide a default value if unspecified

INTERMEDIATE_FILENAME_CITY_BIKEWAY DISSOLVED_FOR_JOIN = arcpy.GetParameterAsText(5)
if INTERMEDIATE_FILENAME_CITY_BIKEWAY DISSOLVED_FOR_JOIN == '#' or not
INTERMEDIATE_FILENAME_CITY_BIKEWAY DISSOLVED_FOR_JOIN:
    INTERMEDIATE_FILENAME_CITY_BIKEWAY DISSOLVED_FOR_JOIN = "A:\\GHG Bikes\\Geodatabases\\
\\AllCities.gdb\\INTERMEDIATE_FILE4_CITY_BIKEWAY DISSOLVED" # provide a default value if
unspecified

# Local variables:
Bike_Facilities_with_Join = ""
BufferswithSEC_JoinOutput = Input_Bikeways
INTERMED_Bikeways_Buffer = "A:\\GHG Bikes\\Geodatabases\\AllCities.gdb\\
\\INTERMED_Bikeways_Buffer"
SECForModel = "SECForModel"
Intermediate_bufferSECintersect = "A:\\GHG Bikes\\Geodatabases\\AllCities.gdb\\
\\INTERMEDIATE_FILE1_CITY_BIKEWAYS_SECBYBG_INTERSECT"
Intermediate_SECIntersectAreas = "A:\\GHG Bikes\\Geodatabases\\AllCities.gdb\\
\\INTERMEDIATE_FILE2_CITY_BIKEWAYS_SECBYBG_INTERSECT_W_AREA"
INTERMEDIATE_FILE2_CITY_BIKEWAYS_SECBYBG_INTERSECT_W_AREA_4 = Intermediate_SECIntersectAreas
bufferSECintersect_3_ = INTERMEDIATE_FILE2_CITY_BIKEWAYS_SECBYBG_INTERSECT_W_AREA_4_
bufferSECintersect_21_ = bufferSECintersect_3_
bufferSECintersect_5_ = bufferSECintersect_21_
INTERMEDIATE_FILE2_CITY_BIKEWAYS_SECBYBG_INTERSECT_W_AREA_7 = bufferSECintersect_5_
bufferSECintersect_17_ = INTERMEDIATE_FILE2_CITY_BIKEWAYS_SECBYBG_INTERSECT_W_AREA_7_
bufferSECintersect_6_ = bufferSECintersect_17_
Output_Feature_Class_2_ = bufferSECintersect_6_
INTERMEDIATE_FILE2_CITY_BIKEWAYS_SECBYBG_INTERSECT_W_AREA_3_ = Output_Feature_Class_2_
bufferSECintersect_22_ = INTERMEDIATE_FILE2_CITY_BIKEWAYS_SECBYBG_INTERSECT_W_AREA_3_
INTERMEDIATE_FILE2_CITY_BIKEWAYS_SECBYBG_INTERSECT_W_AREA_5_ = bufferSECintersect_22_

```

