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ATRC Active Transportation Resource Center

Caltrans Active Transportation Benefit – Cost Tool

Literature Review

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Introduction

In this review we examine the effects of active transportation infrastructure and programs. The goal of the review is to synthesize the current literature on the benefits of investing in walking and bicycling, with the specific purpose of quantifying the benefits (if possible) from the wide variety of infrastructure and programmatic interventions by local or regional governments. While our review is focused on walking and bicycling as modes for destination-oriented travel, we also consider recreation- and exercise-related outcomes from active transportation investments.

For infrastructure interventions, we focus on walking- and bicycling-specific infrastructure (e.g., bike lanes, crossings, sidewalks) but we also review to a lesser extent a broad array of interventions that are likely to have an impact on walking and bicycling regardless of their primary purpose (e.g., road diets, lane narrowing). For programmatic interventions, we focus on incentives, education, and outreach efforts in the context of school and workplace travel but also for general all-purpose travel demand management.

In conducting this review, we began with a systematic search using the following databases: Web of Science, Scopus, Crossref, and Google Scholar. We read titles and abstracts for all returned hits that were published in English until the titles became increasingly irrelevant to our search term. In the case of the pure academic search engines, we more often reviewed every item returned. In some cases, we revised our search term if it proved to be too broad from the initial search (e.g., returning thousands instead of hundreds of articles). The one exception to these general steps was our use of Google Scholar. Because Google Scholar tended to return a much wider variety of material compared to the other search engines with the same search terms, we used it to find material quickly and did not review all the returned documents (often in the hundreds of thousands). Besides our systematic search, we also used citations from publications (especially recent review papers) to expand our review and we included literature from our prior research. About half of our citations were from the systematic search, while the other half obtained from non-systematic means.

The literature we searched for was based on our conceptual framework for how active transportation projects lead to important societal outcomes (Figure 1). In this conceptual framework, changes in perceptions and behavior are assumed to be the root cause of active transportation project benefits, though the causal paths are complex in that societal outcomes then influence individual perceptions and behavior. Research in this area tends to focus on specific aspects of the framework rather than the system as a whole, and so in reviewing the literature we focus on four primary outcomes: change in perceptions, change in small-scale behaviors (e.g., drivers changing speeds, pedestrians using crosswalks), change in large-scale behaviors (e.g., travel mode choice, active travel frequency), and change in societal benefits from the behavioral changes (e.g., improved health, lower GHG emissions).

When reviewing titles and abstracts, we considered the following thresholds for adding the material to our literature database:

(1) Does the study report direct and/or indirect benefits or costs from project interventions?
(2) Does the study report change in large-scale behaviors such as travel mode choice or frequency of walking and/or bicycling?
(3) Does the study report change in small-scale behaviors that may feedback to perceptions which in turn could influence walking and/or bicycling?

If a report or journal article met at least one of these criteria, we recorded details about the study in our database that we used as a synthesis for this report.

Given that the literature we reviewed spanned a variety of study types, we qualitatively weighed studies that proved to have stronger internal[1] and external validity[2] in synthesizing expected outcomes from active transportation investments. While we originally planned to conduct meta-analyses[3] on specific outcomes, this proved too challenging given the number of interventions we considered and the number of differences between studies, even of similar designs and outcomes. Meta-analyses could be conducted in the future for specific interventions if enough sufficiently comparable studies become available; a framework for evaluating outcomes at different temporal scales is needed prior to any formal meta-analysis (i.e., when should the outcomes be measured? How long should they last?). In this review, we report the range of expected outcomes as the various authors report them to provide an understanding of the potential range of effects of each intervention. We ignore outliers in our range summaries (and provide descriptions of outliers when available), and we provide confidence intervals when reporting specific study results where possible[4]. The goal of the effects we report are to provide general order of magnitude differences between different intervention types, they should not be considered expectations for any specific project. We most commonly report results as relative effects (e.g., percent change, odds ratios) because that is how most studies report effects. Unfortunately, relative effects neglect the base rate of the phenomena they represent (e.g., current bike counts, number of existing crashes), and should not always be used to compare projects or programs. For example, a 20% reduction in crashes on a collector may not provide as

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[1] "Internal validity" refers to the degree to which the study establishes a causal relationship between the investment or program and the outcome. Longitudinal and experimental studies have stronger internal validity than cross-sectional studies.

[2] "External validity" refers to the degree to which the results of the study can be generalized to other contexts. Larger studies using random samples of the population tend to have greater external validity.

[3] "Meta-analysis" involves the pooling of data from multiple studies and the analysis of the pooled data to produce an estimate of the effect size across a wider array of contexts and for a larger sample.

[4] We use "95CI" to denote author reported 95% confidence intervals. 95CI indicates that 95% of individual trials will yield a result within the stated range while only 5% will not.

strong of a benefit as a 3% reduction in crashes on an arterial if the number of existing crashes on the arterial are much greater. Because of this challenge, we refrain from directly comparing project types in this review, and future work is needed to calculate absolute effects from the existing literature to improve project comparisons.

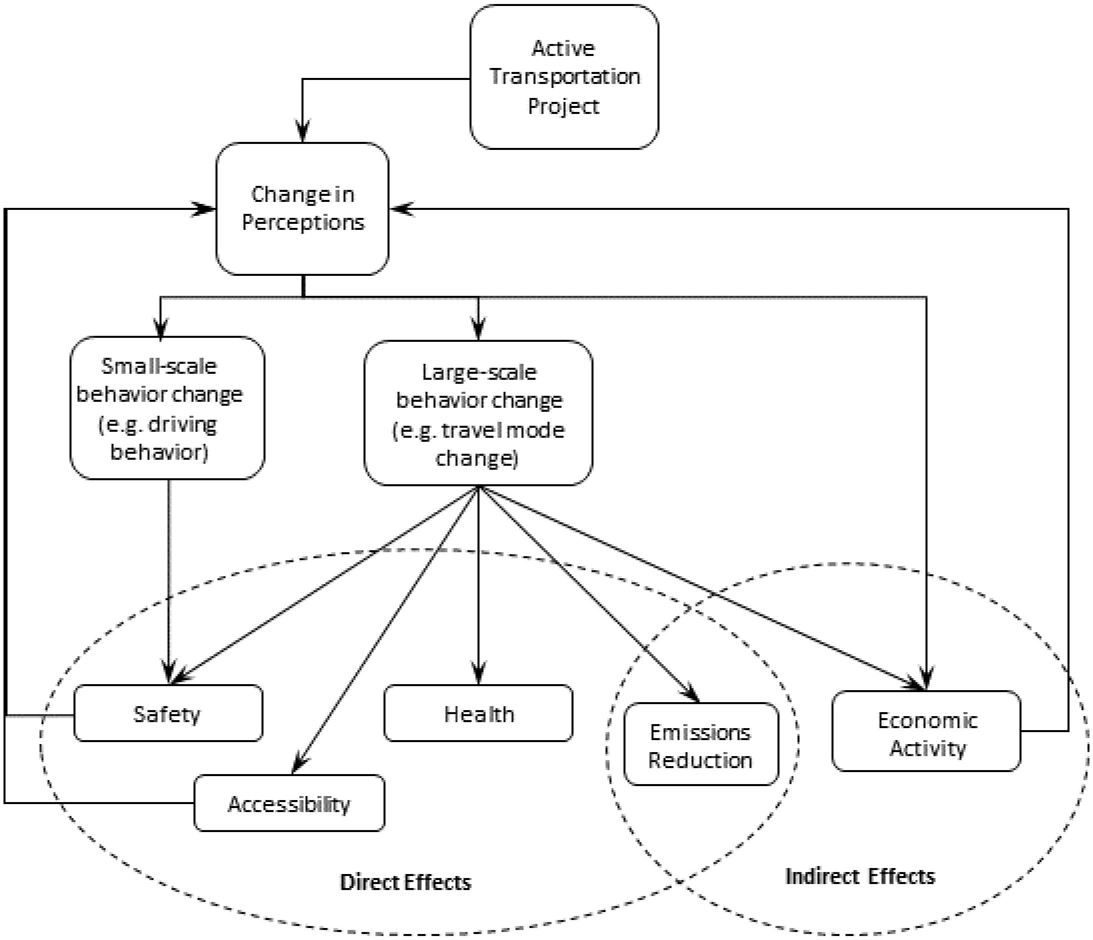

Figure 1. Conceptual framework for the effects of active transportation projects. The effects in the diagram are examples and not an exhaustive list.

Active Transportation Programs and Projects: Behavioral Effects

In the following sections we describe the types of projects and programs in the scope of our review. We also highlight some project types that while beyond our scope are likely to have at least indirect effects on walking and bicycling. We present the evidence for the effects of each project or program on travel behavior using the conceptual framework from Figure 1.

In this framework, the effects of active transportation programs and projects occur by first changing people's perceptions. These changes in perceptions are heterogeneous across the population, but well-designed interventions for walking and bicycling that change many people's perceptions can lead to small- and large-scale behavior changes. Small-scale behavior changes, such as drivers slowing down, occur without much deliberate decision making but nonetheless can increase active transportation safety. Large-scale behavior changes are more significant in terms of societal benefits, such as travel mode shifts, and require people to make decisions about changing their behavior. While the large-scale behavior changes are the most important, ignoring small-scale changes and changes in perceptions could lead to an under-accounting of important societal benefits.

In the following section we review the ways projects and programs have been evaluated; this review helps in articulating why some active transportation project benefits are best estimated at distinct levels of the proposed conceptual framework (Figure 1). We summarize effects by treating infrastructure projects separately from programs because research has tended to focus on one or the other, but evidence clearly shows that integrating infrastructure with non-infrastructure programs to increase active travel is most effective (Keall, Shaw, Chapman, & Howden-Chapman, 2018; Pucher, Dill, & Handy, 2010). For example in Barcelona, Spain, combined investments in the form of a 72 percent increase in bike lanes, 66 percent increase in pedestrian zones, widespread traffic calming, education campaigns, and expansion of a bike share service increased the number of walk trips by 27 percent and bike trips by 73 percent (Pérez et al., 2017). The challenge with estimating the effects of active transportation projects and programs is that they happen in uncontrolled contexts, thus obscuring the degree to which they truly cause the outcomes to occur.

Infrastructure Projects

We differentiated the types of infrastructure projects in this review based on whether they were implemented on corridors or at intersections. Infrastructure projects on corridors include conventional, buffered, and protected bike lanes, multi-use paths, sidewalk characteristics, speed bumps, road diets, shoulder width, midblock crossings, among others. Infrastructure interventions at intersections include roundabouts, pedestrian islands, crosswalks, raised intersections, raised crossings, bike crossings, bike boxes, new signals and signal timers, and protected intersections, among others.

The outcomes of these interventions depend heavily on their detailed designs (which vary across studies). Most research focuses on the presence of a facility or an intervention, with little regard for the details in the design, and the details can have substantial effects (see the discussion of roundabouts below). Additionally, the connectivity of a project to the active transportation network and the surrounding land use and road use all contribute to the ultimate benefits of a project. For example, painting a bike lane in a neighborhood with short trip distances and a moderate bike mode share is likely to have only a small relative effect on bicycling rate but a large absolute effect on bicycling (count of bike trips). The opposite is true of a bike lane placed in a neighborhood with long trip distances and minimal existing bicycling. In that context, the relative effect of painting a bike lane is likely to be large, but the absolute effect negligible.

Conceptually, context is likely to enhance or restrict the effect of infrastructure projects. However, context effects are rarely reported due to the challenge of measuring the complex interactions at play and the lack of consistency in measuring context variables for active transportation. Because of these challenges, existing reviews of how infrastructure influences walking and bicycling (Saelens & Handy, 2008) demonstrate mixed results and highlight important flaws in existing studies. We discuss important design and context differences when they are reported, but for many interventions this is not possible. When we summarize general estimates by infrastructure type, design and context variation within infrastructure type is assumed to be reflected in the uncertainty in the aggregated effects reported. In cases where the variation is large enough to indicate an uncertain direction of effect, we chose to only provide a qualitative synthesis.

Infrastructure for walking and bicycling

Infrastructure types for which there is evidence of their effectiveness to increase walking and bicycling tend to be those that focus on providing better safety and comfort for walking and bicycling. We use a broad definition of "infrastructure" that includes not only traditional changes to the roadway but also things like cameras used to enforce speed limits and speed display signs. Table 1 summarizes the findings on the effects of the interventions as found in the primary literature. The reported effects are not estimates from a meta-analysis. Further detailed study of each intervention would be needed to estimate reliable mean estimates.

