Assessing the Effectiveness of Potential Vehicle-Miles-Traveled (VMT) Mitigation Measures

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A Research Report from the Pacific Southwest Region University Transportation Center

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16. Abstract
This report identifies and summarizes the empirical evidence on potential mitigation measures for State Highway System (SHS) projects. For each of the measures on the list, the research team completed a systematic search of the academic literature to identify studies meeting specified search criteria, focusing on studies from the last decade but drawing on older studies when helpful for selected topics. In each of the sections of the report, the criteria for and results of those searches are summarized, including, where possible, the estimated size of the effect of the measure on vehicle miles traveled (VMT). The quantity and quality of the evidence varies widely across the measures: some measures have strong evidence in support of their use for VMT mitigation, while others have limited evidence as to the impact or good evidence of a limited impact; for some measures, no direct empirical evidence is available. A companion report assesses the available methods for estimating the effectiveness of the potential VMT mitigation measures.

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About the Pacific Southwest Region University Transportation Center

The Pacific Southwest Region University Transportation Center (UTC) is the Region 9 University Transportation Center funded under the US Department of Transportation's University Transportation Centers Program. Established in 2016, the Pacific Southwest Region UTC (PSR) is led by the University of Southern California and includes seven partners: Long Beach State University; University of California, Davis; University of California, Irvine; University of California, Los Angeles; University of Hawaii; Northern Arizona University; Pima Community College.

The Pacific Southwest Region UTC conducts an integrated, multidisciplinary program of research, education and technology transfer aimed at *improving the mobility of people and goods throughout the region.* Our program is organized around four themes: 1) technology to address transportation problems and improve mobility; 2) improving mobility for vulnerable populations; 3) Improving resilience and protecting the environment; and 4) managing mobility in high growth areas.

California Department of Transportation (CALTRANS) Disclaimer

Disclosure

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Abstract

This report identifies and summarizes the empirical evidence on potential mitigation measures for State Highway System (SHS) projects. For each of the measures on the list, the research team completed a systematic search of the academic literature to identify studies meeting specified search criteria, focusing on studies from the last decade but drawing on older studies when helpful for selected topics. In each of the sections of the report, the criteria for and results of those searches are summarized, including, where possible, the estimated size of the effect of the measure on vehicle miles traveled (VMT). The quantity and quality of the evidence varies widely across the measures: some measures have strong evidence in support of their use for VMT mitigation, while others have limited evidence as to the impact or good evidence of a limited impact; for some measures, no direct empirical evidence is available. A companion report assesses the available methods for estimating the effectiveness of the potential VMT mitigation measures.

Methods for Assessing the Effectiveness of Potential Vehicle-Miles Traveled (VMT) Mitigation Measures

Executive Summary

This report identifies and summarizes the empirical evidence on potential mitigation measures for State Highway System (SHS) projects. For each of the measures on the list, the research team completed a systematic search of the academic literature to identify studies meeting specified search criteria, focusing on studies from the last decade but drawing on older studies when helpful for selected topics. In each of the sections of the report, the criteria for and results of those searches are summarized, including, where possible, the estimated size of the effect of the measure on vehicle miles traveled (VMT). The quantity and quality of the evidence varies widely across the measures: some measures have strong evidence in support of their use for VMT mitigation, while others have limited evidence as to the impact or good evidence of a limited impact; for some measures, no direct empirical evidence is available.

The results of the literature search are summarized in Table ES-1 with respect to both 1. the assessment of the strength of the evidence, and 2. what it suggests about the impact of the measure on VMT.

The strength of the evidence, meaning the body of studies available, was classified according to the following definitions:

- “Strong” means that there are many well-designed U.S. studies with consistent results as to the likelihood of an impact and its direction.
- “Moderate” means that there are a few well-designed U.S. studies with mostly consistent results
- “Weak” means that there are only 1 or 2 well-designed U.S. studies or only studies from elsewhere and/or inconsistent results.
- “None” means that no studies that document an impact of the strategy on VMT were identified.

For some measures, the evidence is “indirect,” meaning that there is evidence of an impact on other aspects of travel behavior that are associated with VMT, such as transit use or bicycling, but little direct evidence of the measure’s impact on VMT. The distinction is important because changes in other aspects of travel behavior do not necessarily translate into a reduction in VMT. For example, an increase in bicycle trips could include trips that shift from driving to bicycling but also new bicycle trips that do not replace driving trips.

The impact on VMT is classified as follows:

- “Reduction” if the evidence is direct and either strong or moderate in the direction of a reduction.
- “Possible reduction” if the evidence of reduction is strong or moderate but indirect.
- “Inconclusive” if the evidence of reduction is weak or none.

Table ES-1. Summary of assessment of evidence and impact on VMT by measure.

	Evidence assessment	Impact on VMT
Public transportation measures		
Transit service headways/frequency	Strong indirect	Possible reduction
First/last mile connectivity	Weak	Inconclusive
Transit service coverage	Moderate direct and indirect	Possible reduction
Transit-supportive roadway design	Weak	Inconclusive
Transit fares	Strong indirect	Possible reduction
Transit reliability	Moderate indirect	Possible reduction
Mobility hubs	None	-
TNC/transit partnership	Moderate indirect	Possible reduction
Transit stop amenities	Moderate indirect	Possible reduction
Transit vehicle amenities	Moderate indirect	Possible reduction
Park-and-ride lots	Moderate indirect	Possible reduction
Marketing transit	None	
On-demand transit	Weak	Inconclusive
Commuter/regional rail	Moderate	Reduction
Travel demand management measures		
Telecommuting	Moderate	Reduction
Broadband improvements	None	-
Employer-based Commute Trip Reduction programs	Weak	Inconclusive
Transit pass subsidies	Moderate	Reduction
Ridesharing Programs	Weak	Inconclusive
Car-sharing programs	Weak	Inconclusive
Community-based travel planning	Weak	Inconclusive
Safe Routes to School and other school-based programs	Moderate indirect	Possible reduction

	Evidence assessment	Impact on VMT
Land use measures		
Transit-Oriented Development (TOD)	Moderate	Reduction
Residential density	Strong	Reduction
Employment density	Weak	Inconclusive
Affordable housing	Weak	Inconclusive
Land preservation as growth management	Weak indirect	Inconclusive
Land-use mix	Strong	Reduction
Delivery Hubs	None	-
Jobs/housing balance	Moderate	Reduction
Road management measures		
Congestion pricing	Strong	Reduction
Road diets/ complete streets	Moderate indirect	Possible reduction
Local network connectivity	Strong	Reduction
Traffic calming	None	-
Curb management	None	-
Active transportation measures		
Bicycle facilities	Strong indirect	Possible reduction
Pedestrian facilities	Moderate direct and indirect	Possible reduction
Pedestrian amenities	Weak	Inconclusive
E-bike incentive programs	Moderate direct and indirect	Possible reduction
Bike share and scooter share	Strong direct and indirect	Reduction
Parking management measures		
Parking pricing	Strong indirect	Possible reduction
Parking restrictions	Moderate direct and indirect	Possible reduction

Introduction

According to California's Transportation Analysis Framework (TAF), developed in response to Senate Bill 743, the California Department of Transportation (Caltrans) must analyze the impacts of projects on the State Highway System (SHS) on vehicle-miles-traveled (VMT) as a part of the environmental review process under the California Environmental Quality Act (CEQA). The TAF outlines methods for analyzing these impacts, including the estimation of the impact of SHS projects on VMT, known as the induced travel effect. Identification of viable measures for mitigating VMT impacts is a required part of the CEQA process, and thus guidance on potential mitigation measures as well as methods for estimating the potential effectiveness of these measures are also needed.

This report identifies and summarizes the empirical evidence about potential mitigation measures for SHS projects. An initial list of potential mitigation measures was prepared based on existing sources, including the Caltrans Mitigation Playbook, the California Air Resources Board (CARB) SB375 Policy Briefs[1] and the California Air Pollution Officers Association (CAPCOA) Greenhouse Gas (GHG) Emissions Handbook[2]. Stakeholders were invited to participate in a workshop in October 2022 to discuss potential mitigation measures and were asked to complete a survey to rate these measures with respect to their interest in the measure for VMT mitigation. A final list of potential mitigation measures was approved by Caltrans.

For each of the measures on the list, the research team completed a systematic search of the academic literature to identify studies meeting specified search criteria. In each of the sections that follow, the criteria for and results of those searches are summarized, including, where possible, the estimated size of the effect of the measure on VMT. The quantity and quality of the evidence varies widely across the measures: some measures have strong evidence in support of their use for VMT mitigation, while others have weak evidence; for some measures, no direct empirical evidence is available.

A companion "Estimation Report" assesses the available methods for estimating the effectiveness of the same VMT mitigation measures reviewed in this report (Handy et al., 2024).

[1] https://ww2.arb.ca.gov/our-work/programs/sustainable-communities-program/research-effects-transportation-and-land-use

[2] https://www.aqmd.gov/docs/default-source/ceqa/handbook/capcoa-quantifying-greenhouse-gas-mitigation-measures.pdf

1. Public transportation mitigation measures

In the category of public transportation mitigation, evidence was assessed for fourteen measures. These measures, shown in Table 1, were prioritized based on interest scores garnered from the project advisory panel and the priority given to the measure by staff from CARB. Most but not all of these measures are included in prior reviews—the CARB SB375 Policy Briefs, the CAPCOA GHG Handbook, and Caltrans' Mitigation Playbook—as indicated.

To identify studies on the impact of these measures on transit ridership or vehicle miles traveled, we searched Google Scholar for relevant studies using one or more search terms for each measure. This search produced more than 1,300 studies in total. We then screened the results by scanning the title, abstract, and/or other available summaries. We found and reviewed the full text of more than 110 papers that appeared to be relevant after the screening. Studies included in the review had the following characteristics:

- Included transit ridership or VMT as a dependent variable,
- Used empirical research methods rather than simulation models,
- (Preferably) reported quantitative results,
- Was posted on the Internet or available through the University of California library.

Most studies of the effectiveness of public transit measures report impacts on transit ridership. It is important to note that increases in public transit ridership do not directly translate into reductions in VMT. New transit trips may come from modes of travel other than driving, while some trips may represent additional travel rather than a shift in modes. When a transit trip does replace a driving trip, the trip distances may differ. An increase in transit ridership is thus a strong indicator but not a guarantee that a measure will decrease VMT. Unless otherwise noted, the reported findings are for transit ridership rather than VMT.

Converting an estimate of the impact of a measure on transit ridership to an estimate of its impact on VMT requires evidence of the degree to which transit trips substitute for driving trips. In the absence of such evidence, the mode share of the area could serve as a proxy. Methods for quantifying the impact of transit measures on VMT are discussed further in the companion Estimation Report (Handy et al., 2024).

Table 1. List of public transportation measures with research priorities.

Measures	Interest Score (of 4)	Highest interest percentage	CARB briefs	CAPCOA	Mitigation Playbook
Transit service headways/frequency	3.75	75%	X*	X	X*
First/last mile connectivity	3.68	75%			
Transit service coverage	3.62	62%	X	X	X*
Transit-supportive roadway design	3.53	70%		X	
Transit fares	3.37	43%	X	X	
Transit reliability	3.37	43%	X		
Mobility hubs	3.18	43%			
TNC/transit partnership	3	25%			
Transit stop amenities	3	31%			
Transit vehicle amenities	2.81	12%			
Park-and-ride lots	2.66	26%			X
Marketing transit^	-	-			
On-demand transit^	-	-			
Commuter/regional rail^	-	-			

*Indicates similar measure
^indicates added after the stakeholder workshop

1.1 Transit service headways/frequency

Increasing the frequency of transit service and reducing wait times reduces travel times and improves user experience, encouraging a shift from driving to transit. We searched Google Scholar using the following terms to find relevant studies, with results as indicated.

- "Transit frequency" and "ridership" (with 725 search results)
- "Transit service frequency" and "ridership" (with 417 search results)
- "Public transportation service frequency" and "ridership" (with 4 search results)
- "Transit system service frequency" (with 829,000 search results)
- "Transit service headway" and "ridership" (with 6,800 search results)
- "Transit wait time" and "ridership" (with 20,500 search results)

Out of 219 papers reviewed, twelve studies met the inclusion criteria. The review shows substantial evidence of a positive impact of transit service frequency and amount of service on ridership, or conversely, a negative impact of headways on ridership (Table 2). An increase in transit ridership is likely to translate into a reduction in VMT (National Academies, 2021), but most of these studies do not provide direct evidence of that impact.

One study provides direct evidence of a negative association between transit service frequency and VMT but does not provide sufficient information to determine the effect size (Liu & Cirillo, 2015).

Table 2. Summary of literature review of transit service frequency/headway.

Study	Study area	Sample Size	Effect size/impact	Notes
Erhardt et al., 2022	United States	215 MSAs excluding New York	A 1% increase in the amount of bus service was associated with a 0.56% increase in bus ridership; a 1% increase in the amount of rail service is associated with a 0.82% increase in rail ridership.	Amount of service is measured in vehicle revenue miles
Shantz et al., 2022	Ontario, Canada	61 stations	A 1% increase in service quantity was associated with a 0.22% to 0.56% increase in ridership.	Service quantity measured as number of outbound vehicle trips.
Berrebi et al., 2021	Portland	4 cities; 718 to 1165 route segments per city	A 1% increase in frequency was associated with a 0.66 to 0.78% increase in total weekday ridership. In three cities, the effect was higher on low-frequency routes but in one city it was higher on high-frequency routes.	Frequency is measured as total weekday vehicle-trips. Controlling for population and job density.
Boisjoly et al., 2018	North America	25 cities	A 1% increase in service was associated with an 0.83% increase in ridership.	Service is measured as vehicle revenue kilometers. Ridership is measured as unlinked passenger trips. Controlling for population, area, car ownership, highway mileage, presence of Uber and bike-share, and economic factors.
Chakour and Eluru , 2017	Montreal	8000 stops	A 1-minute increase in headways was associated with a 5 to 10% decrease in boardings and alightings.	Separately elasticities for AM and PM boarding and alighting are provided. Controlling for job density and land uses.
Liu and Cirillo, 2015	Washington DC Metropolitan Area	1420 households	Better coverage and more frequent service was associated with lower auto ownership and lower VMT.	Controlling for household characteristics, income, education, population density, employment density.

Study	Study area	Sample Size	Effect size/impact	Notes
Ma et al., 2015	Washington D.C.	86 Metrorail stations	A 1% increase in transit frequency was associated with a 0.5% increase in average daily Metrorail ridership.	Controlling for bikeshare, housing density, employment density, street connectivity, income.
Lyons et al., 2014	United States	157 Regions	A 1% increase in service frequency was associated with a 1.17% increase in ridership	Controlling for population, population density, fuel price, income, and roadway miles.
Frei and Mahmassani, 2013	Chicago	All stops in the Chicago Metropolitan Agency for Planning area	A 1% increase in headways was associated with a 0.26% to 0.28% decrease in boarding and alightings.	Controlling for land use, employment, population, demographics, Walk Score, time of day.
Tang and Thakuriah, 2012	Chicago	144 bus routes of the Chicago Transit Authority	Average weekday bus ridership was significantly higher for routes with nighttime services.	Quasi-experimental study of the effect of real-time information. Controlling for fares, gas price, population, employment, weather, month.
Chen et al, 2011	Commuter rail trips to/from New York City	156 months between 1996 and 2009	A 1% increase in service level led to a 0.13% increase in ridership in the short term and a 0.27% increase in the long term.	Service level is measured as vehicle revenue miles. The long-term elasticity refers to four months after a service change.
Taylor et al., 2009	U.S. urbanized areas	265 urbanized areas	A 1% increase in annual service miles per route mile is associated with a 0.30% increase in per capita transit ridership.	Controlling for the size of urbanized area and other factors

1.2 First/last mile connectivity

Improving access to and from transit stations expands the catchment area for transit and can increase transit ridership. One of the complications of researching this measure's impact on transit ridership is that first/last mile connectivity can be provided in different ways. For example, two of the studies included here focus on partnerships between transit network companies (TNCs) and transit agencies and are included both in that category and here as a first/last mile connectivity measure. We searched Google Scholar using the following terms to find relevant studies, with results as indicated.

- "First-mile transit connection" and "transit ridership" (with 11,000 search results)
- "First- and last-mile connection" and "transit ridership" (with 11,800 search results)
- "First- and last-mile connection" and "driving" (with 114 search results)
- "First- and last-mile connection" and "VMT" (with 32 search results)

We screened more than 200 studies, focusing the review on seven of these papers. Table 3 summarizes the reviewed studies. All but one of the reviewed papers were conducted in the past three years. The majority of the reviewed papers focused on the role of micro-mobility options, such as bike sharing or e-scooter sharing services, as a strategy for first-last mile transit connections. Most studies found that micro-mobility did not significantly impact transit ridership, though one study in Washington, DC, found a positive association between bike-share use and ridership at Metro stations (Ma et al., 2015). Two papers evaluated TNCs and ride-hailing in general, with only one finding that it significantly increased ridership.

Several simulation studies are suggestive of the impact that TNCs could have on transit ridership, VMT, and GHG emissions. Grahn et al. (2022) concluded that a hybrid model of service design, including first-mile and last-mile mobility services, TNCs, and transit services, could improve total service ridership. A simulation of the San Francisco Bay Area as to the effects of TNCs on transit ridership concluded that 31 percent of the drive-alone trips in the region could be completed via TNC or BART, and half a million daily VMT would be avoided if drivers shifted away from SOV trips (Alemi and Rodier, 2016). Another simulation study by Bürstlein et al. (2021) concluded that on-demand transit as a form of first- and last-mile connections could produce a significant reduction in GHG emissions.

Table 3. Summary of literature about the impact of first-last-mile transit connection on ridership/VMT.

Study	Study area	Sample Size	Effect size/impact	Note
Erhardt et al., 2022	United States	215 MSAs excluding New York	The effect of bike sharing was insignificant. Dock-less scooter service was associated with a decrease in ridership.	Data on scooter ridership was available for only one year of the time period analyzed (2012-2018).
McQueen and Clifton, 2022	Portland	1,968 PSU students	E-scooters did not have a statistically significant effect on ridership.	Study used a stated preference method.
Salter and Alexander, 2022	San Francisco Bay Area	72 transit stations	Bike infrastructure did not have a significant impact on rail ridership.	
Zuniga-Garcia et al., 2022	Austin, Texas	100 zones	Micro-transit service had little impact on bus ridership; TNCs did not have an effect on bus ridership.	Study used a quasi-experimental design with a difference-in-differences analysis.
Ziedan et al., 2021	Louisville, Kentucky	899 unlinked passenger trips	E-scooters did not have a statistically significant effect on ridership.	
Cashmore, 2020	Research Triangle Park, North Carolina	Pilot program	TNC-operated first/last mile service offered similar ridership but greater reductions in per capita VMT and VHT at lower costs than transit-operated demand-responsive fixed-route first/last mile services.	Results from this pilot program may not be transferable to other contexts.
Ma et al., 2015	Washington D.C.	86 Metrorail stations	A 1% increase in annual Capital Bikeshare ridership was associated with a 0.28% increase in average daily Metrorail ridership.	Controlling for transit frequency, housing density, employment density, street connectivity, income.