```

bufferSECintersect__23_ = INTERMEDIATE_FILE2_CITY_BIKEWAYS_SECBYBG_INTERSECT_W_AREA__5_
bufferSECintersect__29_ = bufferSECintersect__23_
Output_Feature_Class__3_ = bufferSECintersect__29_
INTERMEDIATE_FILE2_CITY_BIKEWAYS_SECBYBG_INTERSECT_W_AREA__2_ = Output_Feature_Class__3_
bufferSECintersect__26_ = INTERMEDIATE_FILE2_CITY_BIKEWAYS_SECBYBG_INTERSECT_W_AREA__2_
bufferSECintersect__19_ = bufferSECintersect__26_
SECProportAge = bufferSECintersect__19_
bufferSECintersect__8_ = SECProportAge
bufferSECintersect__7_ = bufferSECintersect__8_
bufferSECintersect__9_ = bufferSECintersect__7_
bufferSECintersect__11_ = bufferSECintersect__9_
bufferSECintersect__10_ = bufferSECintersect__11_
bufferSECintersect__12_ = bufferSECintersect__10_
bufferSECintersect__13_ = bufferSECintersect__12_
bufferSECintersect__14_ = bufferSECintersect__13_
SECIntersectAreas__3_ = bufferSECintersect__14_
SECIntersectAreas__4_ = SECIntersectAreas__3_
SECIntersectAreas__5_ = SECIntersectAreas__4_
bufferSECintersect__16_ = SECIntersectAreas__5_
SECIntersectAreas__6_ = bufferSECintersect__16_
SECIntersectAreas__7_ = SECIntersectAreas__6_
INTERMEDIATE_FILE3_CITY_ALLFIELDS_FORDISSOLVE = "A:\\GHG Bikes\\Geodatabases\\AllCities.gdb\\
\\INTERMEDIATE_FILE3_CITY_ALLFIELDS_FORDISSOLVE"
IntermediateFileUpperBufferDissolveForPopSums = "A:\\GHG Bikes\\Geodatabases\\AllCities.gdb\\
\\IntermediateFileUpperBufferDissolveForPopSums"
Output_Feature_Class = IntermediateFileUpperBufferDissolveForPopSums
IntermediateFileUpperBufferDissolveForPopSums__3_ = Output_Feature_Class
Output_Feature_Class__4_ = IntermediateFileUpperBufferDissolveForPopSums__3_
IntermediateFileUpperBufferDissolveForPopSums__4_ = Output_Feature_Class__4_
INTERMEDIATE_FILE4_CITY_BIKEWAY DISSOLVED =
INTERMEDIATE_FILENAME_CITY_BIKEWAY DISSOLVED_FOR_JOIN

# Process: Add Join
arcpy.AddJoin_management("", "DC_facility_changes_07012016P.OBJECTID", "",
"FID_DC_facility_changes_070120167", "KEEP_ALL")

# Process: Buffer
arcpy.Buffer_analysis(Input_Bikeways, INTERMED_Bikeways_Buffer, "2.4 Miles", "FULL", "ROUND",
"NONE", "", "PLANAR")

# Process: Intersect
arcpy.Intersect_analysis('A:\\GHG Bikes\\Geodatabases\\AllCities.gdb\\
\\INTERMED_Bikeways_Buffer' #;SECFORModel #", Intermediate_bufferSECintersect, "ALL", "",
"INPUT")

# Process: Calculate Areas
arcpy.CalculateAreas_stats(Intermediate_bufferSECintersect, Intermediate_SECIntersectAreas)

# Process: Add Field
arcpy.AddField_management(Intermediate_SECIntersectAreas, "AreaProportion", "DOUBLE", "", "",
"", "", "NULLABLE", "NON_REQUIRED", "")

# Process: Calculate Proportional Area
arcpy.CalculateField_management(INTERMEDIATE_FILE2_CITY_BIKEWAYS_SECBYBG_INTERSECT_W_AREA__4_,
"AreaProportion", "[F_AREA] / [TotalArea]", "VB", "")

# Process: Add Field (2)
arcpy.AddField_management(bufferSECintersect__3_, "ProportPopulation", "DOUBLE", "", "", "",
"", "NULLABLE", "NON_REQUIRED", "")

# Process: Calculate Proportional Population
arcpy.CalculateField_management(bufferSECintersect__21_, "ProportPopulation", "[AreaProportion]
* [Population]", "VB", "")

# Process: Add Field (9)
arcpy.AddField_management(bufferSECintersect__5_, "NullIncomeFlag", "DOUBLE", "", "", "", "",
"NULLABLE", "NON_REQUIRED", "")

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# Process: NullIncomeFlagForIncomePop
arcpy.CalculateField_management(INTERMEDIATE_FILE2_CITY_BIKEWAYS_SECBYBG_INTERSECT_W_AREA__7_,
"NullIncomeFlag", "changenull (!MedianHHIncome!)", "PYTHON_9.3", "def changenull(x):\n    if x
is None:\n        return 0\n    elif x == '-':\n        return 0\n    else: return 1\n")

# Process: Add Field (14)
arcpy.AddField_management(bufferSECintersect__17_, "CleanIncome", "DOUBLE", "", "", "", "",
"NULLABLE", "NON_REQUIRED", "")