Table 1. Infrastructure interventions that influence walking and bicycling and their range of effects.

Intervention	Measured effects on perceptions and behavior change	Measured effects of downstream benefits
Speed enforcement	Reductions in mean absolute speed by between 1-9.5 mph, reductions in all speeds by 2-33%, and reductions in percentage of speeding vehicles by 30-96% (Elvik, Vadeby, Hels, & van Schagen, 2019; Hu & McCartt, 2016; Rodier, Shaheen, & Cavanagh, 2007; Soole, Watson, & Fleiter, 2013).	Reductions in all crashes from 5-69% (Graham, Naik, McCoy, & Li, 2019; Pilkington & Kinra, 2005; L. J. Thomas, Srinivasan, Decina, & Staplin, 2008), reduction in injuries from 12-65% and deaths from 17-71% (Pilkington & Kinra, 2005).
Speed limit reductions	5 mph reduction in speed limit is expected to reduce mean speed by 1-2 mph (Elvik et al., 2019; Silvano & Bang, 2016), increases walking by 1-	5 mph reduction in speed limit is expected to reduce crashes by 10-15%, injuries by 8-15%, fatalities 10-30% (Elvik et al., 2019; Gayah,

	21% and bicycling by 4 – 22% (Tranter, 2018; Wier, 2019), although the large-scale behavioral effects are partially confounded. When combined with other infrastructure interventions, increase in active travel by 12-28% (Kullgren et al., 2019; Tranter, 2018).	Donnell, Yu, & Li, 2018), and bicyclist injuries 2.2-15.2% (Helak K, Jehle D, McNabb D, Battisti A, Sanford S, 2017; Zahabi, Strauss, Manaugh, & Miranda-Moreno, 2011).
Dynamic speed display signs	Reduce mean speed by 1-12 mph or 3-10%, reduce 85th percentile speed by 3-8%, and reduce percent of cars exceeding speed limits by 13-48% (Cruzado & Donnell, 2009; Gehlert, Schulze, & Schlag, 2012; Ullman & Rose, 2005).	We did not review any studies with downstream effects.
Vertical deflectors	One deflector can reduce average speed by 2.7-3.4 mph, and multiple successive deflectors by 8-12 mph (Agerholm, Knudsen, & Variyeswaran, 2017; Cottrell, Kim, Martin, & Perrin, 2006; Ponnaluri & Groce, 2005).	We did not review any studies with downstream effects.
Horizontal deflectors	Reduction in average speeds by 1.3 - 3.2 mph in some contexts (Agerholm et al., 2017; Kacprzak & Solowczuk, 2019; Lantieri et al., 2015)	We did not review any studies with downstream effects.
Lane narrowing	Mixed evidence - wider lanes separate vehicles from pedestrians and bicyclists, but narrower lanes cause drivers to slow down, which have known safety effects (Lee & Abdel-Aty, 2005; Rista et al., 2018; Turner et al., 2019). Lane narrowing on intersection approaches reduce speeds by 3.5-4.8 mph in one study (Gross, Jagannathan, & Hughes, 2009).	Lane narrowing on intersection approaches reduce crashes by 31% on average in one study (Gross et al., 2009).
Shared streets	Reduction of average speeds by 20-40% from meta-analysis of converted residential to shared street (Sørensen, 2011).	Some studies report increasing child play, decreasing crime, increasing real estate price, but with such few details from secondary studies, effect sizes are largely unknown (Alan M.

		Voorhees Transportation Center, 2004; Appleyard, 1983; Delaware Valley Regional Planning Commission, 2018; Eubank-Ahrens, 1985). Reduction in serious traffic injuries by 50% in a Netherlands study (Delaware Valley Regional Planning Commission (2018) citing the FHWA)
Edge lane roads	Changes in mean speed range from reductions of about 3 mph to increases in 1 mph (Davidse, Driel, & Goldenbeld, 2004; Gilpin, Falbo, & Williams, 2017), change in lateral position of cars (e.g., more space when passing bicyclists) of 16 inches of more space, to 8 inches of less space (Davidse et al., 2004).	We did not review any studies with downstream effects.
Multi-use paths	Off-street paths are preferred for bicycling compared to nearly all other bike infrastructure (Broach, Dill, & Gliebe, 2012; Clark, Mokhtarian, Circella, & Watkins, 2019; Fitch & Handy, 2020). Some evidence that living near multi-use paths increases likelihood of physical activity (Kaczynski & Henderson, 2007; Kaczynski, Potwarka, Smale, & Havitz, 2009).	Conflicting evidence of safety of multi-use paths indicates that general safety outcomes are uncertain, and context (especially about intersections with roads) is likely to determine outcomes.
Road diets	Reduce mean speeds 0-4 mph (L. Thomas, 2013), increase bicyclist volumes by 30-240% and pedestrian volumes by 0-30% (City of San Jose, 2015; Gudz, Fang, & Handy, 2016; L. Thomas, 2013).	Reduce crash rates by between 19-47%, with greatest relative effects in rural environments (L. Thomas, 2013; Turner et al., 2019).
Roundabouts	Bicyclists perceive roundabouts as safer than signalized intersections (Wang & Akar, 2018).	Variable bicyclist safety outcomes depending on design (Harris et al., 2013; Kaplan & Giacomo Prato, 2015; Meuleners et al., 2019; Reynolds, Harris, Teschke, Cripton, & Winters, 2009; Shinar,

		2017).Overall safety (including drivers and passengers) is increased: 15-38% reduction in crashes. 35-52% reduction in injuries, and 49-85% reduction in deaths (Elvik, 2017; R. A. Retting, Persaud, Garder, & Lord, 2001)
Protected intersections	We did not review any studies with behavioral effects.	We did not review any studies with downstream effects. However, these are commonly used in the Netherlands which have high rates of cycling and low rates of bicyclist crashes (P. Schepers, Twisk, Fishman, Fyhri, & Jensen, 2017).
Flashing beacons	Flashing beacons have a high yield compliance rate of 70-90%, which is substantially higher than the crosswalk compliance rate of 10-20% (Fitzpatrick, Chrysler, Van Houten, Hunter, & Turner, 2011; Fitzpatrick, Potts, Brewer, & Avelar, 2015; Vanwagner, Van Houten, & Betts, 2011; C. Zegeer et al., 2017).	Reduce pedestrian crashes by an average of 35-50%, with standard errors of 21-38% (Fitzpatrick et al., 2011, 2015; Vanwagner et al., 2011; C. Zegeer et al., 2017).
Traffic signals	Increased pedestrian signal phase allows more people to cross the street, which is especially important for elderly populations (National Highway Traffic Safety Administration, 2020a).	Phasing of left turns and signals with protected left phases decrease total left-turning crashes and injuries (Harkey et al., 2008; Christopher Monsere et al., 2019). Full-red and half-red signal phasing has been shown to decrease injuries by 24% and 19% respectively (Stipancic, Miranda-Moreno, Strauss, & Labbe, 2020).

Speed Enforcement

The effects of manual speed enforcement from police occur during the enforcement campaign, but lasting effects after campaigns are uncertain (Lawpoolsri, Li, & Braver, 2007; Wier, 2019). In addition, at least one study found that while vehicle speeds are reduced in the presence of a parked police car as vehicles approach it, drivers increase their speeds again as they move away from the police car (Virginia P. Sisiopiku & Patel, 1999). One concern about using enforcement to control speed is historical racial profiling of policing. However, some evidence suggests that racial profiling is isolated to investigatory stops, and is *not* a cause for traffic safety stops, especially speeding (Epp, Maynard-Moody, & Haider-Markel, 2017). Nonetheless, automatic enforcement is an alternative which lacks the uncertainty in long-term effectiveness of manual enforcement.

Because speed cameras enforce continually, they have been shown to be effective in many environments. Although speed camera enforcement may also pose important societal costs (e.g., privacy), and at least in the US their use still have many hurdles for implementation, consensus on their ability to reduce speeds is clear (Rodier et al., 2007). Studies in different traffic contexts with different camera technology show that speed camera enforcement reduces mean absolute speed by between 1-9.5 mph, reduces all speeds by 2-33 percent, and reduces percentage of speeding vehicles by 30-96 percent (Elvik et al., 2019; Hu & McCartt, 2016; Rodier et al., 2007; Soole et al., 2013). Furthermore, speed camera enforcement can reduce collisions by 5-69 percent (Elvik et al., 2019; Pilkington & Kinra, 2005), although some reviews suggest that the expected effects are likely to be between 14-25 percent (Graham et al., 2019; L. J. Thomas et al., 2008). In terms of injuries and fatalities, the expected effects are stronger with ranges of 12-65 percent and 17-71 percent for injuries and deaths, respectively (Pilkington & Kinra, 2005). Except for the decision of where to place speed cameras, the enforcement technique is largely unbiased and thus poses much less of an equity risk compared to manual speed enforcement techniques.

Speed limits

Reduced speed limits have overwhelmingly been associated with slower car speeds and improved safety outcomes. The effect of reducing speed limits on mean speed is small. In general, a 5 mph reduction in posted speed is expected to reduce mean speed by about 1-2mph (Elvik et al., 2019; Silvano & Bang, 2016). Reducing speed limits reduces the speed of the fastest drivers to a greater extent (Silvano & Bang, 2016), which may explain why speed limit reductions have substantial safety benefits. A 5 mph speed limit reduction is likely to reduce collisions by 10-15 percent, reduce injuries by 8-15 percent, and reduce fatalities 10-30 percent (Elvik et al., 2019; Gayah et al., 2018). The same 5 mph speed limit reduction has also been shown to reduce collisions by 15 percent (Helak K, Jehle D, McNabb D, Battisti A, Sanford S, 2017; Kullgren et al., 2019) and serious bicyclist injuries with a range of 2.2-15.2 percent (Helak K, Jehle D, McNabb D, Battisti A, Sanford S, 2017; Zahabi et al., 2011).

In terms of large-scale behavior change from speed limit reductions, the literature is much less clear. Some evidence suggests that speed limit reductions increase walking (1-21 percent) and bicycling (4 - 22 percent) (Tranter, 2018; Wier, 2019), but given that speed limit reductions were supplemented with enforcement programs in these studies, it is difficult to equate specific effects to the speed limit reduction. What is clearer is that when speed limit reductions are done in concert with infrastructure effects, increases in active travel can be more substantial at 12-28 percent (Kullgren et al., 2019; Tranter, 2018).

Dynamic speed display signs

Dynamic Speed Display Signs (DSDSs) are signs that measure and display vehicle speeds so that drivers are aware of their speed in relation to the speed limit. Evidence suggests that DSDSs can reduce mean speed by 1-12 mph (Cruzado & Donnell, 2009) or 3-10 percent, 85th percentile speed by 3-8 percent, and percent of cars exceeding speed limits by 13-48 percent (Gehlert et al., 2012; Ullman & Rose, 2005). Some of the variation in the effects are due to context, but also the type of sign matters. Specifically, colored (red and green) numeric displays and message displays (e.g., “slow down” and “thank you”) are more effective and have less attenuation over time compared to non-colored numeric displays of speed (Gehlert et al., 2012). However, the effectiveness of DSDSs after removal is very limited and even when placed permanently, the effects tend to decline over time (Jeihani, Ardeshiri, & Naeeni, 2012), although much less so for colored message displays (Gehlert et al., 2012).

Vertical deflectors

Vertical deflectors include speed bumps, speed humps, and speed tables that encourage speed reduction by acting as physical obstacles to drivers who must pass over them slowly to maintain control and maximize comfort. They have proven quite effective in Denmark and the United States where single deflectors have reduced average speeds by 2.7-3.4 mph and multiple successive deflectors have reduced average speeds by 8-12 mph (Agerholm et al., 2017; Cottrell et al., 2006; Ponnaluri & Groce, 2005). Vertical deflectors are often also noted for increasing air pollution from slowing traffic and increasing acceleration events (Januševičius & Grubliauskas, 2019).

Horizontal deflectors

Horizontal deflectors include chicanes and lane shifts that encourage speed reduction by acting as physical obstacles to drivers who must maneuver them slowly to maintain control and maximize comfort. Some European studies have determined that horizontal deflectors have reduced average speeds by 1.3-3.2 mph in some contexts (Agerholm et al., 2017; Kacprzak & Solowczuk, 2019; Lantieri et al., 2015). However, many researchers have acknowledged that horizontal deflector efficacy depends greatly on design characteristics including degree of deflection and the presence of other speed-reducing interventions (Barbosa, Tight, & May, 2000; Lantieri et al., 2015; Solowczuk & Kacprzak, 2019).