1.3 Transit service coverage

Expanding transit service coverage, geographically or temporally, means that more people can shift from driving to transit at more times of day. We searched Google Scholar using the following terms with results as indicated.

- "Transit service" and "ridership" (with 44,400 search results)
- "Transit network" and "ridership" (with 36,300 search results)
- "Public transportation service coverage" and "ridership" (with 36,400 search results)
- "Public transportation service coverage" and "vehicle miles traveled" (with 43,100 search results)

We screened 127 results by reviewing their abstracts to determine if they were relevant to our review. Table 4 summarizes the results of this review. The review shows that transit service coverage has a significant impact on transit ridership in all studies. One found a nearly one-to-one relationship between increases in route density and increases in ridership at the level of metropolitan regions (Lyons, 2014). An increase in transit ridership is likely to translate into a reduction in VMT (National Academies, 2021), but not all studies provide direct evidence of that impact.

Two studies provide direct evidence that better transit service is associated with lower VMT. Using their empirically derived model of the relationship between transit service and VMT, Liu and Cirillo (2015) estimated that a scenario of improved bus service in the form of increased spatial coverage, service frequency, and service duration could reduce VMT by about 1.6–8.0 percent. In the improved scenario, at least 50 percent of census tract areas had less than 0.25-mile and 0.5-mile walking distance to a bus and rail stop, respectively, with 15-minute headways during 6 peak hours (6:30–9:30 AM and 3:30–6:30 PM). Because the unimproved conditions were not reported, an effect size cannot be calculated. A quasi-experimental study of the opening of the Expo Line in Los Angeles found that while the opening of the line did not reduce VMT for households living in close proximity to stations, their VMT was significantly lower than VMT for households living farther away, whose VMT increased substantially during this time (Spears et al., 2016).

Table 4. Summary of literature about the impact of transit service coverage on transit ridership or VMT.

Study	Study area	Sample Size	Effect size/impact	Notes
Chakour and Eluru, 2016	Montreal	8000 stops	One additional bus stop in a 200m buffer was associated with a 3 to 9% increase in boardings and alightings.	Separately elasticities for AM and PM boarding and alighting are provided. Controlling for job density and land uses.
Liu and Cirillo, 2015	Washington DC Metropolitan Area	1420 households	The combination of better spatial coverage, more frequent service, and longer service duration was associated with lower auto ownership and lower VMT.	Controlling for household characteristics, income, education, population density, employment density.
Spears et al., 2016	Los Angeles County	8219 Households	Households living within 1 km of a new light rail line drove 10 fewer miles per day than households living farther away, but their VMT did not decline following the opening of the rail line.	Controlling for household characteristics, income, race, education, land use, built environment.
Lyons et al., 2014	United States	157 Regions	A 1% increase in route density was associated with a 0.95% increase in ridership.	Controlling for population, population density, fuel price, income, and roadway miles.

1.4 Transit-supportive roadway design

Prioritizing transit at signals and providing bus lanes shortens transit travel times, encouraging a shift from driving to transit and potentially reducing VMT. Few studies focus on transit-supportive roadway design in general, but the impact of its elements, particularly transit signal priority (TSP), on transit ridership are more frequently studied. We did not include studies that evaluated the impact of TSPs on traffic delay and congestion. We searched Google Scholar using the following terms to find relevant studies, with results as indicated.

- “Transit-supportive roadway” and “ridership” (with 16 search results)
- “Roadway design” and “transit ridership” (with 390 search results)
- “Transit signal priority” and “transit ridership” (with 605 search results)
- “Transit signal priority” and “driving” (with 2,010 search results)

Of 160 papers screened, only four met the inclusion criteria. These studies demonstrate the potential of transit-supportive roadway design to improve transit service and increase transit ridership but do not provide direct evidence of an impact on VMT.

- A case study review explored American and international transit improvement strategies and concluded that encouraging transit-supportive networks can help improve bus speed and travel time reliability (Ryus et al., 2015).
- Ozbil et al. (2009) concluded that street connectivity has a significant and positive association with transit ridership after controlling for population density and transit service features.
- Narrigan et al. (2007) found that a signal improvement project decreased the travel time of the route by about 15 minutes across the entire route.
- A simulation of transit signal priority along an arterial corridor in Arlington, Virginia showed that the travel time could decrease by 5 percent (Dion et al. 2004).

1.5 Transit Fares

Decreasing transit fares can lead to an increase in transit ridership and a reduction in vehicle trips. Transit passes and other forms of transit subsidies can have similar effects. We searched Google Scholar using the following terms to find relevant studies, with results as indicated.

- “Transit fare” and “driving” (with 4,559 search results)
- “Transit fare” and “ridership” (with 4,210 search results)
- “Transit pass” and “ridership” (with 1,670 search results)
- “Transit subsidies” and “ridership” (with 285 search results)
- "Transit fare” and “vehicle mile traveled” (with no search results)

All six reviewed studies show a significant negative association between transit fares and ridership, as shown in Table 5, though one study showed the direction of the association differed by income groups (Miller and Savage, 2017). It is important to note that these studies provide evidence of the impact of fare increases rather than decreases, and while they suggest that a decrease in fares will lead to an increase in transit ridership, the effect size for a fare decrease might be different. Indeed, one study found that the effect is not symmetrical: fare decreases tend to increase ridership less than fare increases reduce ridership (Chen et al., 2011). A recent review of the literature on free-and-reduced fares concluded that such programs increase transit ridership but that the effect is likely to vary by time of day and type of rider (King and Taylor, 2023). The authors conclude that, dollar-for-dollar, “service improvements are likely to be a more effective use of resources than fare reductions, even for low-income riders” (pg. 25).

An increase in transit ridership is likely to translate into a reduction in VMT (National Academies, 2021), but these studies do not provide direct evidence of that impact. None of the studies looked directly at the impact of transit fares on VMT.

Table 5. Summary of literature about the impact of transit fare on ridership.

Study	Study area	Sample Size	Effect size/impact	Note
Erhardt et al., 2022	United States	215 MSAs excluding New York	A 1% increase in the average bus fare was associated with a 0.57% decrease in bus ridership; a 1% increase in the average rail fare was associated with a 0.35% decrease in rail ridership.	-
Boisjoly et al., 2018	Canada and United States	25 cities	A 1% increase in average fare was associated with a 0.22% decrease in the number of unlinked passenger trips.	Controlling for population, area, car ownership, highway mileage, presence of Uber and bike-share, and economic factors.
Miller and Savage, 2017	Chicago	8 rail routes	Neighborhood income did not have a consistent effect on the impact of fare changes on ridership.	Based on neighborhood rather than household characteristics.
Tang and Thakuriah,2012	Chicago	144 bus routes of the Chicago Transit Authority	A 1 cent increase in bus fare was associated with a decrease in average weekday bus ridership of 11; a 1 cent increase in rail fare was associated with a decrease in average weekday bus ridership of 6.	Quasi-experimental study of the effect of real-time information. Controlling for gas price, population, employment, weather, month.
Chen et al., 2009	Commuter rail trips to/from New York City	156 months between 1996 and 2009	A 1% increase in fare leads to a 0.40% decrease in ridership in the short term and a 0.80% decrease in the long term.	The long-term elasticity refers to four months after a service change.
Taylor et al.,2009	U.S. urbanized areas	265 urbanized areas	A 1% increase in average fare is associated with a 1.19% decrease in total boardings.	Controlling for the size of urbanized area and other factors

1.6 Transit reliability

Improvements in transit reliability increase the attractiveness of transit and can encourage a shift from driving to transit. We searched Google Scholar using the following terms to find relevant studies, with results as indicated.

- "Transit reliability" and "ridership" (with 513 search results)
- "Transit wait time" and "ridership" (with 20,500 search results)
- "Transit reliability" and "driving" (with 460 search results)

All reviewed papers (four out of 80 screened) indicate a statistically significant association between transit reliability and ridership, as shown in Table 6. An increase in transit ridership is likely to translate into a reduction in VMT (National Academies, 2021), but these studies do not provide direct evidence of that impact. None of the studies looked directly at the impact of transit reliability on VMT.

Table 6. Summary of literature about the impact of transit reliability on ridership.

Study	Study area	Sample Size	Effect size/impact	Note
Pulugurtha et al., 2022	Charlotte, North Carolina	49 local bus routes	Ridership had a positive association with on-time performance percentage, especially for inbound trips.	Ridership is measured as the average number of boarding passengers (per bus) at a bus stop.
Chakrabarti and Giuliano, 2015	Los Angeles	537 directional bus lines	A 1% decrease in late performance was associated with a 0.5-0.6% increase in boardings per hour during peak and off-peak periods	Controlling for population density, employment density, top density, headways.
Carrel et al., 2013	San Francisco	123 MUNI users and 15 non-users from UCSF	Perceived unreliability, especially when the fault of the transit agency, was associated with a stronger preference to not use transit.	Study relies on stated preferences
Perk et al., 2008	Puget Sound region	1700 households	Two-thirds of survey respondents rated the ability of transit to arrive on time as extremely important.	Study relies on stated preferences.

1.7 Mobility hubs

Mobility hubs, also known as multimodal transport hubs, smart mobility hubs, shared mobility hubs, and other names, provide access to multiple non-driving options, such as transit, bike share, and car share, at the same location. They expand on the concepts of park-and-ride lots (see Section 1.11) and transit centers to coordinate a wider range of options for travelers. By facilitating the use of modes other than driving, mobility hubs have the potential to reduce vehicle trips. We searched Google Scholar using the following terms to find relevant studies, with results as indicated.

- “Mobility hub” and “transit ridership” (with 74 search results)
- “Mobility hub” and “VMT” (with 60 search results)
- “Mobility hub” and “driving” (with 507 search results)
- “Mobility hub” and “vehicle mile traveled” (with one search result)

Because mobility hubs are a relatively new strategy, no studies of their impact on VMT have yet been published. Evidence from Europe is suggestive of the effect mobility hubs might have on VMT. A German study found that mobility hubs reduced car ownership by promoting a shift in travel from driving to other modes available at mobility hubs (Czarnetzki & Siek, 2022). A study from the Netherlands found that more than 60 percent of participants would have used public transportation for their last trip if a multimodal transport hub had been available (Horjus et al., 2022).

1.8 TNC/transit partnership

TNCs can increase transit ridership by improving first/last mile connectivity if services are strategically planned in collaboration with transit agencies. Although many articles address the relationship between TNC and transit (90 screened papers), about 80 percent of those focus on the impact of TNC in general rather than the TNC/transit partnership on transit ridership.. We searched Google Scholar using the following terms to find relevant studies, with results as indicated.

- “TNC transit partnership” and “transit ridership” (with search 766 results)
- “Ride-hailing transit partnership” and “ridership” (with search 5920 results)
- “Transportation network companies” and “transit partnership” and “transit ridership” (with no search results)

As shown in Table 7, the majority of reviewed papers fall into one of two categories: articles about the relationship between TNCs and transit ridership in the absence of partnerships, and the effect of TNC/transit partnerships. The six studies examining the effects of TNCs on transit ridership in the absence of partnerships show that the introduction of TNCs is associated with a decrease in bus ridership but may be associated with an increase in rail ridership. Three studies suggest that partnerships with TNCs can lead to an increase in transit ridership. An increase in transit ridership is likely to translate into a reduction in VMT (National Academies, 2021), but these studies do not provide direct evidence of that impact.

Table 7. Summary of literature about the impact of TNC-transit partnership on ridership.

Study	Study area	Sample Size	Effect size/impact	Note about study
Erhardt et al., 2022	United States	215 MSAs excluding New York	Bus ridership decreased by 10% after the introduction of TNCs; ride-hailing had little effect on rail ridership in the largest metropolitan areas but rail ridership decreased by 10% in mid-sized metropolitan areas after TNC introduction.	A longitudinal study of the effect of TNCs on transit in the absence of partnerships.
Erhardt et al., 2021	San Francisco	20% of SFMTA fleet	TNC services contributed to a 10 percent reduction in bus ridership but had no effect on light rail ridership.	A longitudinal study of the effect of TNCs on transit in the absence of partnerships.
Li et al., 2021	Toronto	75 stations	TNC services had a positive association with subway ridership but a negative association with surface transit route ridership.	A longitudinal study of the effect of TNCs on transit in the absence of partnerships.
Meredith-Karam et al., 2021	Chicago	All stations in the Chicago Transit Authority area	Before the COVID-19 pandemic, 45% to 50% of TNC trips substituted for transit; the substitution rate dropped during the pandemic.	A longitudinal study of the effect of TNCs on transit in the absence of partnerships.
Ngo et al., 2021	Eugene-Springfield area, Oregon	1503 bus stops	Bus ridership decreased by 5.4% in the cities where Uber was active compared to the control cities where Uber was not active; declines in ridership persisted in the cities when Uber exited.	A longitudinal study of the effect of TNCs on transit in the absence of partnerships.
Boisjoly et al., 2018	Canada and United States	25 cities	The presence of a privately operated bus service was associated with increased transit ridership; the effects of Uber and bike-sharing systems on transit ridership were not statistically significant.	A longitudinal study of the effect of TNCs on transit in the absence of partnerships.
Benaroya et al., 2023	Innisfil, Ontario	52 zones	Subsidized Uber trips were associated with an increase in transit ridership but unsubsidized trips were not.	A partnership between the city and Uber to provide on-demand services.

Study	Study area	Sample Size	Effect size/impact	Note about study
Shen et al., 2021	King County, Seattle	342 program users	The carpooling trips generated by the app mostly substituted for single-occupancy vehicles; monetary incentives led to more carpooling.	A partnership between the transit agency and an app-based carpooling program, with monetary incentives of $2 per trip.
Cashmore, 2020	Research Triangle Park, North Carolina	Pilot program	TNC-operated first/last mile service offered similar ridership but greater reductions in per capita VMT and VHT at lower costs than transit-operated demand-responsive fixed-route first/last mile services.	Results from this pilot program may not be transferable to other contexts.

1.9 Transit stop amenities

Transit stop amenities such as shelters and lighting have the potential to increase transit ridership by increasing perceived safety and comfort and thereby reduce driving. We searched Google Scholar using the following terms to find relevant studies, with results as indicated.

- "Transit stop amenities" and "ridership" (with 62 search results)
- "Public transportation amenities" and "ridership" (with 28 search results)
- "Station amenities" and "transit ridership" (with 127 search results)

Table 8 summarizes the reviewed papers. Amenities positively associated with ridership increases include shelters, lights, benches, real-time information displays, and bike lockers. An increase in transit ridership is likely to translate into a reduction in VMT (National Academies, 2021), but these studies do not provide direct evidence of that impact.

Table 8. Summary of literature about the impact of transit stop amenities on ridership.

Study	Study area	Sample Size	Effect size/impact	Note about study
Shi, et al., 2021	King County, Washington	96 bus stops	Stops with the combination of new Real Time Information Systems, shelters, and bike hoops were more likely to see increases in boardings. Amenity changes had no statistically significant effect on alightings.	Study uses a quasi-experimental design.
Kim et al., 2020	Salt Lake County, UTA	4472 stops	The growth of bus ridership was 141% higher at the improved bus stops compared to the control group.	Study uses a quasi-experimental design.
Miao et al., 2019	Salt Lake City metropolitan area, Utah	5384 bus stops	Sheltered bus stops moderately reduced the impact of adverse weather events on transit ridership on weekdays but not weekends.	The placement of bus shelters was correlated with other factors.
Brown et al., 2006	Triangle region of North Carolina	148 bus stops	Bus stop amenities have a positive association with total boardings and alightings.	-

1.10 Transit vehicle amenities

Better quality transit vehicles equipped with a real-time information (RTI) system enhance the transit experience and can entice drivers to switch to transit. We searched Google Scholar using the following terms to find relevant studies, with results as indicated.

- “Public transportation fleet” and “ridership” (with 60 search results)
- “Transit vehicle amenities” and “ridership” (with no search result)
- “Public transportation vehicle amenities” and “ridership” (with no search results)
- “Transit fleet” and “ridership” (with 739 search results)
- “Real-time information system” and “ridership” (with 198 search results)

We screened about 80 articles, of which only four met our inclusion criteria. Our review summary is presented in Table 9. The evidence suggests that implementing an RTI system is associated with an increase in transit ridership. An increase in transit ridership is likely to translate into a reduction in VMT, but these studies do not provide direct evidence of that impact (National Academies, 2021). We did not find studies of the impacts of other kinds of transit vehicle amenities.

Table 9. Summary of literature about the impact of transit vehicle amenities on ridership.

Study	Study area	Sample Size	Effect size/impact	Note about study
Shi, et al., 2021	King County, Washington	96 bus stops	Stops with the combination of new Real Time Information Systems, shelters, and bike hoops were more likely to see increases in boardings; amenity changes had no statistically significant effect on alightings.	Study uses a quasi-experimental design.
Brakewood et al., 2015	New York City	1,404 users	Providing RTI was correlated with a median increase of 1.7% of weekday route-level ridership.	Study uses a quasi-experimental design.
Tang and Thakuriah, 2012	Chicago	144 bus routes of the Chicago Transit Authority	Average weekday bus ridership was 1.8-2.2% higher on routes with RTI.	Quasi-experimental study controlling for gas price, population, employment, weather, month.
Carrel et al., 2013	San Francisco	138 transit users and non-users	Perceived unreliability due to lack of information is associated with a stronger preference to not use transit.	Study relies on stated preferences.

1.11 Park-and-ride lots

Park-and-ride (PnR) lots, which provide convenient car parking at transit stops, can encourage drivers to shift to transit for the longest portion of their trip. In contrast to mobility hubs, PnR lots only include car parking spaces and access to transit. We searched Google Scholar using the following terms to find relevant studies, with results as indicated.