# Process: Clean Income
arcpy.CalculateField_management(bufferSECintersect__6_, "CleanIncome", "changenull(!
MedianHHIncome!)", "PYTHON_9.3", "def changenull(x):\n    if x is None:\n        return 0\n
elif x == '-':\n        return 0\n    else: return x")

# Process: Add Field (11)
arcpy.AddField_management(Output_Feature_Class__2_, "PopForIncome", "DOUBLE", "", "", "", "",
"NULLABLE", "NON_REQUIRED", "")

# Process: Pop for Income
arcpy.CalculateField_management(INTERMEDIATE_FILE2_CITY_BIKEWAYS_SECBYBG_INTERSECT_W_AREA__3_,
"PopForIncome", "[NullIncomeFlag] * [ProportPopulation]", "VB", "")

# Process: Add Field (12)
arcpy.AddField_management(bufferSECintersect__22_, "NullAgeFlag", "DOUBLE", "", "", "", "",
"NULLABLE", "NON_REQUIRED", "")

# Process: NullAgeFlag
arcpy.CalculateField_management(INTERMEDIATE_FILE2_CITY_BIKEWAYS_SECBYBG_INTERSECT_W_AREA__5_,
"NullAgeFlag", "changenull (!MedianAge!)", "PYTHON_9.3", "def changenull(x):\n    if x is None:
\n        return 0\n    elif x == '-':\n        return 0\n    else: return 1\n")

# Process: Add Field (16)
arcpy.AddField_management(bufferSECintersect__23_, "CleanAge", "DOUBLE", "", "", "", "",
"NULLABLE", "NON_REQUIRED", "")

# Process: CleanAge
arcpy.CalculateField_management(bufferSECintersect__29_, "CleanAge", "changenull(!MedianAge!)",
"PYTHON_9.3", "def changenull(x):\n    if x is None:\n        return 0\n    elif x == '-':\n
return 0\n    else: return x")

# Process: Add Field (13)
arcpy.AddField_management(Output_Feature_Class__3_, "PopForAge", "DOUBLE", "", "", "", "",
"NULLABLE", "NON_REQUIRED", "")

# Process: Pop forAge
arcpy.CalculateField_management(INTERMEDIATE_FILE2_CITY_BIKEWAYS_SECBYBG_INTERSECT_W_AREA__2_,
"PopForAge", "[NullAgeFlag] * [ProportPopulation]", "VB", "")

# Process: Add Field (3)
arcpy.AddField_management(bufferSECintersect__26_, "ProportAge", "DOUBLE", "", "", "", "",
"NULLABLE", "NON_REQUIRED", "")

# Process: PropAge
arcpy.CalculateField_management(bufferSECintersect__19_, "ProportAge", "[PopForAge] *
[CleanAge] ", "VB", "")

# Process: Add Field (4)
arcpy.AddField_management(SECProportAge, "ProportIncome", "DOUBLE", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")

# Process: PropIncome
arcpy.CalculateField_management(bufferSECintersect__8_, "ProportIncome", "[PopForIncome] *
[CleanIncome] ", "VB", "")

# Process: Add Field (5)
arcpy.AddField_management(bufferSECintersect__7_, "PropBike", "DOUBLE", "", "", "", "",
"NULLABLE", "NON_REQUIRED", "")

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# Process: BikeNumber
arcpy.CalculateField_management(bufferSECintersect__9_, "PropBike", "[Bicycle] *
[AreaProportion]", "VB", "")

# Process: Add Field (6)
arcpy.AddField_management(bufferSECintersect__11_, "PropTransit", "DOUBLE", "", "", "", "",
"NULLABLE", "NON_REQUIRED", "")

# Process: TransitNumber
arcpy.CalculateField_management(bufferSECintersect__10_, "PropTransit", "[AreaProportion] *
[PublicTrans]", "VB", "")

# Process: Add Field (7)
arcpy.AddField_management(bufferSECintersect__12_, "PropStudent", "DOUBLE", "", "", "", "",
"NULLABLE", "NON_REQUIRED", "")

# Process: StudentNumber
arcpy.CalculateField_management(bufferSECintersect__13_, "PropStudent", "[AreaProportion] *
[UniversityStudent]", "VB", "")

# Process: Add Field (10)
arcpy.AddField_management(bufferSECintersect__14_, "ProportHousehold", "DOUBLE", "", "", "",
"", "NULLABLE", "NON_REQUIRED", "")