Lane narrowing

The current evidence is mixed on the overall safety of narrowing lanes. Wider lanes are thought to provide safety benefits due to greater separation of vehicle, but at the same time narrow lanes cause drivers to slow, which is known to improve safety (Lee & Abdel-Aty, 2005; Rista et al., 2018; Turner et al., 2019). In urban areas, the safety benefits for narrowing lanes may be primarily realized for vulnerable road users such as bicyclists and pedestrians (Morrison, Thompson, Kondo, & Beck, 2019). In rural areas, lane narrowing approaches to uncontrolled intersections in one study were shown to reduce speeds by 3.5-4.8 mph and have reduced crashes by 31 percent on average (Gross et al., 2009). Because the effects of lane narrowing are highly variable from study to study, other road characteristics must be considered when analyzing the effects of narrowing lanes. Also, people may still perceive wide streets as safer for walking and bicycling because of increased separation, especially if car speeds are controlled from other mechanisms.

Shared streets

Shared streets encompass a variety of street designs that encourage the slow interaction of all street users and vehicles. This concept is linked to the concept of the *Woonerf,* which originated in the Netherlands in the 1960's and spread throughout Europe. Notable versions include *Home Zones* in the UK and *Wohnstrasse* in Germany (Alan M. Voorhees Transportation Center, 2004). Because design and context matter for shared streets, the evidence of the effects of these interventions are often based on case studies. This allows an in-depth look at specific cases, but it poses challenges for determining general quantified effects. However, in most cases, shared streets have shown positive outcomes. Traffic safety is commonly improved (Delaware Valley Regional Planning Commission, 2018), and in the strict rules for Woonerven in the Netherlands (from 1976 law), evaluations showed vehicle speeds were reduced to averages of between 8-15 mph, and reduced serious traffic injuries by 50 percent (Delaware Valley Regional Planning Commission (2018) citing the FHWA, although FHWA does not cite the original source from the Netherlands). Primary literature in English from the Netherlands is hard to find, but at least one study from Haren showed that crashes declined from 6-14 per year to 3-9 per year, and traffic deaths declined from 2.5 to 0.2 per year (Goeverden & Godefrooij, 2011). In the same study, Haren residents perceived car speed reductions but felt less safe, despite the objective improvements in traffic safety. In a meta-analysis of shared street evaluations, Sorensen (2011) summarized the effects as 20-40 percent speed reduction, but the lack of quality data limited evaluations of other effects.

Unlike many other specific road treatments, several additional positive outcomes besides traffic safety have been reported for shared street interventions. For example, shared streets have been shown to increase children's play in residential contexts (Eubank-Ahrens, 1985), pedestrian activity in residential and commercial contexts (Appleyard, 1983; Delaware Valley Regional Planning Commission, 2018), and even to decrease crime in some UK cases (Delaware Valley

Regional Planning Commission, 2018). Furthermore, at least some cases indicate economic effects such as rising home values in “home zones” (Alan M. Voorhees Transportation Center, 2004). Because shared streets are not common in the US, the planning process is likely to play a vital role for their successful implementation. Indeed, the original cases in the Netherlands were neighborhood led in the 1960’s and even when the intervention achieved legal status in 1976, public participation was paramount to achieving support (Appleyard, 1983).

Edge Lane Roads (Advisory lanes)

In the US, advisory lanes are used as a design for narrow rural roads. However, the design is commonly used in the Netherlands for local roads as well. In a meta-analysis of this design the average effects of converting a center-line rural road to an edge lane road were a slight reduction in speed (1 mph on average), though in some cases speeds increased (Davidse et al., 2004). Although Gilpin, Falbo and Williams (2017) report that the vast majority of European results indicate reductions in speed, the magnitude of mean speed reductions are slight. This does not mean that the safety benefits are not substantial, but unfortunately research is lacking on the safety outcomes of edge lane roads. Of the twelve US case studies of edge lane roads, only one (Edina, MN) included quantitative evaluation, which indicated the 85th percentile speed was reduced by 1-3 mph (Gilpin et al., 2017). However, few methodological details of the US case studies (beyond their road designs) are available which limits their usefulness in understanding the effects of this strategy.

In rural settings, edge lane roads have been shown to increase the lateral position of cars (e.g., more space when passing bicyclists) of about 5 inches on average with a range of 16 inches of more space to 8 inches of less space (Davidse et al., 2004). The combined effect of increasing the lateral position of cars and in reducing speeds are likely to have positive safety benefits, although we could find no direct evidence of safety outcomes. Finally, most of the literature on edge lane roads is in rural highway settings. Although the design is common in low car volume local urban roads in the Netherlands, we could not find any before-and-after evaluations.

Multi-use paths

Although multi-use paths are designed to increase both walking and bicycling, research on outcomes from the building of multi-use paths is predominantly bicycling focused. Before-and-after evaluations (both with and without control locations) have generated limited evidence that multi-use paths increase walking (Ogilvie, Egan, Hamilton, & Petticrew, 2004). However, evidence does indicate that people living near parklands, which commonly include multi-use paths, are more physically active, and that they use those spaces for some of their physical activity (Kaczynski & Henderson, 2007; Kaczynski et al., 2009).

For bicycling, off-street paths (bike specific or multi-use) provide outcomes like or better than protected on-street bike facilities. In terms of perceptions and preferences, off-street paths are strongly preferred over roads with and without bike lanes (Broach et al., 2012; Clark et al., 2019; Fitch & Handy, 2020). Objective measures of bicyclist safety on multi-use paths is less clear since studies report conflicting results (DiGioia, Watkins, Xu, Rodgers, & Guensler, 2017; Jestico, Nelson, Potter, & Winters, 2017; Meuleners, Lee, & Haworth, 2007; Reynolds et al., 2009; Romanow et al., 2012; Teschke et al., 2014, 2012). This may be due to the inconsistency in how multi-use paths are designated in the literature (some paved, some unpaved, some single use, some multi-use), but it is also likely due to differences in context and lack of available bicyclist exposure data.

Road diets

Road diets refer to the reduction of car travel lanes and/or parking lanes and reassignment of that right-of-way to bike lanes and other facilities that separate or protect bicyclists and pedestrians, and/or slowing of car speeds. One of the most common general conversions is the four- to three-lane conversion in which a four-lane road (two in each direction) is converted to a two-lane road with center turn lane. Because road diets include bike and pedestrian infrastructure, change in turn lane configurations, lane widths, and other more detailed design changes such as islands, medians, raised crossings, and signal changes, they are a compilation of multiple infrastructure interventions, and their effects reflect the interactions among these interventions. Studies in North American indicate that road diets reduce mean speeds by 0-4 mph and commonly reduce 85th percentile speeds to a greater extent (L. Thomas, 2013). Road diets also almost universally reduce crashes at rates between 19-47 percent, with the greatest relative effects in rural environments, and absolute effects in urban environments (L. Thomas, 2013; Turner et al., 2019). While evaluations of specific safety benefits for pedestrians and bicyclists are scarce, many of the specific infrastructure changes in a road diet have been shown to make roads safer for walking and bicycling. For example, many road diet configurations include bike lanes (see effects of bike lanes below), and pedestrian refuge islands for mid-block and unsignalized crossings (see effects of those below). In terms of large-scale behavior change, road diets clearly attract bicyclists with increases ranging from 30-240 percent, but they attract pedestrians to a lesser extent (20-30 percent increases) and less commonly, not at all (City of San Jose, 2015; Gudz et al., 2016; L. Thomas, 2013). However, counts of bicyclists and pedestrians generally do not include neighboring streets, making it difficult to know how much of these increases represent shifts from other routes versus a true increase in active travel.

Roundabouts

Roundabout intersections vary widely in their designs and these variations matter for a variety of outcomes. For example, roundabouts with wide entering lanes can encourage fast entering speeds for drivers which can have negative safety effects for vulnerable road users (Shinar, 2017). For bicyclists, one-lane roundabouts have been shown in some cases to improve safety (especially when converting non-signalized intersections to roundabouts), but the majority of studies indicate that changing signalized intersections to roundabouts is likely to increase car-to-bike crashes (Harris et al., 2013; Kaplan & Giacomo Prato, 2015; Meuleners et al., 2019; Reynolds et al., 2009; Shinar, 2017) even though at least one study showed that bicyclists perceive them as safer (Wang & Akar, 2018). This safety risk is greater with two-lane roundabouts (Reynolds et al., 2009). However, of the few studies that have examined roundabout designs that include separated bicycling facilities, some have shown the opposite, that they reduce bicyclist crash risk (Daniels, Brijs, Nuyts, & Wets, 2009; Reynolds et al., 2009). The safety outcomes for pedestrians at roundabouts seem to be mixed, but some studies show increased pedestrian safety (e.g., Richard A. Retting, Ferguson, & McCartt, 2003). Overall safety outcomes (including for car drivers and passengers, the primary users of roundabouts) are overwhelmingly positive, in the range of a 15-38 percent reduction in crashes, 35-52 percent reduction in injuries, and 49-85 percent reduction in deaths (Elvik, 2017; Jensen, 2017; R. A. Retting et al., 2001).

Protected intersections

Protected intersections have several important design characteristics to help improve bicyclist safety at signalized intersections. The treatment has been used extensively in the Netherlands, but has only recently been used in the U.S. We found little evidence of the effectiveness of protected intersections from the Dutch experience, even though the general design is commonplace in major Dutch cities where bike routes parallel car routes when approaching signalized intersections. More common in the Netherlands is the design of bike routes away from car routes to avoid the need for car/bike crossing movements altogether. Current case studies in the U.S. are too recent to provide any meaningful outcomes (Alta Planning + Design, 2015). The best case for the safety benefits of protected intersections is their general use in the Netherlands, which has a history of substantial rates of bicycling and whose “sustainable safety” approach to road design has proved highly effective (P. Schepers et al., 2017).

Flashing beacons

Flashing beacons come in a variety of shapes, colors, and sizes, and have been used in a variety of pedestrian crossing situations where signalized intersections are either not needed, or not suitable. Some common forms include rapid flashing beacons (horizontal and circular) and the Pedestrian Hybrid Beacon. Recent evaluation of these beacons in the U.S. suggests they all have high yielding compliance of 70-90 percent (compared to crosswalk compliance in the 10-20 percent range) and reduce pedestrian crashes by approximately 35-50 percent on average (but with standard errors of 21-38 percent depending on type of beacon) (Fitzpatrick et al., 2011, 2015; Vanwagner et al., 2011; C. Zegeer et al., 2017). Colors and flashing patterns of beacons do not seem to vary these effects (Fitzpatrick et al., 2015; Moshahedi, Kattan, & Tay, 2018). While the primary focus of beacons are in pedestrian safety, they have also shown to have similar yielding rates for bicyclists (Dougald, 2016).

Traffic signals

Signal type, activation, coordination, phasing, and timing are all important parameters for providing safe environments for walking and bicycling through intersections. A wide variety of signal interventions have been used to improve safety and convenience for walking and bicycling through intersections. For example, lengthening signal phases for pedestrians allows more of the population to cross in time to clear the intersection before the end of the pedestrian phase. This is especially important for the elderly who are more susceptible to pedestrian injury (National Highway Traffic Safety Administration, 2020a). One of the signal variables that matters most for bicyclists is the phasing of left turns (Christopher Monsere et al., 2019), and signals with protected left phases decrease total left-turning crashes and injuries (Harkey et al., 2008). For pedestrians, in one study, full-red and half-red has been shown to reduce injury by 24 percent and 19 percent respectively (Stipancic et al., 2020). When signal interventions are implemented in conjunction with intersection redesigns, as is often the case, they must be evaluated jointly with the redesign.

Bicycling Specific infrastructure

Cities' primary mechanism for increasing bicycling is to install infrastructure that supports safe and comfortable bicycling. While in some cases good bike infrastructure failed to result in meaningful amounts of bicycling (e.g., Stevenage, UK (Reid, 2017)), most studies agree that infrastructure is a first necessary condition for bicycling to increase (Pucher et al., 2010). Overall, building higher quality and more extensive bike and pedestrian infrastructure increases biking and walking. Importantly, the context of bike infrastructure investments matters for estimating their behavioral effects. In general, bike infrastructure that provides more separation between bikes and cars and more protection of bicyclists from cars is perceived as safer (Clark et al., 2019), has been stated and "revealed" to be preferred (Dill, 2009; Pucher et al., 2010), and has been shown to have larger impacts on bicycling rates and safety compared to infrastructure with less separation and protection (Harris et al., 2013; D. K. J. Krizek, Forsyth, & Baum, 2009; McNeil, Monsere, & Dill, 2015; Chris Monsere et al., 2014; Winters et al., 2013).