- "Park-and-ride lots" and "transit ridership" (with 3,730 search results)
- "Park-and-ride lots" and "driving" (with 3,240 search results)
- "Park-and-ride lots" and "VMT" (with 892 search results)
- "Park and ride lots" and "vehicle miles traveled" (with 36 search results)

We screened 186 papers, with three meeting our inclusion criteria (Table 10). All three reviewed studies showed a significant impact of PnR lots on transit ridership, with one providing an estimate of the potential increase in VMT that could stem from the removal of a PnR lot (Duncan and Cao, 2021). In contrast, some studies of park-and-ride facilities suggest that their main effect may be to redistribute traffic rather than to reduce driving (Parkhurst, 2000).

Although the empirical evidence on PnR lots is limited, simulation studies are suggestive of the impact that PnR lots could have. Duncan and Cook (2014) estimated the impact of removing PnR lots in North Carolina on Vehicle-Kilometer-Traveled (VKT) and concluded that each PnR user would have an additional 8-15 VKT per round trip, depending on the area that would lose a PnR lot. Truong and Marshall (2014) concluded that, in general, the impact of PnR on VMT and GHG emission is dependent on other variables, such as the location of PnR and parking fee structures at the lot. They suggest that having a PnR lot at end-of-line stations is more effective in reducing GHG emissions than at other locations.

Investigating PnR lots in King County, Washington, Zhao et al. (2019) found that PnR lots can be a practical tool to attract bus riders, especially from younger cohorts and low-income households.

Table 10. Summary of literature about the impact of park-and-ride lots on transit ridership.

Study	Study area	Sample Size	Effect size/impact	Note about study
Pogodzinski and Niles, 2021	San Jose MSA, California	3,084 stations	PnR facilities have statistically significant and strong positive influences on transit use.	-
Duncan and Cao, 2020	Twin Cities region	482 PnR users	80% of respondents would quit using transit if PnR was removed, adding 19 VMT per user to the system.	Study relies on stated preferences of PnR users.
Niles and Pogodzinski, 2016	Los Angeles County and Santa Clara County, California, and King County, Washington	59 routes form 3 transit agencies	An increase of 18-23 parking spaces within ¼ mile of a bus stop is associated with 1 more boarding.	-

1.12 Marketing transit

Advertising can be used to promote transit as an alternative to driving, potentially reducing VMT. We searched Google Scholar using the following terms to find relevant studies, with results as indicated.

- “Marketing transit” and “ridership” (with 121 search results)
- “Advertising transit” and “ridership” (with 26 search results)
- “Marketing for transit” and “ridership” (with 10 search results)
- “Marketing for public transportation” and “ridership” (with 5 search results)
- “Marketing for public transportation” and “driving” (with 7 search results)

Most of the studies identified through this search focused on the revenue-generating potential of advertising on transit vehicles rather than on the impact of marketing on transit ridership. Of the articles screened, only one examined the impact of advertising on ridership, finding a statistically significant impact: Kovalev (2019) studied Moscow’s effort to rebrand the transit system and found after two years of the new advertising methods the overall ridership had increased.

1.13 On-demand transit

On-demand transit might increase ridership by providing flexible service based on the riders' needs. We searched Google Scholar using the following terms to find relevant studies, with results as indicated.

- “On-demand transit” and “ridership” (with 7,370 search results)
- “On-demand transport” and “ridership” (with 231 search results)

- “On-demand transport” and “driving” (with 1,370 search results)
- “On-demand public transportation” and “ridership” (with 37 search results)
- “On-demand transport” and “vehicle miles traveled” (with no search results)

Most papers were about the riders’ perception of these kinds of services or analysis of scenarios with the goal of optimizing the system’s performance. Table 11 summarizes the reviewed papers.

Of the reviewed papers (out of 137 screened), two studies, both from Canada, found that ridership increased following conversion of fixed-route to demand-responsive service (Powell et al., 2023; Zhang et al., 2022). An increase in transit ridership is likely to translate into a reduction in VMT, but these studies do not provide direct evidence of that impact (National Academies, 2021). In addition, when demand-responsive transit replaces fixed-route transit, the miles traveled by transit vehicles is likely to increase (e.g., Lang, 2018).

Table 11. Summary of literature about the impact of on-demand transit on ridership.

Study	Study area	Sample Size	Effect size/impact	Note about study
Powell et al., 2023	Fort Erie, Ontario, Canada	46 users	Total system ridership went up after the fixed-route system was converted to a demand-responsive system.	Study based on system data and an on-board survey of users.
Zhang et al., 2022	Belleville, Canada	264 users	Nighttime bus ridership increased by 300% following a conversion from fixed-route to on-demand service; riders reported more activity participation following the conversion.	Study based on system data and a survey of users of an on-demand transit service.

1.14 Commuter/regional rail

Commuter or regional rail provides a connection to more distant destinations and can be an alternative to driving for regular commutes and for occasional work and non-work trips. We searched Google Scholar using the following terms to find relevant studies, with results as indicated.

- “Regional rail” and “VMT” (with 472 search results)
- “Regional rail” and “ridership” (with search 2,550 results)
- “Commuter rail” and “ridership” (with 9,660 search results)
- “Commuter rail” and “VMT” (with 2,300 search results)

We screened about 100 related results by reviewing their abstracts to determine if they were relevant to our review. Table 12 summarizes the findings. Our review included studies with a variety of dependent variables, including transit ridership, GHG emissions, and vehicle ownership. The findings indicate the important role of commuter and regional rail in increasing transit ridership and reducing VMT. Mendoza et al. (2019), for example, estimated a statistically significant reduction in VMT and GHG emissions owing to the replacement of car trips with transit trips; commuter rail had a disproportionate contribution to these reductions. The studies emphasize the role of strategic planning, the need for supportive infrastructure and policies, and the potential for rail to complement local transit networks in achieving these results.

Evidence of the superiority of rail over bus for attracting long-distance trips is provided by a study in Sweden (Hansson et al., 2021). This study used a quasi-experimental case–control approach to investigate the impact on public transport ridership in rural areas by replacing regional bus services with rail Using a group of 14 villages as treatment group and another 14 as control group, they found that rail services significantly increased public transport use in rural areas, even where bus services were reduced or eliminated (Hansson et al., 2021).

A few studies have explored factors impacting regional rail ridership. Shantz et al. (2022) reported elasticities for station-level weekday boardings related to the conversion of commuter rail systems to regional rail networks in Ontario, Canada: a 1% increase in fare was associated with a 0.13-0.30% increase in ridership, while a 1% increase in distance to the central business district was associated with a 0.90-1.54% decrease in ridership.

Table 12. Summary of literature about the impact of commuter/regional rail on ridership.

Study	Study area	Sample Size	Effect size/impact	Note about study
Shantz et al., 2022	Ontario, Canada	61 stations	A 1% increase in service quantity was associated with a 0.22% to 0.56% increase in ridership.	Service quantity measured as number of outbound trips.
Mendoza et al., 2019	Salt Lake City, Utah	All bus, light-rail, and commuter routes	Commuter rail accounted for 40% of personal VMT eliminated by transit but just 5% of transit VMT; each mile of commuter rail service eliminated 92 miles of personal VMT.	Study assumes that all transit trips replace driving trips and so overstates the effect of commuter rail on VMT.
Rahman et al., 2019	Orlando, Florida	12 stations	An increase in the number of bus stops in proximity to the rail station was associated with higher ridership.	The distance considered for proximity is 1500 meters.
Deka, et al., 2014	New Jersey	1431 passengers of one regional rail line	Annual VMT decreased in the range of 12.4-14.5 million miles because of diversions from driving and other modes after the introduction of off-peak services; peak ridership increased somewhat following the increase in off-peak service.	Study based on system data and an on-line passenger survey

2. TDM mitigation measures

We assessed the empirical evidence for nine types of mitigation measures in the travel demand management category. These measures, shown in Table 13, were prioritized based on interest scores gathered from the project advisory panel. Most but not all of these measures are included in prior reviews—the CARB SB375 Policy Briefs, the CAPCOA GHG Handbook, and Caltrans' Mitigation Playbook—as indicated.

To identify studies on the impact of these measures on driving (using vehicle-mile-traveled, vehicle-kilometer-traveled, or GHG emission reduction metrics), we searched Google Scholar for relevant studies using one or more search terms for each measure. We screened the results by scanning the title, abstract, and/or other available summaries. We then reviewed the full text of the studies that appeared to be relevant after the screening (more than 50 papers in total). We also screened the references from those papers to identify other relevant studies, and we used Google Scholar to find more recent papers citing the studies and included the more recent articles if they met the inclusion criteria. Studies included in the review had the following characteristics:

- Included VMT, VKT, or GHG emissions as a dependent variable,
- Used empirical research methods rather than simulation models,
- (Preferably) reported quantitative results,
- Was posted on the Internet or available through the University of California library.

Table 13. List of TDM mitigation measures with research priorities.

Measures	Interest Score (of 4)	Highest interest percentage	CARB briefs	CAPCOA	Mitigation Playbook
Telecommuting	3.12	31%	X		X
Broadband improvements	2.68	19%			
Employer-based Commute Trip Reduction programs	3	31%	X	X	X*
Transit pass subsidies^	-	-		X	
Ridesharing Programs	2.93	25%	X	X	
Car-sharing programs	3	25%	X	X*	
Community-based travel planning	2.75	19%	X*	X	X*
Safe Routes to School and other school-based programs^	-	-			

*indicates similar measure

^indicates added after the stakeholder workshop

2.1 Telecommuting

Telecommuting programs enable employees to work at home or at another remote location rather than commuting to their regular workplaces on either a full-time or part-time basis. We searched Google Scholar using the following terms with results as indicated.

- “Telecommute” and “VMT” (with 618 search results)
- “Telecommute” and “driving” (with 4,820 search results)
- “Remote work” and “VMT” (with 325 search results)
- “Remote work” and “driving” (with 19,600 search results)

We screened about 110 related results by reviewing their abstract to determine if they were relevant to our review. Table 14 summarizes the findings from U.S. studies. The ten studies reviewed consistently show that telecommuting has the potential to reduce commute trips and VMT. However, it also influences non-commute travel patterns and is often associated with an increase in non-work-related trips. The net impact of telecommuting on overall VMT and travel behavior is contingent on various factors, including regional characteristics, telecommuting frequency, and individual preferences.

Telecommuting, also known as remote working, increased dramatically during the COVID-19 pandemic, leading to a flurry of new studies on the topic. An analysis of telecommuting during COVID-19 shut-downs and early recovery periods found that telecommuting generated new non-commute trips that offset a significant portion of the reduction in commute trips (Obeid et al., 2024). Nevertheless, telecommuting led to a net decrease in total distance traveled (by all modes). A state-level study using longitudinal data from April 2020 to October 2022 found that a 1% decrease in the share of onsite workers was associated with a 0.99% decrease in state-level VMT, suggesting that an increase in telecommuting is associated with a decrease in VMT (Zheng et al., 2024). (This study also documents a negative effect of telecommuting on transit ridership.) These are results are consistent with older longitudinal studies of the effect of telecommuting on VMT (Handy et al., 2013).

Nationwide cross-sectional studies using data from before the COVID-19 pandemic show that telecommuters made more daily trips, travel longer distances and had more complicated trip chains than non-commuters (Reily et al., 2022; Zhu and Guo, 2022; Su et al., 2021). Controlling for household and individual characteristics, all studies concluded that telecommuting is associated with a lower number of one-way commute trips and lower total work VMT. However, telecommuters tend to commute for longer distances on days they go to work (Zhu et al., 2018; Zhu, 2012). Indeed, some evidence suggests that telecommuting enables a move to locations farther from work (Asmussen et al., 2023). Zhu and Mason (2014) show that telecommuters generate more VMT for both daily work and non-work trips than non-telecommuters generate. But because these are cross-sectional studies, these results do not mean that VMT will increase for individual workers when they adopt telecommuting. It is possible, for example, that having a long commute makes workers more likely to adopt telecommuting, the reverse of the presumptive causal relationship. The results of the cross-sectional studies should not be used to predict the impact of telecommuting on VMT.

The total impacts of telecommuting on VMT depend on the number of workers telecommuting, the number of days each worker telecommutes, and the impact on VMT per telecommuting day.

Table 14. Summary of literature review for telecommuting.

Study	Study area	Sample Size	Effect size/impact	Notes about study
Zheng et al., 2024	U.S.	48 states	A 1% decrease in onsite workers is associated with a 0.99% decrease in state-level VMT.	Study uses longitudinal data and an instrumental variable approach to estimate the effect.
Obeid et al., 2024	U.S.	809 workers	Telecommuters make one additional non-commute trip on telecommuting days. The average distance of the extra trip is less than the average distance of commute trips. Telecommuting leads to a net reduction in daily travel distance (across all modes) of 9.1%.	Study uses data from five-wave panel survey conducted from August 2020 through June 2021 to analyze differences in VMT on telecommuting and non-telecommuting days.
Asmussen et al., 2023	Texas	824 workers	For 20% of workers, telecommuting led to a residential move that changed commute distance. A shift from 100% in-person to 100% home-based work would increase average commute distance by 65% owing to residential moves. Reductions in commute VMT were greatest when workers telecommuted about 2 days per week.	Study examines impact of telecommuting on residential location and thus commute distance using data from an original survey (date not specified)
Malik et al., 2022	Southern California Association of Governments (SCAG) region	4045 workers	Telecommuters made more social and recreational trips compared to commuters. Average VMT was lower for telecommuters than for non-telecommuters	Data from an original on-line survey conducted in fall 2020.
Reilly and Tawfik, 2022	U.S.	Not specified	Telecommuters made more trips per day and traveled longer distances than non-telecommuters.	*Cross-sectional* comparison of telecommuters and non-telecommuters using the 2017 NHTS

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Study	Study area	Sample Size	Effect size/impact	Notes about study
Zhu and Guo, 2022	U.S. Metropolitan Statistical Areas	81, 1854 workers	Telecommuting was associated with more frequent and complex trip-chaining.	*Cross-sectional* comparison of telecommuters and non-telecommuters using the 2009 and 2017 NHTS
Su et al., 2021	California	2236 telecommuters and 12,809 commuters	Telecommuters with at least one trip during the workday made more trips and had higher VMT than non-telecommuters.	*Cross-sectional* comparison of telecommuters and non-telecommuters using California add-on to the 2017 NHTS
Chakrabarti, 2018	U.S.	123,810 workers	Telecommuters had 27% higher odds of driving more than 20,000 miles per year compared to non-telecommuters	*Cross-sectional* comparison of telecommuters and non-telecommuters using the 2009 NHTS
Hu and He, 2016	Chicago.	10,552 Households	Household with frequent telecommuters traveled less on telecommuting days than households without telecommuters. Households with less frequent telecommuters traveled similar amounts as households without telecommuters.	*Cross-sectional* comparison of households with telecommuters and households without telecommuters using a 2008 Chicago household travel survey
Zhu and Mason, 2014	U.S.	4713 telecommuters and 101,999 non-telecommuters in 2009	Telecommuters travel 45.3 more vehicle miles per day on average than non-telecommuters. Telecommuters travel more for both work and non-work trips than non-telecommuters.	*Cross-sectional* comparison of telecommuters and non-telecommuters using the 2001 and 2009 NHTS

2.2 Broadband improvements

Broadband improvements, especially in rural areas, enable telecommuting and other remote activities such as e-education and e-medicine, thereby improving access to these activities and potentially reducing driving. We searched Google Scholar using the following terms with results as indicated.

- “Broadband improvement” and “driving” (with 93 search results)
- “Broadband improvement” and “GHG emission” (with 18,100 search results)

We screened about 70 related results by reviewing their abstract to determine if they were relevant to our review. Most of the reviewed studies are from an international context. We did not find studies that directly examined the impact of broadband improvements on VMT or driving. Most of the summarized studies evaluated the impact of broadband on GHG emissions. One study reviewed the impact on urban sprawl and telecommuting and found that counties with improved broadband have a higher rate of teleworking and urban sprawl (Carlson and Howard, 2010). Our review shows that the impact of broadband improvements varies based on the timeline of implementation and the geography. Improving information and communication technology (ICT) in rural areas opens them up to further development and more urban sprawl.

The relationships between energy consumption, GHG emissions, and ICT improvements are mixed. The introduction of such improvements could require higher energy consumption, leading to an increase in GHG emissions. However, in the longer run (over a 20-year span), a significant increase in mobile broadband penetration can lead to a 7 percent reduction of CO2 emissions per capita, according to a study comparing data from 181 countries across the globe (Edquist and Bergmark, 2024). Other international studies from China, New Zealand, EU, and Japan found that broadband improvements are associated with higher GHG emissions and energy consumption (Claussen et al., 2022; Dong et al.2022; Rao et al., 2022; Teppayayon, 2009).

2.3 Employer-based commute trip reduction programs

Employer-based commute trip reduction (EBTR) programs use a variety of strategies to encourage alternatives other than SOV, potentially leading to a reduction in VMT. We searched Google Scholar using the following terms with results as indicated.

- “Employer-based commute trip reduction programs” (with 2,860 search results)

We screened about 100 related results by reviewing their abstracts to determine if they were relevant to our review. Table 15 summarizes the findings. All studies defined EBTR as a package of strategies, such as providing transit pass subsidies, bike-related infrastructure and incentives, carpooling, carsharing, and parking pricing. We also reviewed the literature specific to each of these program components, which are also sometimes implemented as stand-alone programs.

The evidence on EBTR programs is inconclusive. Chen (2023) found that providing transit passes, enabling flexible work schedules, and implementing parking fees at worksites were the most effective in promoting multimodality. Chen and Yang (2023) utilized a longitudinal dataset to assess the effect of TDM measures on vehicle trip rates (VTR) over time in Washington state, finding that while vehicle trip rates (vehicle trips to the worksite per 100 employees) tend to grow over time, TDM measures can decelerate its growth but not entirely reverse the trend. Chen et al. (2021) found that employers investing more time and resources in promoting commute trip reduction programs tend to have a lower VTR but that programs like ride-sharing subsidies and ride-matching programs are associated with higher VTR and higher VMT. A study in Southern California found negligible effects of guaranteed ride home, flextime, and vanpool support on average vehicle ridership, measured as the number of employees divided by the number of vehicles arriving at a worksite (Kane et al., 2020). Shen (2020) found that while “transit benefits” are associated with lower VTR, “parking benefits” are associated with higher VTR, and “other benefits” have no effect on VTR.

Table 15. Summary of literature review for employer-based commute trip reduction programs.