# Process: Calculate Field
arcpy.CalculateField_management(SECIntersectAreas__3_, "ProportHousehold", "[TotalHouseholds] *
[AreaProportion]", "VB", "")

# Process: Add Field (8)
arcpy.AddField_management(SECIntersectAreas__4_, "PropNoVehicle", "DOUBLE", "", "", "", "",
"NULLABLE", "NON_REQUIRED", "")

# Process: NoVehicles
arcpy.CalculateField_management(SECIntersectAreas__5_, "PropNoVehicle", "[AreaProportion] *
[HouseholdsWOVehicles_1]", "VB", "")

# Process: Add Field (15)
arcpy.AddField_management(bufferSECintersect__16_, "PropWhiteNonHispanic", "DOUBLE", "", "",
"", "", "NULLABLE", "NON_REQUIRED", "")

# Process: NonHispanicWhite
arcpy.CalculateField_management(SECIntersectAreas__6_, "PropWhiteNonHispanic",
"[AreaProportion] * [WhiteNonHispanic]", "VB", "")

# Process: Copy Features (2)
arcpy.CopyFeatures_management(SECIntersectAreas__7_,
INTERMEDIATE_FILE3_CITY_ALLFIELDS_FORDISSOLVE, "", "0", "0", "0")

# Process: Dissolve (3)
arcpy.Dissolve_management(INTERMEDIATE_FILE3_CITY_ALLFIELDS_FORDISSOLVE,
IntermediateFileUpperBufferDissolveForPopSums, Dissolve_Field_s__by_Facility, "ProportAge
SUM;ProportIncome SUM;PropBike SUM;PropTransit SUM;PropStudent SUM;ProportHousehold
SUM;PropNoVehicle SUM;PropWhiteNonHispanic SUM;ProportPopulation SUM;PopForIncome SUM;PopForAge
SUM", "MULTI_PART", "DISSOLVE_LINES")

# Process: Add Field (x)
arcpy.AddField_management(IntermediateFileUpperBufferDissolveForPopSums, "BufferMedianAge",
"DOUBLE", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")

# Process: Calculate Field (2)
arcpy.CalculateField_management(Output_Feature_Class, "BufferMedianAge", "!SUM_ProportAge! / !
SUM_PopForAge!", "PYTHON", "")

# Process: BufferMedianIncome
arcpy.AddField_management(IntermediateFileUpperBufferDissolveForPopSums__3_,
"BufferMedianIncome", "DOUBLE", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")

# Process: Calculate Field (3)

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arcpy.CalculateField_management(Output_Feature_Class__4_, "BufferMedianIncome", "!
SUM_ProportIncome! / !SUM_PopForIncome!", "PYTHON", "")

# Process: Add Join (2)
arcpy.AddJoin_management(Input_Bikeways, Bikeways_File_Input_Join_Field,
IntermediateFileUpperBufferDissolveForPopSums__4_,
Dissolved_BGs_Output_Join_Field__FID__from_bikeway_file_, "KEEP_ALL")

# Process: Copy Features
arcpy.CopyFeatures_management(BufferwithSEC_JoinOutput, Output_Lanes_w_SEC_joined, "", "0",
"0", "0")

# Process: Dissolve
arcpy.Dissolve_management("", INTERMEDIATE_FILENAME_CITY_BIKEWAY DISSOLVED_FOR_JOIN,
"FID_DC_facility_changes_070120167", "ProportAge SUM;ProportIncome SUM;PropBike SUM;PropTransit
SUM;ProportPopulation SUM;PropStudent SUM;PropNoVehicle SUM;F_AREA SUM;ProportHousehold
SUM;PropWhiteNonHispanic SUM", "SINGLE_PART", "DISSOLVE_LINES")

# Process: Join Field (2)
arcpy.JoinField_management(INTERMEDIATE_FILENAME_CITY_BIKEWAY DISSOLVED_FOR_JOIN,
"FID_DC_facility_changes_070120167", "", "FID_DC_facility_changes_070120167",
"SUM_ProportPopulation;SUM_PopWeightForIncome;SUM_PopWeightForAge")

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