Bike specific infrastructure has been associated with numerous small- and large-scale behavior changes at a variety of levels of analysis. At the city-level, both correlational and longitudinal evidence strongly suggests that bike infrastructure investment increases bicycling rates (Aziz et al., 2017; B. B. Brown et al., 2017; Buehler & Pucher, 2012; Leclerc, 2002; Pucher et al., 2010). At the project level, although outcome measurement is difficult, similar evidence is found (Mölenberg, Panter, Burdorf, & Van Lenthe, 2019; Chris Monsere et al., 2014). The absolute magnitudes of the effects of different bicycle infrastructure types are difficult to quantify because they depend heavily on context. This is especially the case for understanding safety effects, where design details can be paramount to a facility's safety success. However, generalizations can be made, as summarized below; Table 2 provides expected infrastructure-specific effects.

Table 2. Infrastructure interventions that influence bicycling and their range of effects

Intervention	**Measured effects on perceptions and behavior change**	**Measured effects of downstream benefits**
Conventional bike lane	Bike lanes increase facility usage by approximately 62% on average (ranging from 4 to 438%) and increase bicycling by approximately 22% on average (ranging from -21 to 262%) (Mölenberg et al., 2019). People report greater perceptions of safety, comfort, and willingness to ride by 50-100% in comparison to no bike lanes (Clark et al., 2019), and prefer routes with bike lanes over those without (Broach et al., 2012; P. Chen, Shen, & Childress, 2018; Fitch & Handy, 2020; Hood, Sall, & Charlton, 2011).	Bike lanes usually increase safety with estimated crash reduction between 5-66% and when bike volumes (exposure) are included, bicyclist injury reductions between 60-78% (Abdel-Aty et al., 2016; L. Chen et al., 2012; DiGioia et al., 2017; Goerke, Zolfaghari, Marek, Endorf, & Nygaard, 2019; Hamann & Peek-Asa, 2013; Kaplan & Giacomo Prato, 2015; Kondo, Morrison, Guerra, Kaufman, & Wiebe, 2018; Morrison et al., 2019; Pedroso, Angriman, Bellows, & Taylor, 2016; Reynolds et al., 2009; Robartes & Donna Chen, 2018; Smith et al., 2019; Teschke et al., 2012).
Buffered bike lane	Improved cyclist perceptions of safety and comfort (Clark et al., 2019), preference for routing (Fitch & Handy, 2020), and associated with increases in bicycling from 77-271% (Chris Monsere et al., 2014).	Although we found no evidence for the safety benefits specific to buffered bike lanes, narrower vehicle travel lanes and wider bike lanes show some safety benefits (Morrison et al., 2019).
Protected bike lane (aka cycle tracks)	Increases in bicycling ranging from 21 - 500% (Chris Monsere et al., 2014), with vertical physical objects resulting in higher comfort levels than painted buffers (McNeil et al., 2015; Chris Monsere et al., 2014).	Cycle tracks have been found to reduce injuries 41-99% (Harris et al., 2013; Teschke et al., 2012).
Bike boulevard	Limited results. Bicycle boulevards are appreciated by bicyclists and neighborhood residents (Broach et al., 2012), but it is not clear how effective they are at increasing bicycling (Dill, McNeil, Broach, & Ma, 2014).	In at least one study, collision rates on bicycle boulevards were observed to be between 2 to 8 times lower than those on adjacent arterial routes (Minikel, 2012).
Bike shared lane markings	Some studies show behavioral changes which indicate potential	Limited evidence. Sharrows correlated with poorer safety

	improvements in safety (e.g.,, cars changing lanes to pass, bicyclists lateral position further from parked cars) (Brady et al., 2011; Hunter, Thomas, Srinivasan, & Martell, 2010; Pol, Prasad, Costello, Patel, & Hancock, 2015).	outcomes than bicycle lanes or no infrastructure in at least one study (Ferenchak & Marshall, 2019).
Off-street path	Bicyclists tend to choose routes with off-street paths to a much greater extent compared to other options (Broach et al., 2012; Fitch & Handy, 2020; Wardman, Tight, & Page, 2007; Winters, Teschke, Grant, Setton, & Brauer, 2010). Increases in bicycling between 0-19% (Merom, Bauman, Vita, & Close, 2003; Rissel, Greaves, Wen, Crane, & Standen, 2015). Greenways (linear parks with paths) have been associated with school age children bicycling (Taylor & Coutts, 2018).	Off-street paths have been shown to decrease injuries and injury severity in some studies, but not in others (Cripton et al., 2014; DiGioia et al., 2017; Jestico et al., 2017; Meuleners et al., 2007; Reynolds et al., 2009; Romanow et al., 2012; Teschke et al., 2014, 2012). In one study, greenways have also been shown to increase physical activity in urban residential neighborhoods (Frank, Hong, & Ngo, 2019).
Bike highways	Improvement in perceived traffic safety and personal security and increased in bicycling between 0-77% (Skov-Petersen, Jacobsen, Vedel, Thomas Alexander, & Rask, 2017; Taciuk & Davidson, 2018).	We did not review any studies with downstream effects.
Bike boxes	Increases in perceived safety at intersections and improved bicyclist movements through intersections and reduced conflicts (Dill, Monsere, & McNeil, 2012; Wang & Akar, 2018)	We did not review any studies with downstream effects.
Bike signals	Compliance by bicyclists for bike signals seems similar to normal signals, confusion amongst all road users seems to be minimal (Christopher Monsere et al., 2019).	We did not review any studies with downstream effects.
Bike parking	Increasing rack supply at transit stations increases egress bicycle trips, stations with covered racks have more bike connections, and	We did not review any studies with downstream effects.

	stations with bike lockers have more bike connections (Heinen & Buehler, 2019). Similarly, bicycle parking at work is associated with greater bike commuting, although exact effect sizes are unknown because of lack of causal study designs (Heinen & Buehler, 2019).	

Conventional bike lanes

Conventional bike lanes are perceived to provide a more safe and comfortable bicycling environment when compared to similar roads without bike lanes (Clark et al., 2019). The degree to which bike lanes are valued by bicyclists is also a function of existing car volume and speed. In some contexts, conventional bike lanes on high volume arterials are valued by bicyclists (Fitch & Handy, 2020), in others they are not (Broach et al., 2012), but when car volumes are low to moderate, routes with bike lanes are more commonly chosen (Broach et al., 2012; P. Chen et al., 2018; Fitch & Handy, 2020; Hood et al., 2011). Based on the stated and revealed preferences for bike lanes and the strong positive correlations between bike infrastructure (the vast majority of which are bike lanes) and bicycling rates at the city-level (Pucher et al., 2010), we conclude that bike lanes are likely to cause more bicycling. Bolstering this conclusion, bicycle count studies also indicate increases due to bike lanes, although few studies differentiate mode increases from route shifts (Barnes & Schlossberg, 2013). The length and continuity of bike lanes within a network also play an important role in increasing bicycling (Aziz et al., 2017), a factor that few studies account for. Bike lanes have also been shown to increase facility usage by approximately 62 percent on average (ranging from 4 to 438 percent) and increase bicycling by approximately 22 percent on average (ranging from -21 to 262 percent) (Mölenberg et al., 2019). Importantly, studies that examine “after” effects within six months tend to report much smaller shifts suggesting that either it takes a long time for an investment to cause change, or that longer evaluations encompass other neighborhood and city effects, The role of bike lanes in increasing bicycling is also associated with positive health outcomes such as increased levels of energy expenditure and lower body mass indexes among bicyclists (B. B. Brown et al., 2017).

Many studies have concluded that bike lanes also tend to increase safety with crash reduction between 5-66 percent, and when bike volumes (exposure) are included, bicyclist injury reductions from between 60-78 percent (Abdel-Aty et al., 2016; L. Chen et al., 2012; DiGioia et al., 2017; Goerke et al., 2019; Hamann & Peek-Asa, 2013; Kaplan & Giacomo Prato, 2015; Kondo et al., 2018; Morrison et al., 2019; Pedroso et al., 2016; Reynolds et al., 2009; Robartes & Donna Chen, 2018; Smith et al., 2019; Teschke et al., 2012), although some studies show increases in bike crashes and injuries from bike lanes when bicyclist exposure is not measured or is only estimated (L. Chen et al., 2012; Jensen, 2008). In addition, some researchers raise the concern that bike lanes can encourage risky behaviors (e.g., close car passing distances, bicyclists riding in door zones) (Beck et al., 2019; Hunter & Stewart, 1999; Van Houten & Seiderman, 2005). The safety improvements from bike lanes are likely to depend on car volume and speed, although the results on interactions between traffic characteristics and bike lanes are mixed (Kondo et al., 2018; Morrison et al., 2019; J. Park, Abdel-Aty, Lee, & Lee, 2015; Teschke et al., 2012).

Buffered & Protected bike lanes

Protected bike lanes (also known as cycle tracks) and buffered bike lanes provide an additional boundary between bikes and traffic. Buffered lanes are divided from vehicle traffic with painted lines, while protected lanes provide a physical barrier in the form of vertical barriers such as flexible posts, planters, curbs, or parked cars. Research has shown that bicyclists typically experience a higher level of comfort with buffered lanes than traditional bike lanes and consistently rate infrastructure that have higher degrees of separation from drivers more positively (Clark et al., 2019; Mitra & Schofield, 2019; Chris Monsere et al., 2014). Bicyclists also prefer them when choosing routes (Fitch & Handy, 2020). Several studies observed a measured increase in ridership on nearly all facilities after the installation of buffered and protected cycling facilities, with increases ranging from 77-271 percent for buffered lanes and 21-171 percent for protected lanes (Chris Monsere et al., 2014), although effects in some cases are much greater (e.g., 500 percent initial increase with continued 100 percent increases year over year (Goodno, McNeil, Parks, & Dock, 2013)). The type of barrier has also been found to be a key factor. Barriers with vertical physical objects typically result in higher comfort levels than buffers created only with paint (McNeil et al., 2015; Chris Monsere et al., 2014). The specific effects from using vehicle parking to protect bike lanes are less clear (Clark et al., 2019).

Protected lanes have been found to reduce risk of bicyclist injuries by approximately 41-99 percent (Harris et al., 2013; Teschke et al., 2012), although the range of effects are large and results are likely to be highly dependent on design and context (Harris et al., 2013; Kaplan & Giacomo Prato, 2015; Teschke et al., 2012; B. Thomas & De Robertis, 2013).

Bike boulevards

Bike boulevards are characterized by “low-volume and low-speed streets that have been optimized for bicycle travel through treatments such as traffic calming and traffic reduction, signage and pavement markings, and intersection crossing treatments” (Walker, Tresidder, Birk, Weigand, & Dill, 2009, p. 2). Bicycle ridership data before and after construction of bicycle boulevards is often unavailable, but the treatment is often described as appreciated in communities where implemented (Walker et al., 2009), and valued by bicyclists (Broach et al., 2012). Because bike boulevards have rarely been studied, it is not clear how effective they are at increasing bicycling, and at least one study found negligible effects (Dill et al., 2014). Still, safety seems to improve on bicycle boulevards. In Berkeley, CA, collision rates on bicycle boulevards were observed to be between 2 to 8 times lower than those on adjacent arterial routes (Minikel, 2012).

Shared Lane Markings (Sharrows)

Shared lane markings, also called sharrows, are painted on roads, typically with a chevron and bike decal, which notifies drivers of the presence of bicyclists and indicates safe positioning on the road for biking. We could not find any studies that showed increases in active travel due to sharrows, while evidence on the safety of shared lane markings is mixed. Some studies show behavioral changes which indicate improvements (e.g.,, cars changing lanes to pass, bicyclists lateral position further from parked cars) (Brady et al., 2011; Hunter et al., 2010; Pol et al., 2015). However, sharrows can also create unsafe situations for bicyclists. For example, bicyclists have been observed to more frequently weave between cars after the addition of sharrows (Hunter et al., 2010) and at least one study found that areas with sharrows were associated with worse safety outcomes than those with bicycle lanes or no bike infrastructure (Ferenchak & Marshall, 2019)

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Bike off-street paths & Greenways

Off-street bicycle paths include multi-use paths as well as greenways (also see multi-use paths above). Some studies have found that bicycle paths are more attractive to bicyclists than are bicycle lanes (L. Kang & Fricker, 2013) and bicyclists tend to choose routes with off-street paths to a much greater extent compared to other options (Broach et al., 2012; Fitch & Handy, 2020; Wardman et al., 2007; Winters et al., 2010). However, the preference for off-street paths is certainly not universal, with commuters sometimes preferring lanes (Buehler & Dill, 2015), possibly reflecting a shorter travel time via bike lanes coupled with a higher value of time for these commuters. Greenways (linear parks with paths) have been found to allow for longer distance travel with relative safety and convenience for school age children (Taylor & Coutts, 2018), and to promote physical activity in urban residential neighborhoods (Frank et al., 2019). Residents near new trails report increases in time spent and rate of bicycling for work and recreation (Merom et al., 2003; Stinson, Porter, Proussaloglou, Calix, & Chu, 2014), with proximity to the bicycle trails playing an important role. However, several studies found no difference in frequency of bicycling due to a new bike path (Buehler & Dill, 2015; Rissel et al., 2015).