Study	Study area	Sample Size	Effect size/impact	Note about study
Chen, 2023	King County, Washington	18,591 persons	Transit passes, flexible work schedules, and charging parking fees on worksites were positively associated with using transit, walking or biking, and teleworking	Strategies included flexible work hours, ride matching, multimodal subsidies, employer-provided cars, parking feed, promotional programs
Chen and Yang, 2023	Washington state	926 worksites	Large transit passes and subsidies promoting multimodal transportation were negatively associated with vehicle trip rates. Ride-matching programs, employer-provided cars, and guaranteed ride home programs were positively associated with vehicle trip rates.	TDM programs included subsidies (transit, carpool, bike), parking fees, ride-matching, employer-provided cars, emergency rides home, rental cars, transit passes, and promotional programs.
Chen et al., 2021	Washington state	440 worksites	Promotional efforts were negatively associated with vehicle trip rates. Transit access and bike/walk subsidies were negatively associated with VMT. Ridesharing subsidies and ride-matching programs were positively associated with vehicle trip rates. Ridesharing subsidies were positively associated with VMT. Employers who spent more money on TDM measures had lower vehicle trip rates.	TDM programs included ride-sharing subsidies, ride-matching programs, multimodal trip incentives, transit access, and promotional efforts
Kane et al., 2021	Southern California	2,450 worksites	Strategies to increase average vehicle ridership did not have statistically significant effects, with the exception that implementation of a guaranteed ride home program was positively associated with average vehicle ridership (AVR – the ratio of employees to vehicles) in one of the three geographic zones analyzed.	Mitigation strategies included guaranteed ride home, flexible hours, vanpool support

Study	Study area	Sample Size	Effect size/impact	Note about study
Shin, 2020	Central Puget Sound region	3036 persons	Having transit benefits was associated with more use of transit, non-motorized modes, and carpooling, and less commute, non-work, and total VMT. Having parking benefits was associated with less use of transit, non-motorized modes, and carpooling, and more commute, non-work, and total VMT.	Commuter "benefits" categories included transit benefits, parking benefits, and "other" benefits

2.4 Transit pass subsidies

Transit subsidies in the form of transit passes or reimbursements reduce the cost of a trip made by transit, which can lead to a mode shift from driving to transit. We searched Google Scholar using the following terms with results as indicated.

- “Transit pass subsidy” and “VMT” (with 32 search results)
- “Transit subsidy” and “VMT” (with 219 search results)
- “Transit subsidy” and “driving” (with 757 search results)
- “Transit incentives” and “driving” (with 360 search results)
- “Transit incentives” and “VMT” (with 131 search results)

We screened about 130 related results by reviewing their abstract to determine if they were relevant to our review. Table 16 summarizes the findings. Our review shows that transit pass subsidies (generally implemented in combination with other TDM measures) influence commuter behavior, mainly by encouraging individuals to increase their use of transit. Chen (2023) found that transit pass subsidies increased the likelihood of commuting by transit rather than driving alone, as did Shin (2020). Chen and Yang (2023) found that worksites offering transit subsidies had lower vehicle trip rates, measured as the number of vehicles traveling to the worksite per 100 employees, but in another study this effect was not statistically significant (Chen 2021). Shin (2020) found a significant negative association between an employee having “transit benefits” and their commute, non-work, and total VMT. In Chen (2021), transit subsidies did not have a statistically significant impact on the average VMT for worksites. All these studies controlled for other TDM programs as well as other factors.

Table 16. Summary of literature review for transit pass subsidies.

Study	Study area	Sample Size	Effect size/impact	Note about study
Chen, 2023	King County, Washington	18,591 persons	Transit pass increased the likelihood of using transit rather than driving alone.	A subsidized transit pass was a part of TDM package.
Chen and Yang, 2023	Washington state	926 worksites	Distributing trip passes was negatively correlated with vehicle trip rate (vehicle trips per 100 employees). Larger transit passes (above $103.65 per month) had a larger effect than smaller transit passes.	A subsidized transit pass was a part of TDM package.
Chen et al., 2021	Washington state	440 worksites	Transit subsidies did not have a statistically significant impact on vehicle trip rates (vehicle trips per 100 employees) or average VMT. Employers that spent more time and money promoting commute trip reduction had lower vehicle trip rates.	A subsidized transit pass was a part of TDM package. The study used data from 7 counties.
Shin, 2020	Central Puget Sound region	3036 persons	Having transit benefits was associated with less commute VMT, non-work VMT, and total VMT. Having transit benefits increased the likelihood of commuting by transit rather than driving.	Study measures the effect of having “transit benefits”

2.5 Ridesharing programs

Ridesharing programs facilitate and incentivize carpooling and vanpooling in place of single-occupancy-vehicle (SOV) trips. They may include ride-matching services and/or subsidies, especially for vanpools. They are often implemented as a part of Employer-Based Trip Reduction programs (see Section 2.3). We searched Google Scholar using the following terms with results as indicated.

- "Carpooling" and "VMT" (with 3,170 search results)
- "Vanpooling" and "VMT" (with 775 search results)
- "Ridesharing" and "VMT" (with 3,100 search results)
- "Ride matching" and "VMT" (with 458 search results)

We screened about 100 related results by reviewing their abstracts to determine if they were relevant to our review. Table 17 summarizes the findings. Research on carpooling and vanpooling programs has been limited in the last two decades. Most recent research on ride-sharing focuses on the potential for dynamic ride-matching, often in the context of Transportation Network Companies. This is sometimes called "ride-splitting" and is similar to taxi sharing (Shaheen and Cohen, 2019a).

Studies of employer-based trip reduction programs reviewed in generally find that ride-sharing subsidies and ride-matching programs increase rather than decrease commute vehicle trips (see Table 15). Two international studies found negative associations between car ownership and participation in a carpool program: participation in a citywide carpool program contributed to a delay in purchasing a vehicle (Hui et al., 2019; Kolleck, 2021).

The impact of ride-sharing programs on VMT depends both on the success of the program in encouraging ride sharing and the change in VMT for those who choose to ride share. One recent study of the pilot implementation of carpooling app coupled with a financial incentive led to a reduction in single-occupant vehicle trips and VMT for those who participated. Like telecommuting, carpooling leads to changes in non-commute trips as well (Shen et al., 2020). For example, one study shows that carpoolers make more of their trips for maintenance and discretionary activities outside of the peak period in comparison to solo commuters who often "chain" these trips to their commute trip (Concas and Winters, 2010. These differences potentially impact total VMT as well as emissions.

Transportation Network Companies (TNCs; for example, Uber and Lyft) have at times offered shared-ride options, in which passengers can choose to share a ride with other passenger(s) for a reduced fare. A review of the literature on the impact of Transportation Network Companies (TNCs) on VMT concluded that the current evidence as to the net effect of TNCs, reflecting both solo and shared rides, is inconclusive (Du and Rakha, 2020). Two studies concluded that use of TNCs is associated with increased VMT and GHG emissions, especially on arterial and local roads (Leard and Xing, 2020; Pang and Shen, 2023). Another study found that VMT increased substantially in San Francisco and Los Angeles but declined in Washington, DC (Eliot et al., 2021). Based on a model developed with cross-sectional data, Leard and Xing (2020) examined predicted changes in mode choice for individual trips in the absence of TNC services and concluded that had such services not been available, a majority of those trips would have been made by walking or taxi, and in large cities. Because TNC services replaced these modes rather than single-occupant vehicles, they led to a modest increase in total VMT. Peng and Shen (2023) used data from 2010 and 2017 to examine changes in VMT in metropolitan statistical areas following the introduction of Uber in those areas and found no significant effect on total VMT, though VMT increased on local roads and declined on highways.

Table 17. Summary of literature review for ridesharing programs.

Study	Study area	Sample Size	Effect size/impact	Note about study
Shen et al., 2020	King County Metro in the Seattle region	342 persons	App-based carpooling reduced SOV trips and regional VMT	The Scoop carpooling app (now defunct) was implemented in conjunction with a financial incentive
Leard and Xing, 2020	Nationwide	120,985 trips	34% of ridehailing trips replaced walking. Introduction of TNC services increased VMT by 0.08% nationally and 0.16% in large cities	Does not distinguish between solo and shared TNC trips.
Elliot, Shaheen and Stocker, 2021	San Francisco, Los Angeles, and Washington, DC	8,630 passengers, 5,034 drivers, 1,650 others	VMT per passenger per year increased by 234 miles in San Francisco and 242 miles in Los Angeles but declined by 83 miles in Washington, DC.	Does not distinguish between solo and shared TNC trips.
Pang and Shen, 2023	Nationwide	346 MSAs	TNC services had no significant effect on total VMT in a region. TNC trips were associated with a decrease in VMT on highways but an increase in VMT on collector roads.	Does not distinguish between solo and shared TNC trips.

2.6 Car-sharing programs

Community-wide or site-specific car-sharing programs provide an alternative to private car ownership and may reduce overall VMT. We searched Google Scholar using the following terms with results as indicated.

- “Car-sharing” and “VMT” (with 2,360 search results)

We screened about 70 related results by reviewing their abstracts to determine if they were relevant to our review. Most of the reviewed studies are from an international context. Their findings overwhelmingly show that car-sharing programs are associated with lower car ownership with some evidence that they are associated with fewer single-occupancy vehicle trips. However, these programs might be related to a decrease in transit ridership and an increase in GHG emissions.

Studies from North America also show a strong negative association between membership in car-sharing programs and car ownership (Martin et al., 2010; Mishra et al., 2015; Clewlow, 2016; Namazu and Dowlatabadi, 2018; Dill et al., 2019; Shaheen et al., 2021). Because lower car ownership is associated with less driving, these studies suggest that car-sharing programs have the potential to reduce VMT. However, evidence on reductions in driving is more limited. One study found that car-share members were split between using transit more or less than before joining the program, though the majority walked and bicycled more (Martin and Shaheen, 2011). Another study found that car-share members walk, bike, and use transit more frequently than non-members, though these differences were minor (Mishra et al., 2015). Another study found that members of a peer-to-peer car-sharing service made few changes to their driving behavior, though nearly 4 in 10 decreased their driving by 10% or more (Dill et al., 2019). A 2016 review of the evidence as of that time concluded that carsharing reduces VMT by 27% to 67% upon joining a carshare program for “candidate household members,” defined as individuals who travel shorter total distances and reside in higher-density urban neighborhoods, with good walking, cycling, and transit services (Chen and Kockelman, 2016). Because these studies are cross-sectional, they do not establish that membership in car-sharing programs causes reductions in car ownership

International studies from Europe and elsewhere show that using car-sharing services is associated with reduced car ownership (Nijland and van Meerker, 2017; Becker, et al., 2018; Kim, Park, and Ko, 2019; Le Vine and Polak, 2019; Kolleck, 2021) as well as less driving after controlling for other factors (Nijland and van Meerker, 2017; Ceccato and Diana, 2021). Because auto ownership is lower in Europe and transit service is generally superior, the effects reported in European studies may not be generalizable to the U.S. These studies also do not establish that membership in car-sharing programs causes reductions in car ownership.

2.7 Community-based travel planning

These programs provide households with personalized information about and incentives for modes of travel other than SOV. We searched Google Scholar using the following terms with results as indicated.

- “Community-based travel planning” and “VMT” (with 1,250 search results)
- “Community-based transportation demand management” and “VMT” (with 1,360 search results)
- “Community-based program” and “driving” (with 4,760 search results)
- “Voluntary programs” and “VMT” (with 222 search results)

We screened about 100 related results by reviewing their abstracts to determine if they were relevant to our review. Our review finds evidence that providing personalized information and facilitating access to alternative modes of transport can reduce reliance on personal vehicles and single-occupancy vehicle (SOV) trips.

Studies of two programs in the U.S. point to decreases in VMT. Interviews with students who participated in a UC Berkeley program providing personalized trip planning services showed that participation led to a decrease in the number of SOV trips (Riggs, 2015). Another longitudinal study in King County, Washington, investigated the impact of the IndiMArk program, which provided individualized transportation information to those requesting it and maintained ongoing lines of communication with them (Cooper et al., 2007). The program reportedly shifted 1,688 trips from driving to other modes, leading to a reduction of 25,763 VMT over the span of 12 weeks in four neighborhoods.

International studies also provide evidence of the potential impacts of such programs. Longitudinal studies of voluntary travel behavior change programs from Spain and South Australia showed that participating in such programs led to a reduced number of SOV trips and an increased number of transit trips (Ma et al., 2017; Garcia-Garces et al., 2016). Both studies controlled for household characteristics and included control groups in their analysis.

2.8 Safe routes to school and other school-based programs

The goal of safe routes to school (SRTS) programs is to encourage walking and bicycling to school through infrastructure improvements, traffic enforcement, safety education, and various incentives, with the added benefit of reducing the number of vehicle trips. We searched Google Scholar using the following terms with results as indicated. Since these two measures overlapped in our search, we combined SRTS and school-based strategies in our review.

- “Safe Routes to Schools programs” and “driving” (with 72 search results)
- “Safe Routes to Schools programs” and “VMT” (with 15 search results)
- “School-based transportation demand management programs” and “driving” (with 25,900 search results)
- “School-based programs” and “VMT” (with 17 search results)
- “School-based transportation demand management programs” and “VMT” (with 168 search results)

We screened about 200 related results by reviewing their abstracts to determine if they were relevant to our review. Safe Routes to School (SRTS) and other school-based transportation programs have been implemented across various regions with the primary intent to promote safe and sustainable commuting for students. These initiatives are geared toward enhancing walkability, reducing vehicular congestion around schools, and subsequently decreasing GHG emissions.

While school-based TDM programs, including SRTS, have demonstrated benefits in promoting sustainable and safe commuting practices for students, their effectiveness varies based on specific interventions and regional characteristics. In California, Boarnet et al. (2007) evaluated the state’s pioneering SR2S program, which funded projects designed to improve safety for children walking and bicycling to school. The study found that sidewalk gap-closure projects were positively associated with increased walking among students, though other interventions, such as signal and crosswalk improvements, showed limited or no association. Voulgaris et al. (2020) conducted an assessment in the San Francisco Bay area and concluded that while SRTS programs were effective, their primary role was in reducing barriers to active school travel rather than directly increasing the likelihood of active commuting.

Stronger evidence is available for school-based programs in general. A systematic review of 49 papers on the impact of walking school buses and bike trains on vehicular school trips found a negative association of such strategies with school related vehicle trips. A study involving interviews with families in Portland, Oregon found that Walk and Bike to School Days are among most effective strategies to inform school parents about alternative modes of transport (Weigand and McDonald, 2011).

3. Land use mitigation measures

We assessed the empirical evidence for eight types of mitigation measures in the land use category. These measures, shown in Table 18, were prioritized based on interest scores gathered from the project advisory panel. Most but not all of these measures are included in prior reviews—the CARB SB375 Policy Briefs, the CAPCOA GHG Handbook, and Caltrans' Mitigation Playbook—as indicated.

To identify studies on the impact of these measures on driving (using vehicle-mile-traveled, vehicle-kilometer-traveled, or GHG emission reduction metrics), we searched Google Scholar for relevant studies using one or more search terms for each measure. We screened the results by scanning the title, abstract, and/or other available summaries. We then reviewed the full text of the studies that appeared to be relevant after the screening (more than 100 papers in total). We also screened the references from those papers to identify other relevant studies, and we used Google Scholar to find more recent papers citing the studies and included the more recent articles if they met the inclusion criteria.

Studies included in the review had the following characteristics:

- Included VMT, VKT, or GHG emissions as a dependent variable,
- Used empirical research methods rather than simulation models,
- (Preferably) reported quantitative results,
- Was posted on the Internet or available through the University of California library.

Table 18. List of land use mitigation measures with research priorities.

Measures	Interest Score (of 4)	Highest interest percentage	CARB briefs	CAPCOA	Mitigation Playbook
Transit-Oriented Development (TOD)	3.56	62%	X	X	
Residential density	3.56	62%	X	X	X
Employment density	3.56	62%	X	X	X
Affordable housing	3.37	56%		X	
Land preservation as growth management	3.12	37%			X
Land-use mix/ 15-minute cities^	-	-			
Delivery hubs^	-	-			
Jobs/housing balance^	-	-	X		

^indicates added after the stakeholder workshop

3.1 Transit-oriented development

Transit-oriented development (TOD), consisting of moderate- to high-density, mixed-use development in close proximity to high-quality public transit, can encourage transit ridership and discourage vehicle trips. We searched Google Scholar using the terms below.

- "Transit-oriented development" and "VMT" (with 8,030 search results)
- "Transit-oriented development" and "driving" (with 13,900 search results)
- "Transit-oriented development (TOD)" (with 18,800 search results)

We screened over 90 potentially relevant studies and fully reviewed eight that were directly related to the impact of TOD on VMT and other indicators of driving. Our findings show that in most cases, TOD significantly impacts travel behavior and is associated with lower VMT. Nasri and Zhang (2014), for example, found that people living in TOD areas tend to drive less, with reductions of around 38 percent in Washington, D.C., and 21 percent in Baltimore compared to non-TOD areas with similar land use patterns. The impact of TOD on VMT and driving behavior depends on the specific context and characteristics of the studied areas; studies vary in their precise definitions of TOD.

One of the challenges of investigating the impact of TOD on VMT is to account for the impact of income on travel behavior. An analysis of 22 counties in California showed that households closer to transit had lower VMT, and the gap between VMT when living near transit than when not living near transit was greater for higher-income households than for lower-income households (Bostic et al. 2018). Chatman et al. (2019) compared four Californian metropolitan areas (San Francisco, San Diego, Sacramento, and Los Angeles) and reported that access to rail services affects VMT at the same magnitude regardless of the different income levels. Boarnet et al. (2017) found that building affordable housing in transit-oriented developments (TODs) at higher densities can accommodate both low- and high-income residents, leading to substantial progress in reducing VMT across the income spectrum while addressing affordable housing goals.

3.2 Residential density

An increase in the density of dwelling units through infill development can lead to shorter and fewer vehicle trips. We searched Google Scholar using the following terms with results as indicated.

- "Residential density" and "VMT" (with 2,250 search results)
- "Residential density" and "driving" (with 12,200 search results)
- "Population density" and "VMT" (with 5,960 search results)
- "Population density" and "driving" (with 292,200 search results)
- "Residential infill development" and "driving" (with 123 search results)

We screened about 120 related results by reviewing their abstract to determine if they were relevant to our review. Table 19 summarizes our findings from American and Canadian studies. These studies directly explored the impact of residential density on driving in terms of VMT or

VKT. The reviewed studies used different ways of defining residential density, including population per area and dwelling units per area. Residential density has been studied alongside other land use measured at the neighborhood level, such as employment density, mixed land use (entropy), and transit-oriented developments, which all exhibit negative relationships with VMT. Four studies examine the relationship between density and VMT for geographic areas, such as urbanized areas or traffic analysis zones; four examine the relationship at the level of households or individuals.

The studies reviewed consistently show that higher residential density is associated with lower VMT. Reported (per capita or household VMT/VKT, depending on the study) elasticities vary between -0.58 and -0.07. A meta-analysis by Stevens (2017) of 19 studies found that a 1% increase in density was associated with a 0.1% decrease in VMT. Based on five studies that controlled for residential self-selection, the possibility that individuals who are inclined to drive less are more like to choose locations with higher population density, the effect of a 1% increase in density was a 0.22% decrease in VMT. All else equal, the studies that control for self-selection provide a more robust assessment of the impact of density on VMT.

Infill development is one way to increase residential density in existing areas. One study examined the impact of an infill residential project and concluded that the project significantly reduced VMT for new residents but might not affect VMT for existing residents in the same neighborhood (Merlin, 2018). This makes sense, as a single infill project may have a very small impact on the overall density of the area.

Table 19. Summary of literature review for residential density/infill.

Study	Study area	Sample Size	Effect size	Note about study
Lee and Lee, 2020	U.S. urbanized areas	121 areas	A 1% increase in population-weighted density was associated with 0.07-0.08% reduction in annual household VMT at census tract level.	Controlling for sociodemographic criteria.
Nasri and Zhang, 2014	Washington, D.C., and Baltimore	All TAZs in both cities	A 1% increase in housing unit density at TAZ level was associated with a 0.12% decrease in household level VMT.	Controlling for socioeconomic and demographic characteristics, neighborhood-level build environment, transit accessibility
Ewing et al., 2013	The U.S.	315 urbanized areas	A 1% increase in gross population was associated with a 0.38% decrease in daily VMT per capita.	Controlling for income, fuel price, highway capacity, rail capacity, transit service, transit fares
Zhang et al., 2012	4 U.S. cities	4,746 households	A 1% increase in residential density was associated with a 0.13-0.16% decrease in VMT depending on the city.	Controlling for socio-demographic characteristics, density, land use mix, block size, distance from CBD.
Cervero and Murakami, 2010	The U.S.	370 urbanized areas	A 1% increase in population density was associated with a 0.6% decrease in daily VMT per capita.	Controlling for household characteristics
Heres-Del-Valle and Niemeier, 2011	California	7,666 households	A 1% increase in residential density was associated with a 0.19% reduction in household VMT.	Controlling for household characteristics, percentage of workers, number of cars
Holtzclaw et al., 2010	Chicago, LA, SF	2,820 households	A 1% increase in household per residential acre was associated with 0.14%, 0.11%, and 0.14% decrease in Chicago, LA, and SF, respectively.	Controlling for household characteristics, car ownership and transit use
Brownstone and Golob, 2009	California	2,079 persons	A 1% increase in number of housing units per square-mile was associated with a 0.12% decrease in annual household VMT.	Controlling for sociodemographic characteristics.

Study	Study area	Sample Size	Effect size	Note about study
Merlin, 2018	Atlanta	398 households	The residents of Atlantic station TOD reported less VMT per capita; no significant association between the introduction of the station and VMT of existing residents.	Study included the introduction of Atlantic station to the neighborhood and controlled for household characteristics.
Stevens, 2017	U.S.	Meta-analysis of 19 studies	A 1% increase in population density was associated with a 0.10% decrease in VMT or a 0.22% decrease after accounting for residential self-selection.	Controlling for socio-demographics; 5 studies controlled for residential self-selection.

3.3 Employment density

An increase in the density of jobs in an area through infill development can lead to shorter and fewer vehicle trips. Using the Google Scholar search engine, we looked for studies about the impact of employment density on VMT using the following terms:

- "Employment density" and "VMT" (with 2,100 search results)
- "Employment density" and "driving" (with 5,890 search results)
- "Infill development" and "driving" (with 5,960 search results)

We screened more than 100 potentially relevant papers and fully reviewed 10 of these studies. Table 20 summarizes our findings from the studies that included elasticities. These studies show that employment density has a weak negative impact on VMT and, in certain circumstances, may be positively associated with VMT. Zhou and Kockelman (2008) conclude that employment densities have opposing effects on household VMT depending on location: negative in rural and suburban areas but marginally positive in urban areas where an increase in job density in the central business district may lead to longer commutes on average. Stevens (2017) concludes that employment density has "very little potential" to reducing driving.

International studies have mostly found similarly limited effects of employment density on VMT (Zegras, 2009; Heden and Vance, 2007; Tao and Naess, 2022), though a study in Shanghai found an elasticity of 0.34 (Chen and Costa, 2022).

Table 20. Summary of literature review for employment density/infill.

Study	Study area	Sample Size	Effect size	Note about study
Zhang et al., 2012	4 U.S. cities	4,746 households	A 1% increase in jobs per square mile was associated with between a 0.01% decrease and a 0.1% increase in VMT depending on the city.	Controlling for socio-demographic characteristics, land-use mix, block size, distance from CBD.
Zhou and Kockelman, 2008	Austin, TX	1,903 households	A 1% increase in jobs per square mile was associated with a 0.03% decrease in VMT in suburban areas and a 0.07% increase in VMT in urban areas.	Controlling for socio-demographic characteristics and population density.
Cervero and Duncan, 2006	SF Bay Area	16,000 households	A 1% increase in total jobs within 4 miles of residence was associated with a 0.3% decrease in VMT.	Controlling for sociodemographic characteristics.
Stevens, 2007	U.S.	Meta-analysis of 11 studies	A 1% increase in job density was associated with a 0.01% decrease in VMT, or a 0.07% decrease after accounting for self-selection.	Controlling for socio-demographic characteristics; 2 studies controlled for residential self-selection.

3.4 Affordable housing

Building affordable housing in infill locations can shorten commute distances and reduce VMT for its occupants, especially in transit-oriented and denser areas. We searched Google Scholar using the following terms with results as indicated.

- "Affordable housing" and "VMT" (with 2,470 search results)
- "Affordable housing" and "driving" (with 59,300 search results)
- "Affordable housing" and "travel behavior" (with 89,200 search results)

After screening over 70 potentially relevant studies, we identified five papers for full review, four of which focused on California. In general, the evidence shows that affordable housing has the potential to contribute to reductions in VMT, especially if it is located within areas with good transit access and mixed land uses.

Boarnet et al. (2017) found that building affordable housing in transit-oriented developments (TODs) at higher densities can accommodate both low- and high-income residents, leading to substantial progress in reducing VMT across the income spectrum while addressing affordable housing goals. Another study investigated the impact of developing affordable housing in "location efficient" neighborhoods with high levels of accessibility to jobs and services that could reduce driving either by making trips shorter or by shifting trips to other modes, such as transit, walking, and biking (Newmark and Haas, 2015). Income and location efficiency were identified as significant predictors of VMT (Newmark and Haas, 2015; Bostic et al., 2018).

Disentangling the effects of affordable housing from the effects of income on VMT is challenging. Ong et al. (2022) found that a higher density of Housing Choice Vouchers (HCV) units in a given area was associated with better walkability and transit accessibility as well as lower VMT, but a higher density of HCV units was also associated with higher exposure to pollution and a higher rate of vehicle collisions. Another study in California investigated the transportation impacts of affordable housing in various urban contexts and housing types in California and found significantly lower vehicle trip-making in areas with lower incomes and greater urbanization (Howell et al.,2018).

3.5 Land preservation as growth management

Land conservation is an important strategy for creating permanent growth boundaries that limit the outward expansion of an urban area and promoting more compact communities that tend to produce less VMT. We searched Google Scholar using the following terms to find relevant studies, with results as indicated.

- "land preservation" and "driving" (with 3,810 search results)
- "land preservation" and "VMT" (with 162 search results)
- "smart growth" and "VMT" (with 8,840 search results)

Screening more than 50 studies, we reviewed six studies fully. Table 21 summarizes our findings from three studies that provided relevant quantitative results. Most of the identified studies focused on the impact of smart growth on travel behavior and VMT. Smart growth is an approach to managing growth that results in more compact development. The compactness of a city can be measured at the city level with respect to population and employment density. The average distance to downtown for residents of a city is another way to measure compactness. Other measures of compactness are sometimes used. Hamid et al. (2015) created an overall compactness/sprawl index calculated as the sum of four compactness factors: density, mixed use, centering, and street.

Although the effect of land preservation on VMT is indirect and difficult to assess, the available evidence suggests that land preservation as a part of a growth management policy can significantly impact VMT and GHG emissions. If land preservation contributes to a more compact urban area, it is likely to reduce increases in VMT that would otherwise occur as an urban area grows, especially if combined with other strategies that reduce VMT. A literature review concluded that compact development and land management policies could potentially influence VMT (Southworth, 2001). Hamid, et al. (2015) found that their compactness index was negatively associated with vehicle ownership and driving time. Other studies show that living farther from downtown is associated with higher VMT (Zhang et al., 2012; Stevens, 2017), suggesting that more compact cities with shorter average distances to downtown will have lower average VMT.

In a project for Caltrans, Sciara et al. (2015) concluded that preserving land as a mitigation strategy for transportation projects, particularly if implemented in advance of project development as a part of a regional conservation effort, can yield major ecological benefits and significantly reduce GHG emissions. Their study discusses ways that such an approach could be implemented.

Table 21. Summary of literature review for growth management.

Study	Study area	Sample Size	Effect size	Notes about study
Hamidi et al., 2015	U.S.	221 Metropolitan Statistical Areas	Compactness index is positively associated with walking and transit shares and negatively associated with vehicle ownership and driving time.	Controlling for socioeconomic characteristics.
Zhang et al., 2012	4 U.S. cities	4,746 households	A 1% increase in distance to the CBD was associated with a 0.22-0.3% increase in VMT depending on the city; VMT decreased with distance in Virginia.	Controlling for socio-demographic characteristics, density, block size.
Stevens, 2017	U.S.	Meta-analysis of 14 studies	A 1% increase in distance to the central business district is associated with a 0.63% increase in VMT, controlling for self-selection.	Controlling for socioeconomic characteristics; 3 studies controlled for self-selection.

3.6 Land-use mix

Having a mix of land uses within a neighborhood can lead to shorter trips and fewer vehicle trips; a mix of land uses around job sites can have a similar effect. We used the following search terms in Google Scholar to identify studies on the impact of land-use mix on VMT:

- “Mixed-use” and “driving” (with 34,900 search results)
- “Mixed land use” and “driving” (with 3,340 search results)
- “15-minute city” and “driving” (with 886 search results)
- “Mixed-use planning” and “VMT” (with 6,320 search results)
- “Land use mix” and “VMT” (with 1,770 search results)

We screened over 140 related results by reviewing their abstract to determine if they were relevant to our review, and identified 14 for full review. Table 22 summarizes our findings from the studies that included elasticities. These studies directly explored the impact of land-use mix on VMT or VKT. The reviewed studies used different ways of measuring land-use mix, with most using an “entropy index” (as in Lee & Lee, 2020); one study uses retail employment density (Chatman, 2008). The impacts of land-use mix on travel behavior are mostly studied in conjunction with other built environment factors, such as transit-oriented development (TOD), population and employment density, and distance from the central business district.

Seven reviewed studies provide strong evidence that land-use mix is negatively associated with non-work and total VMT (Table 22). The elasticities range from -0.19 to -0.04. A meta-analysis by Stevens (2017) of 15 studies found that a 1% increase in land-use mix was associated with a 0.03% decrease in VMT. Based on two studies that controlled for residential self-selection, the possibility that individuals who are inclined to drive less are more likely to choose locations with higher population density, the effect of a 1% increase in land-use mix was a 0.11% *increase* in VMT. All else equal, the studies that control for self-selection provide a more robust assessment of the impact of density on VMT, though the result is counter-intuitive.

Table 22. Summary of literature review for land-use mix.

Study	Study area	Sample Size	Effect size	Note about study
Lee and Lee, 2020	U.S. urbanized areas	121 areas	A 1% increase in land use entropy was associated with 0.09% reduction in annual household VMT.	Land-use entropy defined as $(-1\times\{[\sum(pi)\ln(pi)] / \ln(k)\}$ where pi = land use i's % of total land area; k = 4 land use categories (residential, commercial, industrial, and offices)
Nasri and Zhang, 2014	Washington, D.C., and Baltimore	All TAZs in both cities	A 1% increase in land use entropy at TAZ level was associated with a 0.053 decrease in household level VMT.	Controlling for socioeconomic and demographic, neighborhood-level build environment, transit accessibility
Zhang et al., 2012	4 U.S. cities	4,746 households	A 1% increase in land use entropy was associated with a 0.01-0.06% decrease in VMT depending on the city.	Controlling for socio-demographic characteristics, density, block size, distance from CBD.
Chatman, 2008	Alameda, San Francisco, Santa Clara Counties, and the San Diego metropolitan area.	527 people	A 1% increase in number of retail employees within a given radius of home was associated with a 0.19% decrease in nonwork VMT per person.	Controlling for sociodemographic characteristics.
Kuzmayk et al., 2006	Baltimore Metropolitan area, Maryland	3,133 households	A 1% percent increase in land use entropy index was associated with 0.1% decrease in annual household VMT.	Controlling for sociodemographic characteristics.
Chapman and Frank, 2004	Atlanta region (13 counties)	8,592 households	A 1% percent increase in land use entropy index was associated with 0.04% decrease in annual household VMT.	Controlling for sociodemographic characteristics.
Stevens, 2017	U.S.	Meta-analysis of 15 studies	A 1% increase in land use mix was associated with a 0.03% decrease in VMT or a 0.11% increase after accounting for residential self-selection.	Controlling for socio-demographic characteristics; 2 studies controlled for residential self-selection.

3.7 Delivery hubs

Strategies to reduce the impact of package deliveries, including centralized delivery locations, can lead to fewer delivery trips and shorter trip distances. We used the following search terms with indicated results to identify studies investigating the impact of delivery hubs on VMT and driving.

- "Last-mile delivery" and "driving" (with 11,400 search results)
- "Last-mile delivery optimization" and "VMT" (with 12,300 search results)
- "Last-mile delivery optimization" (with 96 search results)
- "delivery hub" and "VMT" (with 8 search results)

Our search did not yield any empirical studies exploring the impact of delivery hubs on VMT, though a few studies are suggestive of the potential impact of delivery hubs on VMT. Ballare and Lin (2020) investigated the use of microhubs (conveniently located sites where customers can pick up their deliveries) and crowdshipping (a method of delivering packages that uses local delivery services) for last-mile delivery in a hypothetical 15-square mile service area, finding that microhubs and crowdshipping significantly reduce VMT, the number of trucks and crowdshippers dispatched, total daily operating costs, and total fuel consumption.

Research that compares the VMT implications of on-line shopping to that of in-store shopping provides additional insights. A study comparing carbon emissions resulting from last-mile delivery with customer pickup for conventional shopping and e-commerce-based online retailing in suburban Ohio and Pennsylvania found that delivery options from two stores emit more GHG emissions than customer pick-ups (Brown and Guiffrida, 2014). Goodchild et al. (2018) used an analytical model to assess VMT and carbon emissions for various goods delivery scenarios, finding that delivery trucks provide emissions benefits when customer density is high and the delivery trucks have similar emissions profiles to passenger vehicles.

Simulation studies are suggestive of the potential for delivery strategies to reduce VMT. For example, a feasibility study for last-mile synergies between passenger and freight transport in Columbus, Ohio proposed a collaborative scheme between private and public transportation for parcel delivery and used simulations to show that it resulted in significant reductions in GHG emissions and VMT compared to the currently applied truck-based delivery system, particularly in areas with concentrated demand in and access to public transportation (Pternea et al., 2018).

3.8 Improving jobs/housing balance

Having access to employment opportunities near residential locations can reduce commute trip length and lead to lower VMT. Searching Google Scholar, we looked for the studies that investigated the impact of job/housing balance on VMT and driving using the following search terms with results as indicated:

- "Job housing balance" and "VMT" (with 404 search results)
- "Job housing balance" and "driving" (with 839 search results)
- "Job housing balance" and "travel behavior" (with 706 search results)

We screened over 80 studies and reviewed nine studies fully. Table 23 summarizes our findings from the five studies that included elasticities. All report the expected negative association between jobs/housing balance on VMT after controlling for other factors, though the effects were small. The largest effect was found in a Bay Area study that used the number of jobs within 4 miles of one's residence in the same occupational category as the resident (Cervero & Duncan, 2006). Other studies in the U.S. context also point to the possibility that improving jobs/housing balance and access to jobs within a shorter distance has the potential to reduce VMT (Boarnet and Wang, 2019; Jin, 2019). A meta-analysis by Stevens concluded that jobs/housing balance had no effect on VMT after controlling for residential self-selection, the possibility that people who are inclined to drive less choose to live in areas with a better balance of jobs and housing.

Table 23. Summary of literature review for jobs/housing balance.

Study	Study area	Sample Size	Effect Size	Note about study
Lee and Lee, 2020	U.S. urbanized areas	121 areas	A 1% increase in job-housing balance index was associated with a 0.01% to 0.02% decrease in annual household VMT.	Controlling for sociodemographic characteristics
Boarnet and Wang, 2019	LA CSA	14,877 households	A 1% increase in job accessibility index was associated with 0.15% decrease in annual household VMT.	Controlling for household characteristics
Bento et al., 2005	U.S.	114 urbanized areas	A 1% increase in job-housing balance was associated with a 0.06% decrease annual VMT per household.	Job-housing balance measured using a Lorenz curve.
Cervero and Duncan, 2006	SF Bay Area	16,000 households	A 1% increase in jobs within 4 miles of home was associated with a 0.3% reduction in household VMT.	Controlling for household characteristics
Stevens, 2017	U.S.	Meta-analysis of 8 studies	Jobs-housing balance was not associated with VMT after accounting for residential self-selection.	

4. Road management mitigation measures

We assessed the empirical evidence for five types of mitigation measures in the road management category. These measures, shown in Table 24, were prioritized based on interest scores gathered from the project advisory panel. Some of these measures are included in prior reviews—the CARB SB375 Policy Briefs, the CAPCOA GHG Handbook, and Caltrans' Mitigation Playbook—as indicated.

One form of roadway management was beyond the scope of this project and is not included in this report: "managed lanes" with pricing and/or occupancy restrictions, such as high-occupancy vehicle lanes and high-occupancy toll (HOT) lanes. In general, additions of such lanes would induce VMT and would themselves require mitigation. Projects that convert general purpose lanes to managed lanes could reduce VMT if they clearly reduce throughput, e.g., through sufficient pricing, and are well enforced. The effects of managed lanes are discussed in Volker and Handy (2022) and Manville (2024).