Bike highways

Bicycle highways are off-street paths with direct connections between distant origins and destinations. The routes are generally wide with fewer intersections, allowing users to ride at a constant speed without stopping and starting (Dias & Ribeiro, 2020). Because they are a relatively new infrastructure type and have only been constructed in countries with large bicycling populations, evidence on their outcomes is scant. The few studies we could find showed bike highways improvement perceived traffic safety and personal security and increased in bicycling between 0-77 percent (Skov-Petersen et al., 2017; Taciuk & Davidson, 2018) A study that reported no significant differences in the distance or frequency of bicycle travel still saw a 6 percent increase in the number of bicyclists who previously would not have made the trip by bicycle (i.e. induced travel) (Skov-Petersen et al., 2017).

Bike boxes

Bike boxes are painted areas in the vehicle right-of-way, the goal of which is to protect bicyclists from motorists and pedestrians. While we found no studies measuring increases in bicycle mode share or safety as a result of bike boxes, studies have shown increases in perceived safety at intersections and improved bicyclist movements through intersections with fewer conflicts (Dill et al., 2012; Wang & Akar, 2018).

Bike signals

Increased wait time at signals increases the likelihood of bicyclist non-compliance with the signals while opposing/crossing traffic has been shown to improve signal compliance (Christopher Monsere, 2012; Wu, Yao, & Zhang, 2012). However, little evidence about the outcomes of bike-specific signals exists. From the few studies available, compliance by bicyclists for bike signals seems similar to their compliance at normal signals, and confusion amongst all road users seems to be minimal (Christopher Monsere et al., 2019).

Bike parking

Many studies demonstrate the importance of bike parking for increasing bicycling (Pucher & Buehler, 2008; Pucher et al., 2010), especially for commuting (Heinen & Buehler, 2019). Secure bike parking facilities are widely viewed as an important factor that may enable cycling (Akar & Clifton, 2009), and some stated preference surveys find increased likelihood of biking if bike parking were made available (Gilderbloom, Grooms, Mog, & Meares, 2016). In a recent systematic review Heinen and Buehler (2019) synthesized 94 peer-reviewed studies that included bike parking as a focus or a variable for statistical adjustment and found that while evidence of bike parking facilities increase bicycling is abundant, the quality and scope of the research is limited. For example, most studies focused on transit connections and commuting, with few examining the effect of bike parking supply around cities for all other destinations. The authors could find no intervention studies to estimate causal effects of how increasing parking supply changes bicycling behavior. However, the mounting evidence—even if purely cross-sectional—indicates that quantity and quality of bike parking is likely to be essential infrastructure for bicycling. Studies focusing on bike parking at transit stations suggest that increasing rack supply increases egress bicycle trips, stations with covered racks have more bike connections, and stations with bike lockers have more bike connections (Heinen & Buehler, 2019). Similarly, bicycle parking at work is associated with greater bike commuting, especially when it is provided in concert with other bicycle infrastructure and end of trip facilities (e.g., showers). In all studies that examine bike parking quality, having secured parking (e.g., indoors, lockers) was associated with more bicycling, but some studies concluded that a variety of bike parking facilities was important (Heinen & Buehler, 2019).

Walking specific infrastructure

The motivation for most pedestrian infrastructure is improved safety rather than an increase in walking. Because pedestrians are most unsafe during dark hours, when alcohol is involved (by pedestrian and/or driver), and when crossing at midblock (National Highway Traffic Safety Administration, 2020a), infrastructure designed to make these scenarios safer are likely to provide safety benefits. Pedestrian injuries and deaths are relatively more common (per capita) in rural areas, likely due to more driving, faster speeds, lack of pedestrian infrastructure, and distance to emergency medical facilities (Stoker et al., 2015). However, the vast majority of pedestrian injuries and deaths are in urban areas (81 percent) where pedestrian exposure is much greater (National Highway Traffic Safety Administration, 2020a). In efforts to encourage walking, project-level infrastructure is clearly a factor, but quantifying the effects of infrastructure on walking is difficult. In general, people prefer to walk in environments that are both visually appealing (cleanliness, trees, sidewalk pavement) and safe (from traffic and crime) (Arellana, Saltarín, Larrañaga, Alvarez, & Henao, 2020; Cao & Duncan, 2019). Studies of walking more commonly identify land use characteristics, which relate to accessibility, as a key factor.

Table 3. Infrastructure interventions that influence walking and their range of effects

Intervention	Measured effects on perceptions and behavior change	Measured effects of downstream benefits
Sidewalks	Greater width is associated with 12-33% more walking in small and large cities (Aziz et al., 2017; Barnes & Schlossberg, 2013; Guo, 2009; Guo & Loo, 2013).	Sidewalks are associated with lower pedestrian and bicyclist crash risk (Berhanu, 2003; M. Kim, Kim, Oh, & Jun, 2012; Raihan, Alluri, Wu, & Gan, 2019; Saad, Abdel-Aty, Lee, & Cai, 2019), and relative safety effects are greater in rural settings, while absolute safety effects are greatest in urban settings (Arellana et al., 2020).
Lighting	Street lighting is one of the strongest contributors to perceived safety and security for pedestrians (Y. Park & Garcia, 2019).	Lighting is associated with 32-55% fewer crashes (combined 95CI 18-71%), 22-32% fewer injuries (combined 95CI 3-39%), and 66% fewer deaths (95CI 32-8%) (Beyer & Ker, 2009), with even greater pedestrian safety effects (Siddiqui,

		Chu, & Guttenplan, 2006; Wanvik, 2009). In addition, 27% fewer (95CI 9-47%) crimes in areas with street lights compared to control areas (Welsh & Farrington, 2008).
Crossing islands	10-20 percentage point increase in driver yielding, 2-5 mph reduction in speed, and a 10 percentage point increase in crosswalk use (Mead, Zegeer, & Bushell, 2014).	Islands results in 23-50% reduction in pedestrian crashes (B. Kang, 2019; Mead et al., 2014) and some evidence suggests that they are perceived as unsafe for bicyclists at intersections (Wang & Akar, 2018); although islands have mixed results on bicycling crash risk (D. Kim & Kim, 2015; M. Kim et al., 2012; Raihan et al., 2019).
Crosswalks	Marked crosswalks increase pedestrian channeling and thus reduce variation in crossing behavior (V. P. Sisiopiku & Akin, 2003; S. R. Zegeer, Huang, & Lagerwey, P, 2001).	Marking crosswalks alone is unlikely to provide much safety benefit (S. R. Zegeer et al., 2001). However, combining crosswalks with other traffic calming mechanisms can have substantial safety benefits for pedestrians (Poswayo, Kalolo, Rabonovitz, Witte, & Guerrero, 2019).
Raised crossings	Decrease vehicle speed (Loprencipe, Moretti, Pantuso, & Banfi, 2019; Mohammadipour, Mohammadipour, & Alavi, 2020), increase driver yielding, and increase use of the designated crosswalk or crossing, although they are associated with reductions in pedestrian stop rates prior to crossing (Gitelman, Carmel, Pesahov, & Chen, 2017).	Limited evidence suggests decreases in pedestrian crashes by 40% and injuries by 24% (Stipancic et al., 2020; Turner et al., 2019) in addition to safety improvements for bicyclists (J. P. Schepers, Kroeze, Sweers, & Wüst, 2011).
Curb extensions	Reduced turning speed for vehicles (Fitzpatrick & Schneider, 2005), and reduced crossing distances for pedestrians (reducing exposure and therefore crash risk) (R. J. Schneider et al., 2010; R. J. Schneider, Sanatizadeh, & Santiago, 2017).	Decreases in pedestrian injuries by 24% on average with 95CI of 4-40% (Stipancic et al., 2020).

Sidewalks

Sidewalks provide separation for pedestrians from vehicles and have been shown to provide positive safety benefits, although magnitudes are small, uncertain, and seem to be strongly dependent on context (Aziz et al., 2017; Berhanu, 2003; Gu & Peng, 2019; Guo, 2009; Lucken et al., 2018). For example, in rural settings sidewalks result in much larger percent reductions in pedestrian injuries, but much smaller reductions in absolute number of pedestrian injuries in comparison to urban settings due to differences in pedestrian exposure and differences in injury severity (Arellana et al., 2020). Beyond the mere presence of sidewalks, sidewalk characteristics can be important for increasing walking. For example, greater sidewalk width is associated with 12-33 percent more walking in large and small cities (Aziz et al., 2017; Barnes & Schlossberg, 2013; Guo, 2009; Guo & Loo, 2013) and lower pedestrian and bicyclist crash risk (Berhanu, 2003; M. Kim et al., 2012; Raihan et al., 2019; Saad et al., 2019).

Lighting

Because a large percent of pedestrian collisions, injuries, and deaths occur during dark hours (National Highway Traffic Safety Administration, 2020a), improving street lighting for pedestrian detection is an important safety strategy. In general, meta-analyses suggest that in comparison to roads without street lighting, roads with street lighting have 32-55 percent fewer crashes (combined 95CI 18-71 percent), 22-32 percent fewer injuries (combined 95CI 3-39 percent), and 66 percent fewer deaths (95CI 32-83 percent) (Beyer & Ker, 2009). The effects of lighting on pedestrian safety are even stronger. For example a study in the Netherlands showed that rural roads without street lighting increased pedestrian risk by 70% (95CI 61-77 percent) while overall injury risk increased by 54% (95CI 52-56%) (Wanvik, 2009). Similarly, pedestrian deaths were 42 percent lower (reduction of 5.5 percentage points) at midblock crossings, and 54 percent lower (reduction of 7.3 percentage points) at intersections in a Florida study (Siddiqui et al., 2006). In addition, street lighting is one of the strongest contributors to perceived safety for pedestrians (Y. Park & Garcia, 2019). Lastly, lighting also improves personal security: a meta-analysis of 13 studies showed that crime was 27 percent lower (95CI 9-47 percent) in areas with street lights compared to control areas (Welsh & Farrington, 2008).

Crossing islands

Median islands work to slow traffic speeds by narrowing the road and eliminating long, wide, straight sections. In addition, islands provide a refuge area for pedestrians, making it easier to cross two-way traffic. Although the number of studies focusing on crossing islands is small, evidence suggests a 10-20 percentage point increase in driver yielding, 2-5 mph reduction in speed, and a 10 percentage point increase in crosswalk use (Mead et al., 2014). For safety benefits, some studies show negligible effects, but most agree that the expected effect is between 23-50 percent reduction in pedestrian crashes (B. Kang, 2019; Mead et al., 2014). While pedestrian islands have these positive outcomes, some evidence suggests that they are perceived as unsafe for bicyclists at intersections (Wang & Akar, 2018); although islands have mixed results on bicycling crash risk (D. Kim & Kim, 2015; M. Kim et al., 2012; Raihan et al., 2019).

Crosswalks

Marked pedestrian crossings at unsignalized intersections increase the rate at which pedestrians look for vehicles, increase pedestrian use of the crosswalk, reduce vehicle speeds, and in general have little to no unintended costs for pedestrian safety (Knoblauch, Nitzburg, & Seifert, 2001). However, evaluation of safety outcomes in the US from thousands of uncontrolled, marked crosswalks, in comparison to uncontrolled, unmarked crossings, suggests that marking crosswalks alone is unlikely to provide much safety benefit (S. R. Zegeer et al., 2001). While cities use a variety of types of crosswalk markings (e.g., high visibility, zig-zag approaches), we did not review the distinctions between marking types, except for raised crosswalks, below, and we did not review the effects at controlled crossings (where crosswalks are nearly always used). Importantly, the lack of clear independent benefit of marking crosswalks does not indicate that they should not be used. Instead it suggests the need to combine markings with other infrastructure (e.g., traffic calming (Poswayo et al., 2019)) to improve uncontrolled crossings.