To identify studies on the impact of these measures on driving (using vehicle-mile-traveled, vehicle-kilometer-traveled, or GHG emission reduction metrics), we searched Google Scholar for relevant studies using one or more search terms for each measure. We screened the results by scanning the title, abstract, and/or other available summaries. We then reviewed the full text of the studies that appeared to be relevant after the screening. We also screened the references from those papers to identify other relevant studies, and we used Google Scholar to find more recent papers citing the studies and included the more recent articles if they met the inclusion criteria. Studies included in the review had the following characteristics:

- Included VMT, VKT, or GHG emissions as a dependent variable,
- (Preferably) used empirical research methods rather than simulation models,
- (Preferably) reported quantitative results,
- Was posted on the Internet or available through the University of California library. .

Table 24. List of road management mitigation measures with research priorities.

Measures	Interest Score (of 4)	Highest interest percentage	CARB briefs	CAPCOA	Mitigation Playbook
Congestion pricing	3.62	75%	X*		X
Road diets/ complete streets	3.5	56%			X
Local network connectivity	3.43	50%	X	X*	X
Traffic calming	3.25	37%	X		
Curb management	2.62	6%			

*indicates a similar measure.

4.1 Congestion pricing

Congestion pricing imposes a higher price on driving at congested times, thereby shifting some driving to off-peak periods and potentially to other modes. We searched Google Scholar using the following terms with results as indicated.

- "congestion pricing" and "VMT" (with 1,420 search results)
- "congestion pricing" and "driving" (with 8,000 search results)
- "Road pricing" and "driving" (with 8,490 search results)
- "cordon pricing" and "driving" (with 757 search results)
- "road user pricing" and "driving" (with 180 search results)

Most of the empirical studies were from an international context, as congestion pricing has been implemented in only a limited way in the U.S. (e.g., on tolled bridges). A literature review on different forms of congestion pricing, such as pay-as-you-drive, distance-based, and congestion-based pricing, in 21 international areas found that pay-as-you-drive pricing could reduce CO2 emissions by 8%-12% (Cavallaro et al. 2018). Results from international studies include the following:

- Odesk and Brathen (2008) looked at 19 road segments before and after toll implementation in Norway. While elasticities between traffic counts and the price varied depending on the location, characteristics of the project, and road type, the average elasticity for short-term impact (a year after toll implementation) was - 0.45, while the long-run (more than a year) elasticity was -0.82 (Odesk and Brathen, 2008).
- A study evaluating congestion pricing in Stockholm, London, and Milan found wide variation in annual changes in traffic volume across the cases as differences in the rate of shifting from driving to transit: London saw a 10 percent increase in transit ridership, while ridership at rail stations in Milan increased by 12.5 percent; Stockholm saw an elasticity of -0.85 for commuters who switched to public transport (Croci, 2016). This study concluded that the elasticities of car travel in response to congestion charges are significantly higher than the elasticities in response to fuel price.
- A study of congestion pricing in Sweden compared the performance of this program in two big cities: Stockholm and Gothenburg (Börjesson et al., 2018). The reported price elasticities for traffic volumes within the cordon pricing areas were -0.28 and -0.16 for Stockholm and Gothenburg, respectively, though the elasticities were considerably higher when the program first started.
- An evaluation of London's congestion charges showed that implementing tolls was associated with lower traffic counts, even on untolled roads during rush hours (Herzog, 2023).

Simulation studies are suggestive of the potential impact of congestion pricing on VMT in the U.S. A simulation study by Baghestani et al. (2020) explored the potential impact of various cordon pricing schemes in New York CBD. They concluded that a $20 fee for entering the central business district would result in an increase in transit ridership of 6% and a decrease in single-occupant vehicles and taxi trips by 30% and 40%, respectively (Baghestani et al., 2020). Another simulation analysis for five metropolitan areas in the U.S. found that the impact of tolling on VMT for commuters, who have a relatively high value of time (VOT) would be less than for non-commuters, who tend to have lower VOT (Mishra et al., 2013).

4.2 Road diets/complete streets

Road diets and complete street programs, which involve reallocating road space, can promote a shift to modes other than driving. We searched Google Scholar using the following terms with results as indicated.

- "road diet" and "VMT" (with 904 search results)
- "road diet" and "driving" (with 904 search results)
- "complete streets" and "VMT" (with 952 search results)
- "complete street" and "driving" (with 1830 search results)

Reviewed studies focused on the impact of changing the streetscape and reallocating the road space on mode choice, equity, safety, travel speed, capacity, and crashes.

Schlossberg et al. (2013) reviewed 25 complete street projects from around the U.S., including different types of improvements, such as speed controls, and adding/ improving bicycle, pedestrian, and transit facilities by reducing the traffic lanes and lane reconfigurations. Among the projects that reported before and after average daily traffic data, the majority reported reduced average daily traffic (ADT) numbers after the implementation. The reduction in ADT could potentially indicate lower VMT depending on the degree to which vehicle trips were eliminated rather than simply shifting to other streets.

Other studies also show that road diets lead to an increase in walking and biking and a decrease in vehicles on that street. Shu et al. (2014) studied the impact of Ocean Park Boulevard retrofit in Santa Monica, CA, on air pollutants and active transportation trips. After the retrofit, which included reducing one of the traffic lanes, widening the sidewalk, and repainting bike lanes, the number of pedestrians increased by 37%, the number of bicyclists remained the same, and ultrafine particle emission decreased by 26%, though traffic counts in the segment remained the same. A study in Davis, California, reported a 243% increase in bicyclists using a major arterial following a road diet project but no increase in travel times for vehicles; this study did not determine whether bicyclists had shifted from other streets rather than shifting modes (Gudz et al., 2016). Sallaberry (2000) reported that after the reconfiguration of Valencia Street in San Francisco from 4 lanes to two lanes and bike lanes, PM peak hour bike trips increased by 144 percent and vehicle traffic dropped by 10 percent on Valencia Street but redistributed to other streets. These studies do not, however, document the impact on total VMT.

International studies provide evidence of the potential impact of a reduction in vehicle capacity on vehicle travel. A study of Centre Bridge in Calgary, Alberta, Canada, showed that closing the bridge to vehicular traffic for 14 months resulted in a net reduction in daily vehicle trips of 4.4% for all trips inbound to the city center (Hunt et al., 2002). Almost 92 percent of automobile users reported that they continued their trips via automobile during the closure. A Norwegian study evaluated the performance of temporary capacity reduction of a main road tunnel in Oslo, a city with good alternatives to driving (Tennøy and Hagen, 2021). The closing of two lanes out of four for 14 months led to a reduction in traffic volume of 24-36% in rush hours and 23% per day. Although this result does not directly translate into a reduction in the total VMT in the area, a follow-up survey of public businesses located within the borders of Oslo municipality and the eastern parts of the neighboring municipality showed that 50% of respondents changed their mode of commute during the lane closure.

Often the concern with such projects is that traffic congestion will worsen. Cairns et al. (2002) report on a study of 70 case studies from eleven countries in which road space was reallocated from vehicles to other modes. They conclude that traffic congestion following the reallocation is rarely as bad as expected beforehand, either because vehicle trips disperse to other routes or disappear altogether. Indeed, an analysis of twelve of the case studies shows that traffic levels, measured in terms of vehicle counts, can decline following the intervention, although the results were inconclusive as to the overall effect across the cases. The authors conclude, "in half the cases, over 11% of the vehicles which were previously using the road or the area where roadspace for general traffic was reduced, could not be found in the surrounding area afterwards" (pg. 16). A survey of transportation experts found that 90% agree that at least in some circumstances, traffic levels in the local area decline following the reallocation of road space. Reductions in vehicle counts are likely to mean a reduction in VMT, though the effect on VMT depends on the share of trips that disappear (rather than dispersing to other routes) and the length of these trips.

4.3 Local network connectivity

Improving the connectivity of the local network can reduce travel distances, potentially leading to direct decreases in VMT and also encouraging a shift to walking and bicycling. We searched Google Scholar using the following terms with results as indicated.

- "local street connectivity" and "VMT" (with 21 search results)
- "local street connectivity" and "driving"(with 36 search results)
- "network connectivity" and "VMT" (with 710 search results)
- "street network connectivity" and "driving" (with 554 search results)
- "intersection density" and "VMT" (with 874 search results)
- "block length" and "VMT" (with 181 search results)

We screened about 150 related results by reviewing their abstract to determine if they were relevant to our review, summarized in Table 25. Most of the reviewed studies included intersection density and block size (the converse of intersection density) as measures of connectivity, as one among a set of built environment factors. These studies provide strong evidence of a relationship between street network connectivity and travel behavior, including VMT and vehicle ownership. A meta-analysis of four studies by Stevens (2017) found that a 1% increase in the percent of four-way intersections is associated with a 0.06% decrease in VMT.

Simulation studies are suggestive of the impact of connectivity on VMT. Zlatkovic et al. (2019) used simulation analysis to explore the impact of intersection density and connectivity index on peak hour (three-hour) VMT. They concluded that the effect of connectivity on peak hour VMT varies between urban, suburban, and rural contexts but was associated with less VMT in all cases (-1% to -52.2%). Another simulation study by Sardari et al. (2018) analyzed more than 330 metropolitan areas in 16 states and found an elasticity of -0.13 for daily VMT per driver and intersection density.

Table 25. Summary of literature review for local network connectivity.

Study	Study area	Sample Size	Effect size/impact	Note about study
Ding et al., 2017	Baltimore metropolitan area	2,366 persons	A 1% increase in intersection density was associated with a 0.14% decrease in commute trips and a 0.05% decrease in non-commute trips.	Explored the effect as a package of built environment factors.
Ewing et al., 2016	Greater Salt Lake region, Utah	962 households	The cumulative impact of built environment was twice the effect of residential preferences.	Included density of 3-way and 4-way intersections.
Hong et al., 2014	Seattle metropolitan area	4,746 households	Living in areas with a more connected street network (number of 4-way intersections) was associated with fewer non-work trips.	Controlling for socio-demographic characteristics.
Wang et al., 2013	LA county	4,631 persons	Having high four-way intersection density areas was associated with more non-motorized trips.	Explored the effect as a package of built environment factors.
Zhang et al., 2012	4 U.S. cities	4,746 households	A 1% increase in block size was associated with a 0-0.1% decrease in VMT depending on the city.	Controlling for socio-demographic characteristics, density, land-use mix, distance from CBD.
Nasri and Zhang, 2012	6 Metropolitan areas in the U.S.	Around 17,000 households	A 1% increase in block size was associated with a 0.74% increase in VMT.	Controlling for socio-demographic characteristics.
Liu and Shen, 2011	Baltimore metropolitan area	3,519 households	Urban form, including intersection density, did not have a statistically significant relationship with annual VMT.	Controlling for socio-demographic characteristics.
Stevens, 2017	U.S.	Meta-analysis of 15 studies	A 1% increase in the number of four-way intersections was associated with a 0.06% decrease in VMT. A 1% increase in intersection/street density was associated with a 0.14% decrease in VMT.	Controlling for sociodemographic characteristics.

4.4 Traffic calming

Traffic calming, involving the use of physical measures to reduce driving speeds and improve conditions for other street users, can encourage a reduction in vehicle trips. We searched Google Scholar using the following terms with results as indicated.

- “traffic calming” and “driving” (with 1,470 search results)
- “traffic calming” and “VMT" (with 16,200 search results)
- “roundabout” and “VMT” (with 569 search results)
- “speed control” and “VMT” (with 759 search results)
- “traffic calming” and “average daily trips” (with 81 search results)
- “traffic calming” and “benefits” (with 21,100 search results)

We did not find studies that directly examined the impact of traffic calming measures on VMT or driving. Most of the screened studies focused on how traffic calming improvements impact safety, pedestrian trips, health, travel speed, emissions, and traffic counts, which could potentially lead to a lower VMT. The traffic calming strategies that were mentioned in the screened studies include sidewalk widening, roundabouts, bulb-outs, middle islands, pedestrian crossings, stop signs, bike lanes, speed bumps, and raised intersections. Patel (2021), for example, examined the effects on traffic volumes as well as traffic speeds, collision frequency, and collision severity of speed humps, bike lanes, partial closures, and stop signs on residential streets in Los Angeles. The impact of bike lanes is included in this project's Active Transportation category.

4.5 Curb management

Designating curbsides for purposes other than parking can improve conditions for transit, bicycling, and other modes. We searched Google Scholar using the following terms with results as indicated.

- “Curb management” and “driving” (with 270 search results)
- “Curb management” and “VMT" (with 113 search results)

We did not find studies that directly examined the impact of curb management on VMT or driving. Most of the screened studies focused on the impact of reallocating curb space from parking to transportation network companies (TNCs) and carpooling, bike-share stations, movement zones, and parklets. The studies variously examine outcomes with respect to mode shift to carpool and ridesharing, safety, economic, social, and health benefits (e.g., Sener et al., 2023). The effect of parking management on VMT and driving is reported under the topic of Parking Management.

5. Active transportation measures

In the category of active transportation mitigation, evidence was assessed for five measures. These measures, shown in Table 26, were prioritized based on interest scores garnered from the project advisory panel and the priority given to the measure by staff from the California Air Resources Board (CARB). Most but not all of these measures are included in prior reviews—the CARB SB375 Policy Briefs, the CAPCOA GHG Handbook, and Caltrans' Mitigation Playbook—as indicated.

To identify studies on the impact of these measures on vehicle miles traveled (or relevant correlates), we searched Google Scholar for relevant studies using one or more search terms for each measure. Where applicable, we started our review with existing literature reviews, and then searched Google Scholar for subsequent studies. Additional details on our search and review processes are provided for each measure in the subsequent subsections.

Most studies of the effectiveness of active transportation measures report indirect effects, often bicyclist or pedestrian counts or modal substitution estimates. It is important to note that increases in active travel do not necessarily translate into reductions in VMT. For example, any additional bicycle, scooter, or pedestrian trips could be replacing existing transit or carpool trips, rather than personal automobile trips. However, VMT effects can be estimated where there is reasonable evidence on modal substitution and trip lengths.

Table 26. List of active transportation measures with research priorities.

Measures' categories	Interest Score (of 4)	Highest interest percentage	CARB briefs	CAPCOA	Mitigation Playbook
Bicycle facilities	3.47	59%	X	X	X*
Pedestrian facilities	3.41	53%	X	X*	
Pedestrian amenities	3.17	29%	X		
E-bike incentives	2.76	18%			
Bike share and scooter share	2.75	19%		X	X*

*indicates similar measure

5.1 Bicycle facilities

Bicycle infrastructure measures include providing bicycle paths (class I facilities), bicycle lanes (class II facilities), bicycle routes (class III), and protected bicycle lanes (class IV; also known as cycle tracks), providing end-of-trip facilities (like bicycle parking and showers), and improving (expanding or densifying) the on- and off-street bicycle facility network.

Previous reviews of the empirical literature indicate that bicycling infrastructure generally correlates with increased bicycling levels (Buehler & Dill, 2016; Handy et al., 2014a, 2014b; Mölenberg et al., 2019; Muñoz et al., 2016; Pucher et al., 2010; Schoner & Levinson, 2014).

However, many of the empirical studies are difficult to use for estimating VMT reductions that could be expected from a particular bicycle infrastructure project, as detailed in Volker et al. (2019a). As a result, we focus this review on studies that report results most readily usable to calculate, at the facility level, VMT reductions associated with bicycle infrastructure improvements. Those most applicable results include bicycle counts before and after installation of a facility and information relevant to contextualizing those counts, including modal substitution.

To find relevant studies, we searched Google Scholar using the following query:

- “bicycling” AND (“ridership” OR “counts” OR “substitution” OR “before-and-after” OR “vehicle miles traveled” OR “VMT”) (with 7,930 search results)

We screened about 360 total records by scanning the title, abstract, and/or other available summary. We stopped screening once we reached 100 consecutive irrelevant records. We also reviewed the reference lists from the selected sources to identify additional studies that did not appear in our web searches or previous literature reviews. We excluded studies not written in English and we focused on studies in the United States.

Table 27 summarizes the facility-level studies that report changes in bicycle ridership after installation of class I, class II, class III, or class IV bicycle facilities.

Table 27. Before/after bike counts – Class I, II, III, or IV facilities.