Raised crossings (mid-block and intersections)

Raised pedestrian crossings yield similar speed reductions as vertical deflectors (see above) in most cases, and the slope index of the raised crossing is directly correlated with a decrease in vehicle speed (Loprencipe et al., 2019; Mohammadipour et al., 2020). They also result in many positive small-scale behavior changes such as increased driver yielding, and increased use of the designated crosswalk or crossing, although they are associated with reductions in pedestrian stop rates prior to crossing (Gitelman et al., 2017). Raised crossings may also improve safety for pedestrians as well as bicyclists. In Sweden and the Netherlands, raised crossings for bicyclists have been shown to reduce pedestrian and bicyclist crash risk, although with high variability is some settings (Garder, P; Leden, L.; Pulkkinen, 1998; Kullgren et al., 2019; J. P. Schepers et al., 2011). In the U.S., raised crosswalks are mostly used to improve the pedestrian environment, though they are sometimes used where multipurpose or bike-only trails cross streets.

Curb extensions

Curb extensions can be used to reduce crossing distance thereby reducing pedestrian exposure during crossings at intersections and midblock. They also provide shorter turn radii when placed at intersections (shorter turn radii reduce turning speed for vehicles (Fitzpatrick & Schneider, 2005)). At least one study has shown curb extensions to be associated with a reduction in pedestrian injuries (24 percent on average with 95 percent CI of 4 to 40 percent (Stipancic et al., 2020)). This effect also agrees with evidence that intersections with right-turn only lanes and longer crossing distances without curb extensions are associated with greater pedestrian risk (R. J. Schneider et al., 2010, 2017).

Bike share systems

Most bike share systems operate as one-way rentals either as one-time transactions or through weekly or monthly subscriptions. In general, bike share systems have been shown to increase bicycling and to reduce driving and use of transit (Fishman, Washington, & Haworth, 2013). The magnitude of the bicycling increase is difficult to estimate because most bike share evaluations focus on bike share trips and cities often increase bike infrastructure when establishing bike share services (Pucher et al., 2010). However, because surveys show that some bike share trips are new trips altogether and some trips replace travel modes other than walking and bicycling, it is reasonable to assume they cause an increase in bicycling. The greatest benefits of bike share come when these systems are integrated with transit which helps solve what is often referred to as the first-last mile problem. Bike share programs are an efficient and effective way to help people reach final destinations which transit may not be able to serve and, thus, can help address the first-last mile problem. In fact, some bike share systems have found success in a rental model that focuses on transit access (e.g., OV-fiets system in the Netherlands (Kager & Harms, 2017)). Although evidence for outcomes related to bike share improvements that could be thought of as active transportation projects is scarce, any project that increases bike share demand and/or increases the use of bike share as a connection to transit is likely to produce active travel benefits.

Programs

Non-infrastructure programs designed to increase bicycling and walking (and improve safety) include promotional activities such as bike to work day/week/month, media campaigns, educational events, demonstration projects, and open street events. These programs are designed to change behavior through the causal mechanism of changing perceptions and norms about travel. Because of the connection to behavior through perceptions, programs can be evaluated in terms of both their effects on perceptions and/or their downstream effects on behavior. Some programs target specific populations (e.g., safe routes to school, bike training events), while others are more general (e.g., Ciclovia events where streets are closed to cars for walk and bike only traffic). The impact of programs on walking and bicycling (or reductions of car travel) are difficult to estimate because programs are often implemented with corresponding changes to the built environment, and because many programs do not have adequate funds to evaluate their interventions.

Safe Routes to School (SRTS)

STRS programs often integrate education, incentives, and other mechanisms to increase walking and bicycling to K-8 schools. In general, reviews of the effects of school active travel programs indicate that they increase walking and bicycling but that effectiveness ranges widely (Chillón, Evenson, Vaughn, & Ward, 2011). Many studies have suffered from small sample sizes or designs which did not account for important potential confounders (McDonald et al., 2014). In the U.S., the estimated effect of a SRTS program on active travel is expected to be about a 25 percent increase over 5 years or a 1 percentage point increase per year (McDonald et al., 2014). This increase in active travel per year seems to be linear, at least in the short term (similar increase per year for 5 years), although it is not clear when that rate begins to flatten (McDonald et al., 2014). This general effect size is similar to those from evaluations of active travel to school programs in Europe and Australia (Chillón et al., 2011). Differentiating infrastructure projects from education and enforcement is difficult in SRTS programs because they are commonly applied in tandem. However, a few studies of SRTS focused on the project level suggest infrastructure investments can be an important driver of the success of SRTS. For example, a study of 10 California schools shows that children with infrastructure projects completed somewhere along their route to school are three times as likely to walk or bike to school compared to their peers whom do not have an infrastructure project along their route to school (Boarnet, Day, Anderson, McMillan, & Alfonzo, 2005). However, in the same study, the overall effect of the infrastructure projects at the school level were slightly negative suggesting that gains from infrastructure investments can be lost from other factors (Boarnet et al., 2005). At least one California study focusing on education and engagement showed that a “citizen science” component added to SRTS has the potential to boost active travel to school (Rodriguez et al., 2019).

In terms of safety benefits, the few studies on SRTS indicate substantial reductions in bicyclist and pedestrian collisions due to STRS-funded infrastructure projects (usually in concert with education and enforcement campaigns) (DiMaggio, Brady, & Li, 2015; Ragland, Pande, Bigham, & Cooper, 2014). For example, a longitudinal 5-year study in Texas that tracked pedestrian accidents before and after the implementation of a SRTS intervention program found a 42.5 percent decline in annual pedestrian and cyclist injuries (DiMaggio et al., 2015). This included a 33 percent decline in fatalities for people 30-64 years old and 37.1 percent decline in school-age pedestrian fatality rates. A similar study conducted in New York City yielded a 38.2 percent reduction in pedestrian crashes involving school-aged children over a span of 9 years (DiMaggio & Li, 2013). School-aged pedestrian injuries during the study decreased from 8.2 percent to 5.7 percent during the peak morning travel period. Similar pedestrian and bicycling collision declines were observed in a study of 47 schools in California, with a predicted 75 percent reduction in bike and pedestrian collisions, and a 50 percent reduction for school-age bike and pedestrian collisions (although this estimate was uncertain and quantification of the uncertainty was not reported) (Ragland et al., 2014).

Social marketing

While social marketing for transportation demand has been used for decades (Thøgersen, 2014), the few evaluations specific to bicycling marketing suggest a likely increase in bicycling in the range of 1-2 percentage points (Pucher et al., 2010). Like many programs, evaluations of marketing campaigns that target behavior are often hard to separate from other (and likely more substantial) effects from infrastructure interventions. While social marketing campaigns for walking do exist, they are often one component in a broader program (e.g., SRTS).

Active travel events and safety education campaigns

Bike to work/school days, Ciclovias, bike buses, bike festivals, and awareness campaigns are some of the many event-type promotional programs specific to bicycling. They are likely to range in effectiveness but have in most cases had little evaluation. Bike to work days seem to have some lasting effects with evaluations showing increased ridership during and weeks after the event, and increases in first-time participants year over year (Pucher et al., 2010). Similarly, regular Ciclovias have been shown to increase moderate-to-vigorous physical activity and decrease sedentary time (Triana et al., 2019), and be cost effective from a public health perspective beyond the event itself (Montes et al., 2012).

Besides events, safety education campaigns that train people how to ride a bike safely in settings with vehicle traffic are often provided by cities, schools, or non-profit organizations. Although these programs clearly increase bicycling skills and confidence, they have not generally been evaluated for lasting effects on behavior (Pucher et al., 2010).

Other programs and projects that influence walking and bicycling

Interventions that have a different primary focus (e.g., congestion pricing) can have effects on active transportation. However, because of the complexities in understanding cause and effect in real-world interventions, the effects of those that only indirectly influence walking and bicycling are difficult to quantify. Below we review some of these indirect effects, but we do not cover them exhaustively in this report. We also do not cover the downstream benefits of these interventions. Instead, this section can best be used to highlight the challenge of estimating the benefits of any specific intervention in isolation. Because each project or program exists within the context of other projects and programs, changes in socio-demographics and economics, estimates of active travel outcomes are always likely to be imprecise.

Programs and projects designed to decrease car use may also increase active transportation. Local policies that use pricing schemes to reduce car use include charging for on-street parking, congestion pricing, vehicle registration/license fees. Other ways of reducing car use include car bans from city centers, which are increasingly common in European cities. For example a recent increase in the size of the car-free zone in Ghent, Belgium resulted in a 25-35 percent increase in bicycling traffic (Mobiliteitsbedrijf i.s.m. Transport & Mobility Leuven, 2019). General employer-based travel programs have shown some success in reducing vehicle travel by shifting employees to walking and transit, although less so for bicycling (Pucher et al., 2010).

Local policies on bicycles, tricycles, and emerging light electric vehicles (LEVs) for urban freight not only increase active transportation in the freight workforce but may increase active transportation in general. Exchanging LEVs for trucks for first- and last-mile deliveries may have a strong impact on bicycling safety given truck and bike conflicts have unique safety issues (e.g., right side impacts) (National Highway Traffic Safety Administration, 2020a), and in some cities have disproportionately injure and kill bicyclists (Morgan, Dale, Lee, & Edwards, 2010). The growing number of urban deliveries to residential neighborhoods with rising e-shopping suggest that interactions between trucks and people walking and bicycling are rising.

Transit investments may also increase walking and bicycling. While the direct relationships between public transit quality, speed, and frequency, and active transport have been difficult to quantify, there does seem to be a positive relationship between active travel and transit use. Several studies have observed that people that use public transit are more likely to walk (Besser & Dannenberg, 2005; Bopp, Gayah, & Campbell, 2015; Freeland, Banerjee, Dannenberg, & Wendel, 2013; Saelens, Moudon, Kang, Hurvitz, & Zhou, 2014). Bicycling is less commonly used to access transit, although it has been shown to help extend the catchment of transit (K. J. Krizek & Stonebraker, 2010). Several strategies have been used to increase bicycling to and from transit including bikes-on-transit, secure bike parking (R. Schneider, 2005), bike share services (Kager & Harms, 2017) but we could not find specific evidence of the effects of these interventions on transit or bicycling ridership.

Land use policies promoting transit-oriented development, mixed use, and greater residential density could encourage bicycling and walking as travel methods. A cross-sectional study conducted across the United States found that transit-oriented development areas were associated with significantly higher rates of active travel (Thrun, Leider, & Chriqui, 2016). Land use policies are all linked to active travel through the increase in accessibility that results from the reduction of distance between activity locations (Saelens & Handy, 2008).

Synthesis of Benefits

Traffic Safety

The direct effects of infrastructure on bicycling and walking safety with respect to vehicle traffic can be grouped into three primary classes: those that decrease car speeds, those that separate active travelers from cars (thereby reducing the exposure to cars), and those that protect bicyclists and pedestrians from cars. Many infrastructure projects do all three of these things because they incorporate many design changes at once. In the prior sections, we reviewed the expected effects of specific interventions, and noted that the general road context (e.g., urban arterial, rural highway, local road) moderates the effects of infrastructure interventions. Another important consideration is that any infrastructure that encourages more active travel is likely to provide additional safety benefits due to the decreased risk associated with increasing active travelers (see below). Below we synthesize the effects of infrastructure projects on safety by intervention class and context.

Reducing car speeds

Many studies have established a relationship between speed and safety of pedestrians and bicyclists. Of all three categories of safety interventions, reducing car speeds has the most evidence of support. This is because the vast majority of active travel injuries and deaths are caused by cars colliding with pedestrians and bicyclists, and the speed of cars are the root cause of injury and death (Grembek et al., 2020). As reviewed above, lowering speed limits and using other traffic calming measures have been shown to provide positive safety benefits for all travelers. For bicycling, lower speed limits combined with other infrastructure projects have also been associated with reduction in bike related crashes (Kaplan & Giacomo Prato, 2015; Klop & Khattak, 1999; Kullgren et al., 2019). When estimating effects for specific projects using results from other locations, street context should be considered. For example, arterial roads tend to be more dangerous for bicyclists and pedestrians, likely due to increased exposure to vehicles and higher vehicle speeds (P. Chen, 2015; Dumbaugh & Li, 2011), so designing routes that avoid those roads may provide better safety outcomes than improving them. However, destination accessibility is paramount for increasing active travel, so if key destinations are found along arterials, improving the arterials cannot be avoided. When arterials allow car speeds much above 30 mph, physical separation and protection are needed to reduce injury risk (Grembek et al., 2020).