Study	Study Area	Facility Type	Facility Length	Impact on Ridership	Notes
Duggan (2021)	New York City, New York	Class IV	1 mile	+88%	
Sam Schwartz (2021)	Seattle, Washington	Class III	Not reported	+473%	Roadway modifications styled as a "greenway" rather than a bicycle boulevard
Sam Schwartz (2021)	Tucson, Arizona	Class III	Not reported	+145%	
Sam Schwartz (2021)	Seattle, Washington	Class III	Not reported	+129%	Roadway modifications styled as a "greenway" rather than a bicycle boulevard
Sam Schwartz (2021)	Seattle, Washington	Class III	Not reported	+116%	Roadway modifications styled as a "greenway" rather than a bicycle boulevard
Sam Schwartz (2021)	Portland, Oregon	Class III	Not reported	+98%	Roadway modifications styled as a "greenway" rather than a bicycle boulevard
Sam Schwartz (2021)	Tucson, Arizona	Class III	Not reported	+91%	
Sam Schwartz (2021)	Chicago, Illinois	Class III	Not reported	+40%	Roadway modifications styled as a "greenway" rather than a bicycle boulevard
Sam Schwartz (2021)	Chicago, Illinois	Class III	Not reported	+25%	Roadway modifications styled as a "greenway" rather than a bicycle boulevard
Sam Schwartz (2021)	Portland, Oregon	Class III	Not reported	+20%	Roadway modifications styled as a "greenway" rather than a bicycle boulevard

Study	Study Area	Facility Type	Facility Length	Impact on Ridership	Notes
Sam Schwartz (2021)	Chicago, Illinois	Class III	Not reported	+6%	Roadway modifications styled as a “greenway” rather than a bicycle boulevard
Matute et al. (2016)	Los Angeles, California; San Francisco, California; Austin, Texas; Chicago, Illinois; Denver, Colorado; Honolulu, Hawaii; Portland, Oregon; Washington, DC	Class I, Class III, Class IV	Not reported	Mean = +86% Median = +48%	Percent change numbers reflect combined data for 10 facilities: two bike paths, two bike boulevards and six cycle tracks
Matute et al. (2016)	Los Angeles, California; San Francisco, California; Austin, Texas; Chicago, Illinois; Denver, Colorado; Honolulu, Hawaii; Portland, Oregon; Washington, DC	Class II	Not reported	Mean = +113% Median = +73%	Percent change numbers reflect combined data for 34 class II facilities across all eight study locations. Found “no relationship” between pre-facility bicyclist volumes and percent ridership change.
Gudz et al. (2016)	Davis, California	Class II	0.8 miles	+160%	Bike lanes were added as part of a road diet
McClain & Peterson (2016)	Oakland, California	Class IV	0.5 miles	+87%	Cycle tracks were added as part of a road diet
Davis et al. (2015)	San Jose, California	Class II	1 mile	+13%	Bike lanes were added as part of a road diet
Dill et al. (2014)	Portland, Oregon	Class III	0.9 to 4.2 miles	+22%	Percentage change reflects combined data for seven facilities. Facility length

Study	Study Area	Facility Type	Facility Length	Impact on Ridership	Notes
					and percent changes not reported for each facility individually
Monsere et al. (2014)	Austin, Texas	Class IV	0.5 miles	+58%	
Monsere et al. (2014)	Austin, Texas	Class IV	0.7 miles	+46%	Two-way cycle track replaced existing bike lanes
Monsere et al. (2014)	Austin, Texas	Class IV	0.4 miles	+126%	Two-way cycle track replaced existing one-way bike lane
Monsere et al. (2014)	Chicago, Illinois	Class IV	1.2 miles	+171%	
Monsere et al. (2014)	Chicago, Illinois	Class IV	0.8 miles	+21%	Replaced existing bike lanes
Monsere et al. (2014)	Portland, Oregon	Class IV	0.8 miles	+68%	Cycle tracks were added as part of a road diet and replaced existing bike lanes
Monsere et al. (2014)	San Francisco, California	Class IV	0.3 miles	+46%	Cycle tracks replaced parking on one side of the street and an existing bike lane on the other
Monsere et al. (2014)	Washington, DC	Class IV	1.12 miles	+65%	Cycle track was added as part of a road diet
Goodno et al. (2013)	Washington, DC	Class II	~1 mile	+>250%	
Goodno et al. (2013)	Washington, DC	Class IV	1.5 miles	+>500%	
Parker et al. (2011)	New Orleans, Louisiana	Class II	3.1 miles	+57%	
Fitzhugh et al. (2010)	Knoxville, Tennessee	Class I	2.9 miles	+189% (median)	Counts did not distinguish between bicyclists and pedestrians

Study	Study Area	Facility Type	Facility Length	Impact on Ridership	Notes
Cohen et al. (2008)	Los Angeles, California	Class I	14 miles	+38%	A couple miles of the bikeway is actually a class II bike lane. Counts did not distinguish between bicyclists and pedestrians.
Sallaberry (2000)	San Francisco, California	Class II	2 miles	+144%	

The studies summarized in Table 27 show that providing class I, class II, class III, and class IV bicycle facilities increases ridership within the same corridor. These results comport with studies that found greater increases in ridership over time in corridors with bicycle facilities than in nearby corridors without bicycle facilities (Fields et al., 2022; Karpinski, 2021). The average percentage increases[3] reported in the studies listed in Table 27 were lowest for class III bike boulevards or greenways (77%), and relatively similar for class I (100%), class II (112%), and class IV (105%) facilities. For class IV facilities, the average increase was noticeably greater (125%) for those not reported to have replaced existing bike lanes. Class IV facilities that replaced existing bike lanes showed an average ridership increase of 61%. Class IV facilities more than a mile long generally showed greater percentage increases in ridership, but the sample sizes are so small that definitive conclusions cannot be drawn about the relationship between facility length and ridership increases. Facility lengths were not reported for most class I, class II, and class III facilities. Bicycle boulevards showed the lowest percentage increase in ridership. The average was 77% across the 19 new Class III bike boulevards or greenways for which (aggregate) ridership change percentages were reported.

Another important factor in determining the VMT impacts of bicycle facilities is automobile substitution—the percentage of the additional bicycle trips that would have otherwise been made by automobile. The rate is generally much lower than the existing automobile mode share in the corridor because most of the “new” cyclists would have also cycled before installation of the new infrastructure, just on a different route. The available evidence on modal substitution comes mostly from intercept surveys on class IV facilities (Matute et al., 2016; Mitra et al., 2017; Monsere et al., 2014; Thakuriah et al., 2012). The evidence indicates that the overall stated substitution rate is around 0.3 (which includes all substitution from automobile trips, transit trips, walking trips, and any other mode for bicyclists who did not bike on the same route prior to bicycle facility installation) and that the automobile substitution rate is about 0.1 (Volker et al., 2019a).

Beyond class I-IV bicycle facilities, other streetscape modifications as well as end-of-trip facilities can also affect bicycling ridership and reduce VMT, though there is less empirical evidence. Shu et al. (2014) studied a “complete streets” retrofit of an arterial in Santa Monica, California that widened the sidewalks, added street furniture, planted new trees, and more clearly demarcated the existing crosswalks and bike lanes. They found no change in bicycle ridership. Lyons et al. (2020) similarly found no significant change in bicycle ridership after an intersection in Salt Lake City, Utah was redesigned to improve safety by, among other things, adding bike boxes, pavement demarcations (painting), and curb protections for bicyclists and pedestrians. By contrast, Barnes and Schlossberg (2013) found that a complete streets retrofit of a street in Eugene, Oregon that actually removed one of the two bike lanes (combining it instead with the vehicular travel lane) increased bicycle ridership by nearly 70% in one direction and nearly 100% in the other direction. With respect to end-of-trip facilities, the best available

[3] Calculated for each class of facilities as the sum of the percentage changes for each facility studied, divided by the number of facilities in that same class. Where only aggregate percentage changes were reported for multiple facilities combined, we applied the reported average change to each of the studied facilities. Other caveats are listed in Notes column, including where the reported counts include both bicyclists and pedestrians.

empirical evidence still appears to be Buehler's (2012) study of bicycle commuting in Washington, DC. They found that commuters with showers, clothes lockers, and free bike parking at work had 4.86 times greater odds of bicycling to work than commuters without those amenities, and that commuters with just bike parking had 1.78 times greater odds of bicycling to work. However, they did not analyze the effect of end-of-trip bicycle facilities on automobile use, so it is difficult to infer how the facilities might affect VMT.

5.2 Pedestrian facilities and amenities

Pedestrian infrastructure measures include providing pedestrian paths (like sidewalks, off-street paths, or crosswalks or other cross-street pathways) and improving the quality of the walking environment via street-level amenities like benches or shade. Previous reviews of the empirical literature indicate that pedestrian infrastructure often correlates with increased walking levels (Fitch et al., 2021; Handy, Sciara, & Boarnet, 2014; Krizek et al., 2009; Owen et al., 2004; Saelens & Handy, 2008; Volker et al., 2019b; Wang et al., 2016). However, increases in walking do not necessarily translate into reductions in VMT, particularly if the additional walking is for recreational purposes rather than utilitarian purposes (e.g., commuting). Even increases in utilitarian walking will not reduce VMT unless it substitutes for automobile travel. As a result, we focused our review on empirical studies that estimate the effect of pedestrian infrastructure on VMT or a related outcome like vehicle trips or automobile mode share. We also reviewed studies that examine the effect of specific pedestrian infrastructure projects, including studies that report before and after pedestrian counts or provide information relevant to contextualizing those counts, like modal substitution rates.

To find relevant studies, we first canvassed the studies cited in other recent literature reviews regarding the travel behavior effects of pedestrian infrastructure (e.g., Fitch et al., 2021; Handy Sciara, & Boarnet, 2014; Krizek et al., 2009; Owen et al., 2004; Saelens & Handy, 2008; Volker et al., 2019b; Wang et al., 2016). We then searched Google Scholar for more recent studies (since 2018) using the following query:

- "sidewalks" AND ("walking" OR "counts" OR "substitution" OR "before-and-after" OR "vehicle miles traveled" OR "VMT") (with >20,000 search results)

We screened hundreds of records by scanning the title, abstract, and/or other available summary. We stopped screening once we reached 100 consecutive irrelevant records. We also reviewed the reference lists from the selected sources to identify additional studies that did not appear in our web searches or previous literature reviews. We excluded studies not written in English and we focused on studies in the United States.

Table 28 summarizes the seven studies we located that examine the effect of pedestrian infrastructure on VMT or a related outcome like vehicle trips or automobile mode share. Two studies found that increased sidewalk coverage in a household's neighborhood was associated with a statistically significant reduction in household VMT (Frank et al., 2011; Guo & Gandavarapu, 2010), with Frank et al. (2011) estimating an elasticity of -0.05 (0.5% reduction in VMT with a 10% increase in sidewalk coverage) in the Seattle region. However, Cervero and

Kockelman (1997) found no statistically significant correlation between sidewalk width and household VMT. And most studies found no statistically significant association between pedestrian infrastructure and automobile mode choice, though Cervero and Kockelman (1997) estimated that increasing the average sidewalk width in a household's neighborhood would increase by 0.9% the probability of that household making a non-work trip by non-personal vehicle modes (shared rides, transit, and non-motorized modes).

Table 29 summarizes the three facility-level studies we located that report changes in pedestrian counts after installation of pedestrian infrastructure. The change in counts range from 10% to 850%, with wide fluctuation between. In addition to the wide variation, it is hard to generalize from these facility-specific studies because the counts from Fitzhugh et al. (2010) do not distinguish between bicyclists and pedestrians, the counts from Boarnet et al. (2005) are specific to children walking to and from school, and the infrastructure changes studied in Barnes and Schlossberg (2013) included more than just widening sidewalks.

Another important factor in determining the VMT impacts of pedestrian facilities is modal substitution—the percentage of the increased walking trips that replace automobile trips. We found a single study that examined the substitution rate of pedestrians using a new pedestrian facility. Thakuriah et al. (2012) found that the auto substitution percentages for five new sidewalks in Chicago ranged from 6.25% to 38.1%, with an approximate average of 21.5%. However, it is unclear if the study's respondent pool included any people who walked the same route before facility installation anyway. If it did, the true auto substitution rate (using as the denominator just those pedestrians who started using the route after facility installation) would be higher.

Table 28. Summary of literature review for VMT-related outcomes of pedestrian infrastructure.

Study	Study area	Sample Size	Pedestrian Infrastructure Measure or Treatment	Effect Type	Effect Size
Cervero & Kockelman (1997)	San Francisco Bay Area region, California	896 households (for VMT model) 1,544 households (for commute mode choice model)	Sidewalk width (average width in respondent's neighborhood – one or two Census tracts)	VMT Commute mode choice Non-commute mode choice	No statistically significant effect on VMT No statistically significant effect on automobile mode choice 0.9% increase in the probability of making a non-work trip by non-personal vehicle modes (shared rides, transit, and non-motorized modes) with a 10% increase in average sidewalk width (0.09 elasticity)
Fan (2007)	Raleigh-Durham-Chapel Hill region, North Carolina	4,937 persons	Sidewalk length (within a 0.25-mile radius of respondent's home)	Person miles traveled (across all modes)	0.2% reduction in daily miles traveled with a 10% increase in sidewalk length (-0.02 elasticity)
Frank et al. (2011)	King County, Washington (cities with sidewalk data)	1,654 households	Sidewalk coverage (ratio of sidewalk length to street length within 1-km radius of respondent's home)	VMT	0.5% reduction in household VMT with a 10% increase in sidewalk coverage (-0.05 elasticity)
Guo & Gandavarapu (2010)	Dane County, Wisconsin	4,974 households	Sidewalk coverage (length of roadway with no sidewalk within 1-mile radius of respondent's home)	VMT	Lower sidewalk coverage was associated with a statistically significant increase in VMT
Kitamura et al. (1997)	San Francisco Bay Area region, California	~1,300 households	Sidewalk presence (within respondent's neighborhood)	Person trips (across all modes)	No statistically significant effect on person trips

Study	Study area	Sample Size	Pedestrian Infrastructure Measure or Treatment	Effect Type	Effect Size
Aziz et al. (2018)	New York City, New York	3,357 persons	Sidewalk width (average width in origin and destination Census tracts)	Commute mode choice	No statistically significant effect on automobile mode choice
Koo et al. (2022)	Atlanta, Georgia	318 trips	Sidewalk coverage (percent of total streetscape within 150-meter radius of trip origin)	Mode choice (walk/non-walk)	No statistically significant effect on mode choice

Table 29. Before/after pedestrian counts.

Study	Study Area	Facility Description	Facility Length	Impact on Pedestrian Activity	Notes
Barnes & Schlossberg (2013)	Eugene, Oregon	Existing facility had, a one-way automobile lane, a two-way bike lane, sidewalks on both sides of the street, and parallel parking on both sides of the street. The street was redesigned to create a combined eastbound vehicular and bike lane, add a one-way contraflow bike lane going westbound, widen sidewalks by 5 feet on both sides, and replace parallel parking with back-in angle parking on one side of the street only.	1 block	+17.4% (mid-block pedestrian crossings)	2-week counts before and after
Boarnet et al. (2005)	Malibu, California	Safe Routes to Schools program-funded installation of a pedestrian pathway of decomposed granite, in a predominately residential area with a “rural character”	Not reported	+10% (total counts)	2-day counts before and after
Boarnet et al. (2005)	Murrieta, California	Safe Routes to Schools program-funded installation of a sidewalk, curb and gutter, in a neighborhood with a mix of residential, commercial and civic land uses	Not reported	+39% (total counts)	2-day counts before and after

Study	Study Area	Facility Description	Facility Length	Impact on Pedestrian Activity	Notes
Boarnet et al. (2005)	El Sobrante, California	Safe Routes to Schools program-funded installation of a sidewalk gap closure, in a suburban neighborhood	Not reported	+66% (total counts)	2-day counts before and after
Boarnet et al. (2005)	Yucaipa, California	Safe Routes to Schools program-funded installation of a sidewalk gap closure, in a neighborhood changing from a rural to suburban character	Not reported	+10% (total counts)	2-day counts before and after
Boarnet et al. (2005)	San Bernardino County, California	Safe Routes to Schools program-funded installation of a sidewalk gap closure	Not reported	+850% (total counts)	2-day counts before and after
Fitzhugh et al. (2010)	Knoxville, Tennessee	Urban greenway in a neighborhood that previously lacked connectivity of the residential pedestrian infrastructure to non-residential destinations was retrofitted with an eight-foot-wide pedestrian and bike path, which connected to nearby retail establishments and schools	2.9 miles	+189% (median of peak two-hour morning, midday and afternoon counts)	2-hour counts taken three times per day on two days before and two days after. Counts did not distinguish between bicyclists and pedestrians.

5.3 E-bike incentives

E-bikes are bicycles that use electric motors to either assist the user in pedaling or propel the bicycle via throttle controlled by the user. Because e-bikes are expensive compared to non-electric bicycles—very few cost less than $1,000—dozens of e-bike incentive programs have been implemented in the U.S. and Canada, most of which take the form of post-purchase cash rebates (Bennett et al., 2022). Owning an e-bike can reduce a household's VMT if they use it to replace trips they would have otherwise made by automobile. Knowing the automobile substitution rate, along with the average number and length of e-bike trips, is thus key to estimating the VMT effects from changes in e-bike ownership. As a result, we focused our review on empirical studies that either directly estimate the effect of e-bike ownership on VMT or estimate related components, like trip generation and modal substitution rates.

To find relevant studies, we first canvassed the studies cited in two recent literature reviews regarding the travel behavior effects of e-bikes (Bigazzi & Wong, 2020; Fitch, 2019). We also obtained lists of relevant literature from two e-bike researchers. Finally, we conducted a forward citation search of the relevant articles on Google Scholar. We excluded studies not written in English and we focused on studies in the United States.

E-bike studies in the U.S. remain sparse—we found only three empirical studies that estimated the effect of e-bike ownership on VMT or related components in the U.S. However, all three studies indicate that e-bike ownership could have a substantial effect on VMT. Johnson et al. (2023), the most recent study, analyzed data from follow-up surveys of nearly 600 people who had purchased an e-bike with assistance from one of three different e-bike rebate programs offered in California (one in San Mateo County, one in Contra Costa County, and one in Humboldt County, offering a maximum rebate of $300-$800, depending on the program). They estimated that the respondents replaced about 35-44% of their VMT with e-bike trips within a month or two of purchasing their e-bike, which translated to a reduction in monthly CO2-equivalent emissions of 12-44 kilograms.

The two other studies both analyzed a survey of 1,796 e-bike owners in the U.S. and Canada, including 402 in California. MacArthur et al. (2018) reported that 49.2% of e-bike owners ride their e-bikes daily, while 42.3% ride weekly, 5.8% ride monthly, 1.8% ride a few times a year, and 0.9% never ride. That averages out to about 200 e-bike trips per year per owner using the conservative assumptions that daily users ride only once per day, weekly users ride only once per week, monthly users ride only once per month, and infrequent users rider only three times per year. MacArthur et al. (2018) also estimated that 64% of the e-bike trips reported by respondents were made for utilitarian purposes, and that e-bikes were much more likely to replace automobiles for utilitarian trips than trips for recreation or exercise. McQueen et al. (2020) estimated that 67.9% of utilitarian e-bike trips replaced automobile trips, and that 72.4% of the person miles traveled for utilitarian e-bike trips replaced automobile travel. They also estimated that the average length of a utilitarian e-bike trip was 4.65 miles. They used those results to estimate that if e-bikes were used for 15% of all person miles traveled in Portland, Oregon, the automobile share of person miles traveled would reduce from 84.7% to 74.8%, reducing CO2 emissions from passenger travel by 12%.

5.4 Bike share and scooter share

Shared micromobility includes both bike share and scooter share programs, which are often operated at a city or sub-city level. These programs provide bicycles or scooters for short-term rental. They are usually available to both casual users and members (membership generally provides a monetary discount for program use). Bike share programs can be either docked (where the bike must be picked up from and returned to a docking station in the service area) or dockless (where bikes can be parked—and picked up—anywhere in the service area). They can also provide either human-powered pedal bikes or e-bikes (bikes that use electric motors to either assist the user in pedaling or propel the bicycle via throttle controlled by the user). Scooter share programs are generally dockless and employ electric kick scooters. As of 2023, at least 421 cities in North America have a bike share or scooter share system, including 27% that have both bike and scooter share programs, 37% that just have a bike share program, and 36% that only have a scooter share program (North American Bikeshare Association, 2023). Most (62%) bike share programs now provide e-bikes, while 38% only have pedal bikes (North American Bikeshare Association, 2023).