Intersection frequency along arterial roads has been associated with fewer and less severe pedestrian crashes because they lead to slower car speeds (Lee & Abdel-Aty, 2005; Marshall & Ferenchak, 2019). In the US, pedestrian risk at midblock crossings seems to be the greatest, and during low light conditions (National Highway Traffic Safety Administration, 2020b). Conversely, intersections are generally the most dangerous parts of the road for bicyclists, often resulting in more crashes, especially with higher vehicle volumes (Kaplan & Giacomo Prato, 2015; Klassen, El-Basyouny, & Islam, 2014; Morrison et al., 2019; Romanow et al., 2012; Saad et al., 2019). While studies show more frequent bicycle related crashes at intersections, the crashes tend to be less severe, likely due to slower travelling vehicles (Cripton et al., 2014), and bicyclist deaths are still less common at intersections (National Highway Traffic Safety Administration, 2020a). This suggests that intersection treatments may provide more safety benefits for bicyclists, while midblock crossing treatments provide more safety benefits for pedestrians.

Reducing speed limits and implementing automatic speed enforcement offer large safety benefits and are likely to be effective in cases where physical road interventions alone cannot slow traffic. For local roads, adoption of very low speed limits (15 mph) with shared space designs to prioritize pedestrians and child play can greatly improve traffic safety (Delaware Valley

Regional Planning Commission, 2018; Goeverden & Godefrooij, 2011; Sørensen, 2011). For collectors and minor arterials, road diets offer great safety benefits because they combine speed management with separation and protection for bicyclists and pedestrians.

Speed management is critical for active travel safety. While the following sections summarize solid evidence of the effectiveness of infrastructure that separates and protects pedestrians and bicyclists, the fact remains that interactions between pedestrians, bicyclists, and cars are inevitable, especially in urban contexts. Speed management can improve safety when pedestrians and bicyclists do interact with cars.

Separating and protecting bicyclists and pedestrians from cars

Because many bike and pedestrian facilities are designed to both separate and protect people from cars, we discuss both types together here. Bike lanes are the most used intervention for road segments to increase bicycling safety. They act to separate bicyclists from cars, but they provide no protection (barrier) between cars and bikes. Nonetheless, bike lanes have been shown to decrease bicyclist crash rates and injuries more often than they increase them (Abdel-Aty et al., 2016; L. Chen et al., 2012; DiGioia et al., 2017; Goerke et al., 2019; Hamann & Peek-Asa, 2013; Jensen, 2008; Kaplan & Giacomo Prato, 2015; Kondo et al., 2018; Morrison et al., 2019; Pedroso et al., 2016; Reynolds et al., 2009; Robartes & Donna Chen, 2018; Smith et al., 2019; Teschke et al., 2012). Where more separation is provided (e.g., buffers, off-street paths), more safety benefits are observed (Cripton et al., 2014; Minikel, 2012; Romanow et al., 2012; Winters et al., 2013). When protective elements are also added (e.g., curb, trees, parked cars), safety is further improved (Harris et al., 2013; Kaplan & Giacomo Prato, 2015; J. P. Schepers et al., 2011; Teschke et al., 2012; Winters et al., 2013). Separation and protection are also fundamental elements for pedestrian infrastructure. For example, sidewalks along roads, curb extensions, and crossing islands all provide important separation from cars as well as some protection (thanks to the curb), and all provide safety benefits to pedestrians (Aziz et al., 2017; Berhanu, 2003; Gu & Peng, 2019; Guo, 2009; B. Kang, 2019; Lucken et al., 2018; Mead et al., 2014; Stipancic et al., 2020; Turner et al., 2019). However, because most pedestrian deaths occur at night and not at intersections or on sidewalks (National Highway Traffic Safety Administration, 2020a), interventions aimed at improving pedestrian visibility at night and at midblock crossings are likely to provide greater safety benefits. Crossing islands, raised crossings, and beacons provide the best safety benefits for midblock crossings, especially if they are used in concert with other traffic calming interventions.

Intersections are a crucial safety problem for active travel. Although crashes at intersections make up a minority proportion of bicyclist and pedestrian deaths (National Highway Traffic Safety Administration, 2020a, 2020b), active travelers spend far less time in intersections than they spend elsewhere, meaning that the rate of crashes in intersections is quite high. For intersections on arterials, reducing crossing distances with curb extensions while implementing traffic calming (e.g., diverters before or raising entire intersections) offers important safety benefits for pedestrians. Protected intersections, although little studied, show promise at providing separation and protection for bicyclists and pedestrians. At unsignalized intersections, roundabouts can provide considerable safety improvements, especially if they are designed with separated bicycling paths.

No road intervention is likely to influence bicyclist safety as much as designing a bicycling network that is in large part separate from the road network. Networks of off-street paths not only provide great safety benefits, but they enable and encourage bicycling for a much wider portion of the population which itself can improve safety (see discussion of Safety in Numbers below). Although care must be taken on designing crossings between off-street paths and roads, and on integrating the two in commercial districts and other areas with destination demand, off-street paths provide the most separation and protection of any infrastructure type and can be implemented as multi-use paths for pedestrians as well.

Context

Arterial roads tend to be more dangerous for cyclists and pedestrians, likely due to increased exposure to vehicles and higher vehicle speeds (P. Chen, 2015; Dumbaugh & Li, 2011). Bike infrastructure on arterial roads is correlated with a higher number of bike crashes compared to infrastructure off arterial roads (P. Chen, 2015). However, bike infrastructure on arterial roads does help reduce injury risk. Bike lanes shared with cars, and bike lanes exclusive for cyclists have both been shown to reduce the likelihood of sustaining injuries; the effect is stronger when there are no parked cars (Winters et al., 2013). When speeds are high, greater separation is needed. If speeds can be reduced, the safety benefits of bike lanes (less separation that an off-street path) are greater. For example, arterials with greater congestion (and thus slower speeds) are associated with fewer bike crashes (Saha, Alluri, Gan, & Wu, 2018).

For the decision of where to improve infrastructure, streets with low active travel volume with a few crashes usually show the greatest relative crash reductions, but absolute risk (where the most crashes and injuries occur regardless of exposure) is where the greatest safety benefits can be achieved. Indeed, the use of so-called High Injury Networks (the small proportion of roads that have a substantial proportion of injuries and deaths) for identifying investment is become common. However, High Injury Networks are not only a function of poor design and infrastructure, they are a function of existing active travel volumes—so shifting those volumes by improving parallel streets can also work as targeted investments. The role of exposure is also exemplified in the differences between urban and rural investments. Rural investments have a much greater relative effect (Abdel-Aty et al., 2016; Saha et al., 2018), while urban investments have a much greater absolute effect on safety (Osama & Sayed, 2017).

Because of the large variation in the effectiveness of infrastructure in urban and rural environments, crash modification factors are generally developed separately for urban and rural roads. Most of the evidence on infrastructure outcomes for active travel are from urban environments. This is especially true of the large-scale behavioral outcomes that have important implications for safety (see Safety in Numbers below). While rural-specific effects are available from the literature for some infrastructure, for many types they are not. Furthermore, what may be designed in a city may be cost prohibitive in a rural setting, suggesting comparing urban and rural intervention outcomes may be inappropriate.

Safety in Numbers

Infrastructure projects for active transportation can influence the safety of people who walk and bike by reducing their crash (and thus injury) risk. In addition, infrastructure projects that improve walking and bicycling safety can increase people's perceptions of safety for walking and bicycling causing them to increase their walking and bicycling activity. This increase in walking and bicycling generates a positive feedback for safety since the relative risk for people walking and bicycling is reduced when more people walk and bike; this is commonly known as the "safety in numbers" phenomenon which was observed at least as early as 1998 (Garder, P; Leden, L.; Pulkkinen, 1998), coined in 2003 (P L Jacobsen, 2003), and examined extensively since (Elvik & Bjørnskau, 2017; Fyhri, Sundfør, & Laureshyn, 2016; Peter Lyndon Jacobsen, Ragland, & Komanoff, 2015; Tasic, Elvik, & Brewer, 2017).

The mechanisms behind the safety in numbers effect are still uncertain, but some findings support, at least in part, a behavioral explanation that drivers on routes with more bicyclists or pedestrians are more aware of them and take greater precautions (Peter Lyndon Jacobsen et al., 2015). The safety in numbers effect for active travel crashes is strongly non-linear, with estimated elasticities near 0.5 for motor vehicle volume, 0.43 for bike volume, and 0.51 for pedestrian volume (Elvik & Bjørnskau, 2017). These elasticities may be even lower for more severe injuries and deaths, although results have been mixed thus far (Elvik & Bjørnskau, 2017; Kaplan & Giacomo Prato, 2015). While the mechanisms for reduced relative risk given increasing rates of bicycling and walking have been explored, the similar effects of vehicle volume have not. It is possible that increasing vehicle volumes are indicative of congested (and thus slower) speeds which can increase safety. However, most studies only adjust for average annual daily traffic, rather than a measure of speed or congestion.

Health

Active transportation projects can influence physical health in three primary ways (Table 4). First, they improve safety for existing bicyclists and pedestrians, as summarized above. If the projects lead individuals to shift from driving to active modes, however, these individuals are now at greater risk of injury and death (though at less risk than they would have been if they had shifted modes without the project). The net effect at the population-level depends on the increase in the amount of walking and biking versus the decrease in the risk resulting from the project. Second, when active travelers increase their amount of walking and/or bicycling they themselves experience higher exposure to air pollutants, although when drivers shift from car to active modes they are likely to reduce their exposure to air pollutants (Kingham, Longley, Salmond, Pattinson, & Shrestha, 2013). The population, however, benefits from an improvement in air quality resulting from the shift from driving to active travel. The third way that active transportation projects influence health is by increasing physical activity, the benefits of which dwarf any downsides with respect to safety and exposure to air pollutants (de Hartog, Boogaard, Nijland, & Hoek, 2010). Increases in physical activity resulting from active transportation projects have clear benefits at both the individual and population levels.

Table 4. Health Effects of Active Transportation Projects – Individual versus Societal

	Individual-Level Effects	**Population-Level Effects**
Safety	Positive for existing active travel (risk goes down) Negative for new active travel (risk is higher than for driving)	Uncertain (depending on increase in total amount of walking and biking versus reduction in risk)
Air Pollution	Negative for increased active travel (exposure goes up) Positive active travel that replaces driving (exposure is lower)	Positive (emissions go down)
Physical Activity	Positive (health goes up)	Positive (health costs go down)

Physical activity and related health outcomes

Disease associated with physical inactivity has been quantified since the 1950's (Fox & Haskell, 1968) and has reached pandemic status (Kohl et al., 2012). The long history of research linking physical activity to disease and mortality provides the bases for estimates of generalized risk reductions (i.e., reductions in the risk of health problems) associated with physical activity. Evidence suggests that the effects of physical activity on health outcomes are non-linear (i.e. the greatest benefits come from transitioning from sedentary to moderate physical activity) (Woodcock, Franco, Orsini, & Roberts, 2011). Meta-analyses of cohort studies from decades of research indicates that increasing from no physical activity (0 MET-h)[5] to 2.5 hours of moderate intensity physical activity (11 MET-h) per week is expected to result in the following reductions in risk (for diseases, the risk reduction is for the vulnerable age groups specific to each disease):

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[5] MET is the metabolic equivalent task, a commonly used metric to standardize energy expenditure (time and intensity) across activities. Combined time spent in activities results in an estimate of total MET-hours/week (MET-h/week).

- Mortality: 19% (15-24% 95% CI) (meta-analysis, (Woodcock et al., 2011))
- Dementia: 11-18% (multiple meta-analyses mean effects, (Woodcock et al., 2009))
- Cardiovascular diseases: 19-23% (multiple meta-analyses mean effects, (Woodcock et al., 2009)
- Diabetes: 18-19% (multiple meta-analyses mean effects, (Woodcock et al., 2009))
- Breast cancer: 13% (meta-analysis, (Woodcock et al., 2009))
- Colon cancer: 5-13% (multiple meta-analyses mean effects, (Woodcock et al., 2009))
- Depression: 3-14% (multiple meta-analyses mean effects, (Woodcock et al., 2009))
- Obesity: 18% (95 CI: 3-31%) (single cohort study, (Sadarangani et al., 2018))

The specific rates for walking and bicycling are slightly lower than those of all moderate intensity physical activity with reductions in mortality of 11% (95CI 4-17%) for walking, and 10% (95CI 6-13%) for biking (meta-analysis,(Kelly et al., 2014)). While most of the active travel and health research has focused on physical health, mental health is also clearly improved (see expected effects on depression above). In general, active travel generates mental health benefits by reducing stress and increasing satisfaction (Gatersleben & Uzzell, 2007). And while less is known about the magnitude of effects on mental health, given the prevalence of mental illness (e.g., in the US 19 percent of adults and 26 percent of young adults (Substance Abuse and Mental Health Services Administration, 2018)), mental health benefits from active travel could be substantial.

While active travel is not the only form of physical activity that has declined, this decline is one of the most widespread across the globe. The research community is in consensus that new or improved infrastructure that increases active travel increases physical activity (B. B. Brown et al., 2017; Goodman et al., 2019; Goodman, Sahlqvist, & Ogilvie, 2014). However, much of the evidence linking active transportation projects to health outcomes comes from integrating research in transportation (on the link between projects/programs and travel behavior change) with research on physical activity and health (the disease outcomes outlined above). The field has recently seen a proliferation of model-based simulations that estimate the health effects from interventions based on assumptions about mode shifts or physical activity gains (V. Brown et al., 2019; Goodman et al., 2019; Gotschi, 2011; Grabow et al., 2012; Johansson et al., 2017; Kriit, Williams, Lindholm, Forsberg, & Sommar, 2019; Lindsay, Macmillan, & Woodward, 2011; Macmillan et al., 2014; Maizlish, Linesch, & Woodcock, 2017; Mizdrak, Blakely, Cleghorn, & Cobiac, 2019; Rodrigues et al., 2020; Rojas-Rueda et al., 2016). These studies estimate the potential health benefits from active transportation projects, but they do not provide empirical evidence of benefits actually achieved. However, these simulations consistently show that shifting even moderate amounts of driving to walking or bicycling could result in substantial health benefits.

Of the studies that attempt to measure physical activity changes (and thus health benefits) directly from active travel the results show that people with 30 minutes or more of active commuting have lower rates of obesity by 25-50 percent (95CIs 10-67 percent) (Gordon-Larsen et al., 2009; Steell et al., 2018), and lower rates of metabolic syndrome 33 percent (95CI 19-48 percent) (Steell et al., 2018). Active travel rates and obesity are also highly correlated at the population level (-.76 for measured and -0.86 for self-reported obesity) (Bassett, Pucher, Buehler, Thompson, & Crouter, 2008). Active travelers tend to have lower diastolic blood pressure (-1.67 95CI -0.15 to -3.2) and reduced cardiovascular risk 12 percent (95CI 2-20 percent) (Gordon-Larsen et al., 2009). Even fewer studies attempt to show the effect of specific active transportation projects on health outcomes. The few that do show that health gains can be measured at the project level. For example, when a complete bike lane was implemented along a new light rail line in Salt Lake City, UT, it caused a significant increase in average energy expenditure among commuters who shifted to active travel (1.16 more kilocalories per minute) (B. B. Brown et al., 2017). In three mid-sized cities in the United Kingdom where bike and pedestrian infrastructure were improved, substitution of active travel for car travel led to an average gain of 12.5 minutes of physical activity per week for each kilometer closer people lived to the interventions (Goodman et al., 2014). Furthermore, Up to 90 percent of this increase in activity can be attributed directly to new or increased use of active transportation infrastructure (Panter & Ogilvie, 2015). Similarly, a study in Vancouver, Canada showed that living within 1,000 feet of new greenway doubled (95CI 1-4) the odds of reaching 20 minutes of moderate or vigorous physical activity per day, and halved the odds (95CI 15-75 percent) of being sedentary for more than 9 hours (Frank et al., 2019).

Transit use has also been associated with greater physical activity due to the nature of walking to and from transit stops and origins and destinations. In the US, about a third of transit walkers achieve 30 minutes or more of physical activity from walking to and from transit alone which is thought to meet minimum physical activity guidelines (Besser & Dannenberg, 2005; Freeland et al., 2013). Transit users walk 12.4 minutes (95CI 8.7 – 16) more than non-transit users (Saelens et al., 2014). Another study conducted in the United States found that those who rode public transit, even just once a week, reported nearly three times the amount of active travel per week compared to those who did not use public transit (Bopp et al., 2015). Considering that in the US half of the population does not meet the national physical activity guidelines, getting sedentary people to use transit can have considerable health benefits from associated walking.

Air Quality Effects

Increasing active travel has primary health outcomes related to air quality. First, it improves air quality if that active travel substitutes for travel modes with mobile emissions (Grabow et al., 2012; Johansson et al., 2017). Second, it increases exposures to outdoor air for those who increase travel or were using transit, but in most cases decreases exposure when substituting for car travel (Kingham et al., 2013).

Infrastructure investments that provide more separation between active travelers and cars (see above) not only provide greater traffic safety protection, but they also reduce active travelers' exposure to car emissions (Kendrick et al., 2011; King, Murphy, & McNabola, 2009). Furthermore, the details of street design can have important effects of reducing active travelers' exposure. For example, street trees and other greenery has been shown to reduce pedestrian exposure to harmful emissions (Amorim et al., 2013), as do shorter building roof heights and slanted angle of roofs (Yassin, 2011). Nonetheless, physical activity gains from active travel provide health benefits far beyond those from changing exposure to outdoor urban air in many contexts (de Hartog et al., 2010; Mizdrak et al., 2019).

Healthcare cost savings

An alternative way to value the health benefits from active transportation projects and programs is to estimate the health-care cost savings. Many studies have estimated large reductions in health-related costs that are associated with the increased physical activity from more active travel (Aldred & Croft, 2019; Jarrett et al., 2012; Mizdrak et al., 2019; Rodrigues et al., 2020; Standen, Greaves, Collins, Crane, & Rissel, 2019; Zapata-Diomedi, Gunn, Giles-Corti, Shiell, & Lennert Veerman, 2018), but the magnitudes of the benefits always depend on the estimates of increased physical activity.

Network connectivity

Walking and bicycling will be used as modes of travel only if destinations are within acceptable walking and bicycling distances (Handy, van Wee, & Kroesen, 2014; Saelens & Handy, 2008). Distances to destinations depend on land use policies, but they also depend on how directly the network connects travelers to their destinations. The layout of pedestrian and bicycle networks is thus crucial in promoting active travel. The evidence is strong that people with more and better connections to destinations via active transportation infrastructure are more likely to actively travel (Braun, Lindsay M., Rodriguez, Daniel A., Gordon-Larsen, 2019; Cao & Duncan, 2019; Faghih Imani, Miller, & Saxe, 2019; Veillette, Grisé, & El-Geneidy, 2019).

Metrics like Walk Score[6] and Bike Score[7], bicycle level of traffic stress (Mekuria, Furth, & Nixon, 2012), and bicycle level of service (BLOS) are often used to assess network connectivity and accessibility to destinations. Measurements of bicycling connectivity have been shown to improve predictions of bicycling travel to school at the individual level (Fitch, Rhemtulla, & Handy, 2018; Fitch, Thigpen, & Handy, 2016), and are associated with bicycling trips at zonal levels (Lowry & Loh, 2017).

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[6] https://www.walkscore.com/

[7] https://www.walkscore.com/bike-score-methodology.shtml

Active transportation infrastructure that reduces travel time often goes hand in hand with good connectivity. In general, when given the option, people will most often choose travel modes with the shortest travel time (Hochmair, 2015; Wuerzer & Mason, 2015). While existing bicyclists may be willing to increase their distance to ride on better infrastructure (Broach et al., 2012; Fitch & Handy, 2020), ultimately reducing the added distance for accessing destinations safely and comfortably is a way to attract new bicyclists.

Vehicle Miles Traveled and Greenhouse Gas Emissions

Most reductions in GHG emissions associated with active transportation projects are due to mode-shift and consequent reductions in vehicle use. Model-based simulations of mode shifts show considerable GHG reductions are possible (Mizdrak et al., 2019; Rodrigues et al., 2020). At least one intervention study in case cities in New Zealand showed that investments in active transportation of nearly 3 million dollars (2011 USD) resulted in a 1.6 percent reduction in vehicle kilometers traveled with a corresponding 1 percent reduction in CO2 emissions (Keall et al., 2018). Assessments of car use reductions, and thus GHG reductions, from project-level interventions are less common. Of those focusing on bicycling infrastructure, they tend to agree that bike infrastructure reduces vehicle miles traveled (VMT) and thus GHGs (Matute, Huff, Lederman, Peza, & Johnson, 2016; Piatkowski, Krizek, & Handy, 2015; Thakuriah, Metaxatos, Lin, & Jensen, 2012). Although the magnitudes vary by type of infrastructure and the surrounding context, Volker et al., (2019) propose a generic method that can be used to estimate VMT change from any bicycling intervention. Using this method, Volker et al., (2019) estimate the effects of a road diet project in Davis, CA (Gudz et al., 2016) having decreased VMT from between 55,613 and 95,740 miles per year and reduced CO2 emissions by between 24.4 and 42.0 metric tons per year. Estimates for hypothetical bike lanes in Los Angeles, CA from a life cycle assessment are reported to have a wide range of potential GHG reductions, where a project with a low change in bicyclist volume shows an increase in 8.2 metric tons of CO2 per year (due mostly to emissions from construction) while the same project with a very high change in user volume would result in a net decrease of 221.7 metric tons of CO2 per year (Matute et al., 2016).

Economic Activity

Active transportation projects also have downstream effects on local economies. These effects have manifested in changes in consumer behavior, property values, and cost savings. Local business owners are often unsupportive of active transportation projects limiting car travel and parking near their businesses for fear of decreased sales even though many studies have shown that active travelers spend just as much as, if not more than drivers (Bent & Singa, 2009; Clifton et al., 2012; Gilderbloom et al., 2016; Popovich & Handy, 2014); although one study did conclude that adding bike infrastructure and reducing parking would not help or harm local businesses (McCoy, Poirier, & Chapple, 2019). Additionally, consumers that travel by means other than vehicles are more frequent visitors for businesses, which presents unique marketing opportunities (Clifton et al., 2012).

In addition to stimulating spending in commercial areas, some studies have concluded that active transportation projects raise residential property values. For example, one study in Austin, Texas concluded that a one percent increase in bike score increases condominium and single-family house prices by 0.3 and 0.03 percent, respectively (Li & Joh, 2017). In another study, single family homes were found to have greater property value if located near an off-street bike facility, but less value if near an on-street bike facility (Welch, Gehrke, & Wang, 2016). Finally, one study found that in a neighborhood with bike-share, each additional bike-share station was associated with a mean home sale value increase of 2.7% (El-Geneidy, van Lierop, & Wasfi, 2016).

These increases in property value may not benefit everyone equally, however. Studies have shown that new biking infrastructure is associated with gentrification and is more likely to be implemented in gentrifying and affluent neighborhoods than in working class neighborhoods (Flanagan, Lachapelle, & El-Geneidy, 2016; Stein, 2011). Moreover, bicycle advocacy groups have historically presented infrastructure investments to attract wealthy investors to working class areas rather than a way to improve the lives of working-class people (Stehlin, 2015). Nonetheless, active transportation infrastructure itself has not been causally linked to gentrification or the displacement of longtime residents in working class neighborhoods. More broadly, investments in alternative transportation modes (those other than personal vehicles) in working class neighborhoods have not been shown to cause significant displacement; however, they have been shown to prevent low-income households from moving to areas which have just experienced such investments (Boarnet, Painter, Burinskiy, & Swayne, 2020).

Generalized cost effectiveness

In every study we reviewed on generalized benefit-to-cost ratios for active transportation infrastructure, ratios always exceeded one, although they had wide variation (Brey et al., 2017; Macmillan et al., 2014; Meletiou, Lawrie, Cook, O’Brien, & Guenther, 2005). Simulations of investments that result in large behavior changes are expected to have large benefit-to-cost ratios between 1.5-25 to 1 (Gotschi, 2011; Macmillan et al., 2014). However, in real world before-after analyses, they tend to be slightly more uniform with a lower maximum (2-14 to 1) because of only moderate mode shifts (Chapman et al., 2018; Deenihan & Caulfield, 2014; Sælensminde, 2004; Standen et al., 2019). The benefits of active transportation projects generally exceed the costs from the health benefits alone. For example, in a review of only the generalized health benefits, the benefits exceed costs by 9 (median) with a range from -2 to 360 (Mueller et al., 2015).

Conclusion

The evidence is strong that active travel projects and programs have many positive effects, with few negative ones, though the evidence is stronger for some kinds of projects and programs than others. Although context is likely to moderate expected effects of projects, the evidence indicates that a more targeted evaluation of projects and programs that control for context variation is needed. This is especially the case for California's Active Transportation Program, which future project-level evaluations should be possible through standardized data collection and benefit calculation.

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