Bike and scooter share programs can reduce VMT if program participants use it to replace trips they would have otherwise made by automobile. Knowing the automobile substitution rate, along with the frequency and length of bike and scooter share trips, is thus key to estimating the VMT effects from changes in shared micromobility programs. As a result, we focused our review on empirical studies that either directly estimate the effect of bike or scooter share programs on VMT or estimate related components, like trip length and modal substitution rates.

To find relevant studies, we first canvassed the studies cited in recent literature reviews regarding the travel behavior effects of shared micromobility (e.g., Fishman et al., 2013; Fukushige et al., 2023; Meroux et al., 2023; Ricci, 2015; Shaheen & Cohen, 2019b; Shaheen et al., 2013; Wang et al., 2023). We also obtained lists of relevant literature from two shared mobility researchers. Finally, we conducted a forward citation search of the relevant articles on Google Scholar. We excluded studies not written in English and we focused on studies in the United States.

The simplest way to estimate the effect of bike and scooter share use on VMT is to multiply the average trip length by the automobile substitution rate—the percentage of shared micromobility trips that would have been otherwise made in an automobile, which is usually self-reported retrospectively by users. Average trip lengths for both bike and scooter share are usually between one and two miles (e.g., Babagoli et al., 2019; Buehler et al., 2021; Fishman et al., 2014; Meroux et al., 2023; Noland, 2019; Portland Bureau of Transportation, 2019; Sanders et al., 2022; Wang et al., 2023). For example, the North American Bikeshare Association (2023) reported that average trip lengths were 1.4 miles for pedal bike share programs in North America, 2.0 miles for bike share programs with e-bikes, and 1.2 miles for scooter share programs.

Table 30 and Table 31 summarize the automobile substitution rates reported in the studies we reviewed on bike share and scooter share programs, respectively. The automobile substitution rate for bike share trips ranges from 11% to 37% across the eight studies that estimated it. The most comprehensive assessment—using data from 22 different programs or cities—estimated an automobile substitution rate of 37% across all types of bike share and scooter share programs (North American Bikeshare Association, 2023). A recent comprehensive literature review of scooter share studies found a much greater range in the automobile substitution rate for scooter share trips—6-71% across the 20 U.S. studies that did not allow survey respondents to select multiple substitution modes for their e-scooter trips (Wang et al., 2023). However, 17 of those 20 studies estimated substitution rates between 32% and 49%. Meroux et al. (2023) similarly calculated an average substitution rate of 40% across nine U.S. studies.

An increasing number of studies have also gone the extra step and directly estimated the effect of shared micromobility use on VMT, often using trip length and modal substitution data. Table 30 and Table 31 summarize the relevant studies we located for bike share and scooter share programs, respectively. Fishman et al. (2014) was one of the first studies to directly estimate the effect of bike share use on VMT. Using average trip lengths and user-reported modal substitution rates, they estimated that each trip with the docked pedal bike share programs in Washington, DC and the Twin Cities region in Minnesota reduced 0.14 and 0.41 VMT, respectively. However, those numbers decreased to 0.08 and 0.21 VMT after accounting for the VMT associated with operation of the bike share programs. More recently, Fitch et al. (2021) found an inconclusive effect of the former dockless e-bike share program in California's Sacramento region, though they relied on user-reported VMT estimates. Fukushige et al. (2023) revisited the same Sacramento-area program using a more robust data set and statistical approach, and estimated an average reduction of 0.79 miles per bike share trip on weekdays, accounting for both the added VMT associated with operation of the bike share program and the reduced VMT from deadheading and searching associated with foregone ride share trips. One likely reason their VMT reduction estimate was greater than either of Fishman et al.'s (2014) estimates is that Fukushige et al. (2023) did not simply use average trip length—they estimated the length of automobile-replacing trips, which is generally greater than the average bike share trip length. Another reason is that Fukushige et al. (2023) accounted for reduced VMT from deadheading and searching associated with foregone ride share trips. A third potential reason is that bike share users might be more likely to replace automobile trips with e-bikes than with regular pedal bikes (as in the two programs studied by Fishman et al., 2014).

For scooter share programs, the Portland Bureau of Transportation (2019) used average trip length and user-reported automobile substitution rates to estimate a reduction of 0.43 VMT per trip. However, as with bike share, scooter share trip distances are correlated with automobile substitution—longer scooter trips are more likely to have been otherwise completed by an automobile (Chen, 2021; Meroux et al., 2023). Meroux et al. (2023) corrected for this by estimating the scooter share's effect on VMT using the average length of trips that users reported (at the end of their trips) they would have otherwise made by automobile. They estimated reductions of 0.58 VMT per trip in San Francisco, 0.66 VMT per trip in Portland, 0.68 VMT per trip in Tampa, and 0.54 VMT per trip in Washington, DC. However, they did not account for the VMT associated with operation of the scooter share programs, which would offset the VMT reductions to some degree.

Table 30. Summary of literature review for VMT-related outcomes of bike share.

Study	Study area	Sample Size	Bike Share Program or Measure	Effect Type	Effect Size
Choi et al. (2023)	United States (all urbanized areas)	177 urbanized areas	Bike share programs (all types)	VMT	Urbanized areas with bike share programs had a statistically significant reduction in VMT per capita Urbanized areas with both scooter share and bike share programs had an even greater statistically significant reduction in VMT per capita
Fishman et al. (2014)	Washington, DC	5,287 persons	Docked bike share programs (only regular bikes)	VMT Modal substitution Trip length	Total annual (2012) reduction of 276,005 VMT (0.14 VMT/bike share trip) across all user trips (except trips <2 minutes or >3 hours). Net reduction of 151,174 VMT (0.08 VMT/trip) after accounting for the VMT associated with operation of the bike share program. 13% reported substitution for an automobile trip (7% for private automobile trips and 6% for taxi trips). Note: Data are the same as in LDA Consulting (2012). 1.9 miles on average
	Twin Cities region, Minnesota	685 persons	Docked bike share programs (only regular bikes)	VMT Modal substitution Trip length	Total annual (2012) reduction of 110,995 VMT (0.41 VMT/bike share trip) across all user trips (except trips <2 minutes or >3 hours). Net reduction of 56,314 VMT (0.21 VMT/trip) after accounting for the VMT associated with operation of the bike share program. 19 % reported substitution for an automobile trip (private automobile) 2.2 miles on average

Study	Study area	Sample Size	Bike Share Program or Measure	Effect Type	Effect Size
Fitch et al. (2021)	Sacramento region, California	Varies based on sample and model	Dockless e-bike share program	VMT Modal substitution	Inconclusive effect of e-bike sharing on either weekly personal VMT or total annual household VMT 35% reported substitution for an automobile trip (private automobile or ride share)
Fukushige et al. (2023)	Sacramento region, California	142,936 trips	Dockless e-bike share program	VMT Modal substitution	Average reduction of 0.79 miles per bike share trip on weekdays, accounting for both the added VMT associated with operation of the bike share program and the reduced VMT from deadheading and searching associated with foregone ride share trips. Average reduction was 0.58 miles per bike share trip on weekdays without accounting for bike share operational VMT or ride share-related deadheading and searching. 28% estimated substitution rate for an automobile trip (private automobile or ride share) on weekdays
Bartling et al. (2019)	Chicago, Illinois (Lincoln Park neighborhood)	297 persons	Docked bike share program (only regular bikes)	Modal substitution	16.83% reported substitution for a single-passenger vehicle trip (private automobile, taxi, or commercial ride share)
Krauss et al. (2022)	Seattle, Washington	690 persons	Dockless e-bike share program	Modal substitution	21.9% reported substitution for an automobile trip (9.3% for private automobile trips, including personal car, car share, motorcycle, and moped trips; 12.6% for taxi or ride share trips)

Study	Study area	Sample Size	Bike Share Program or Measure	Effect Type	Effect Size
Langford et al. (2013)	Knoxville, Tennessee (University of Tennessee campus)	37 persons	Docked e-bike share program	Modal substitution	11% reported substitution for a “car” trip
LDA Consulting (2012)	Washington, DC	5,464 persons	Docked bike share program (only regular bikes)	Modal substitution	13% reported substitution for an automobile trip (7% for private automobile trips and 6% for taxi trips)
North American Bikeshare Association (2023)	North America	22 programs or cities	Bike and scooter share programs (all types)	Modal substitution	37% reported substitution for an automobile trip (25% for private automobile trips, including carpooling, and 12% for taxi and ride share trips)
Martin et al. (2013)	Washington, DC	5,248 persons	Docked bike share programs (only regular bikes)	Modal substitution	41% of respondents reported driving an automobile less due to their use of bike share in Washington, DC
	Twin Cities region, Minnesota	1,230 persons	Docked bike share programs (only regular bikes)	Modal substitution	53% of respondents reported driving an automobile less due to their use of bike share in the Twin Cities

Table 31. Summary of literature review for VMT-related outcomes of scooter share.

Study	Study area	Sample Size	Scooter Share Program or Measure	Effect Type	Effect Size
Choi et al. (2023)	United States (all urbanized areas)	177 urbanized areas	E-scooter share programs	VMT	No statistically significant effect on VMT per capita (average in the urbanized area) from scooter share programs alone Urbanized areas with both scooter share and bike share programs had a statistically significant reduction in VMT per capita
Meroux et al. (2023)	San Francisco, California	1,996 trips	E-scooter share program	VMT Modal substitution	Reduction of 0.58 VMT/trip (distance share method) Reduction of 0.51 VMT/trip (trip share method) 30% reported substitution for an automobile trip (private automobile or ride share; distance share method) 26% reported substitution for an automobile trip (private automobile or ride share; trip share method)
	Portland, Oregon	2,636 trips	E-scooter share program	VMT Modal substitution	Reduction of 0.66 VMT/trip (distance share method) Reduction of 0.60 VMT/trip (trip share method) 33% reported substitution for an automobile trip (private automobile or ride share; distance share method) 30% reported substitution for an automobile trip (private automobile or ride share; trip share method)

Study	Study area	Sample Size	Scooter Share Program or Measure	Effect Type	Effect Size
	Tampa, Florida	2,027 trips	E-scooter share program	VMT Modal substitution	Reduction of 0.68 VMT/trip (distance share method) Reduction of 0.67 VMT/trip (trip share method) 33% reported substitution for an automobile trip (private automobile or ride share; distance share method) 33% reported substitution for an automobile trip (private automobile or ride share; trip share method)
	Washington, DC	5,312 trips	E-scooter share program	VMT Modal substitution	Reduction of 0.54 VMT/trip (distance share method) Reduction of 0.50 VMT/trip (trip share method) 32% reported substitution for an automobile trip (private automobile or ride share; distance share method) 29% reported substitution for an automobile trip (private automobile or ride share; trip share method)
Portland Bureau of Transportation (2019)	Portland, Oregon	700,369 trips (trip data) 2,170 persons (survey data)	E-scooter share program	VMT Modal substitution	Reduction of 0.43 VMT/trip 34% reported substitution for an automobile trip (private automobile or ride share)

Study	Study area	Sample Size	Scooter Share Program or Measure	Effect Type	Effect Size
Chen (2021)	Atlanta metropolitan region, Georgia; Phoenix metropolitan region, Arizona; Austin metropolitan region, Texas; and Tampa Bay metropolitan region, Florida	295 persons	E-scooter share programs	Modal substitution	5+ miles (last trip length): 59% reported substitution for an automobile trip (private automobile, taxi, or commercial ride share) 3-4 miles: 46% reported substitution for an automobile trip 1-2 miles: 32% reported substitution for an automobile trip <1 mile: 13% reported substitution for an automobile trip
North American Bikeshare Association (2023)	North America	22 programs or cities	Bike and scooter share programs (all types)	Modal substitution	37% reported substitution for an automobile trip (25% for private automobile trips, including carpooling, and 12% for taxi and ride share trips)
Wang et al. (2023)	Global	33 studies (including 22 in the U.S., and 5 in California). Sample size within each study varies.	E-scooter share programs	Modal substitution	5-46% reported substitution for a personal automobile trip, including carsharing and carpooling (U.S. studies only). 6-51% reported substitution for a taxi or ride share trip (U.S. studies only) Combined substitution rate (personal automobile + taxi and ride sharing) is between 32-49% in most cases (17 of the 20 U.S. studies that did not allow survey respondents to select multiple substitution modes for their e-scooter trips)

Study	Study area	Sample Size	Scooter Share Program or Measure	Effect Type	Effect Size
Asensio et al. (2022)	Atlanta metropolitan region, Georgia	47,477 trips	E-scooter share ban between 9pm-4am	Travel time	Statistically significant increase in travel time during the ban, which was interpreted as a statistically significant substitution between e-scooters and personal automobile use

6. Parking management measures

Evidence was assessed for two measures in the parking management category, shown in Table 32. Both measures are included in prior reviews—the CARB SB375 Policy Briefs, the CAPCOA GHG Handbook, and Caltrans' Mitigation Playbook—as indicated.

To identify studies on the impact of these measures on transit ridership or vehicle miles traveled, we searched Google Scholar for relevant studies using one or more search terms for each measure. Where applicable, we started our review with existing literature reviews, and then searched Google Scholar for subsequent studies. We included both peer-reviewed studies and high-quality "gray" literature. We then focused on empirical studies based on observed data, rather than theoretical studies or those that use simulation modeling. We also focused on studies in the United States. Additional details on our search and review processes are provided for each measure in the subsequent subsections.

Most studies of the effectiveness of parking management measures report indirect effects, often the effect on parking space demand, commute mode choice, or vehicle ownership. Parking demand can be measured in multiple ways, including parking occupancy (the percentage of time that a given spot is occupied), parking dwell time (how long vehicles remain parked), and parking volume (the total number of vehicles using a given spot, which should equal the parking occupancy divided by the average dwell time). We focused on parking volume because it can be the most easily translated into vehicle trips and thence VMT (vehicle trips * by average trip length = VMT).

Table 32. List of parking management measures with research priorities.

Measures' categories	Interest Score (of 4)	Highest interest percentage	CARB briefs	CAPCOA	Mitigation Playbook
Parking pricing	2.93	25%	X	X	X
Parking restrictions	2.81	19%	X	X	X

*indicates similar measure

6.1 Parking pricing

We reviewed three measures related to pricing parking: pricing workplace parking (including cash-out programs), pricing on-street parking, and adaptive parking pricing. We started with the literature cited in previous reviews and meta-analyses on the three subtopics of interest, and then searched Google Scholar for relevant articles that have been published since those reviews using the following search terms:

- "parking pricing" AND ("VMT" OR "ownership" OR "volume" OR "demand") (with >5,000 search results)

While an increasing number of empirical studies have examined the effect of pricing policies on parking demand, very few have focused on the impact of parking pricing on VMT directly. Another challenge is that parking pricing is often included as one component of a bundle of travel demand management (TDM) and infrastructure measures, making separate evaluation difficult. The nine most relevant results that isolate the effect of parking pricing are summarized in Table 33.

Most of the empirical literature focuses on pricing workplace parking, and is consistent in showing reductions in VMT or related outcomes, like vehicle counts, drive-alone mode share, or parking volume. With respect to VMT, Shoup (1997) examined the effects of parking cash-out programs at seven sites in Los Angeles County, California, and found a 12 percent reduction in commute VMT/employee. A more recent study found that a tax increase on parking providers in Chicago, Illinois reduced vehicle counts on the major roadways used to access the central business district by 3.1% about four months after the tax increase, which equated to a short-term elasticity of about -0.3 (Miller & Wilson, 2015). The study also found evidence of increased transit use and carpooling during the same time period, suggesting some modal substitution. However, the study did not assess longer-term effects, including whether vehicle counts rebounded in the long run (with travelers incentivized to drive more by the initial reduction in congestion in the first few months after the tax increase). A number of other studies also indicate that pricing workplace parking reduces regional VMT, but they rely on simulation modeling rather than empirical analysis and so are not included in Table 33 (Deakin et al., 1996; Dueker et al., 1998).

The majority of empirical studies on workplace parking estimate the effect on either commute mode choice or parking demand. A recent study conducted a meta-analysis of 50 studies that estimated elasticities of parking demand with respect to parking price (Lehner & Peer, 2019). They found a baseline elasticity of workplace parking volume of -0.52, based on revealed preference studies. They also found an elasticity of -1.07 based on stated preference studies, but indicated that the elasticity based on revealed preference studies would likely be more accurate.

With respect to mode choice, Khordagui (2019) analyzed California Household Travel Survey data from 26 counties and estimated that a 10% increase in parking price would reduce the probability of driving alone to work by 1.3% to 2.6% (an elasticity of -0.13 to -0.26). Two other studies found similar results. Su and Zhou (2012) estimated an elasticity of -2.3 in the Seattle, Washington region. And Peng et al. (1996) estimated elasticity ranges of -0.12 to -1.346 for urban residents in the Portland, Oregon region and -0.091 to -1.151 for suburban residents. A fourth study estimated that having free workplace parking (and no other workplace-related transportation benefits) increased drive-alone mode share by 20.7 percentage points in Washington, DC (Hamre & Buehler, 2014).

Parking pricing has also been shown to be effective outside of the workplace and commute context. Lehner and Peer (2019) assessed the effect of parking price on parking volume for non-commute trips. Their meta-analysis estimated an elasticity of -0.32, based on revealed preference studies, and an elasticity of -0.87, based on stated preference studies. They noted that the lower-magnitude elasticity would likely be more accurate in areas with high parking demand and occupancy, while the higher-magnitude elasticity would be more accurate in areas with occupancy rates significantly lower than 100%.

With respect to adaptive pricing, Krishnamurthy & Ngo (2019) estimated that the SFpark program reduced average daily weekday vehicle counts per Census block by 6% (albeit not a statistically significant result) and reduced average daily weekend vehicle counts by 12%. Millard-Ball et al. (2014) studied the first two years of SFpark and estimated that the adaptive parking pricing program reduced cruising by 50 percent relative to what was estimated for control blocks that were not part of the adaptive pricing program, but their findings were based on a simulation and they did not attempt to quantify the effect on VMT. Other studies have also analyzed the effects of SFpark (Pierce & Shoup, 2013) and Seattle's performance-based parking program (Ottosson et al., 2013) on parking occupancy, but those results cannot as easily be translated into VMT. For example, parking occupancy must be divided by parking duration to calculate parking volume. As a result, those studies are not included in Table 33.

Table 33. Summary of literature review for parking pricing.

Study	Study area	Sample Size	Parking Treatment	Effect Type	Effect Size
Hamre & Buehler (2014)	Washington, DC (urban core and inner suburbs)	4,630 persons	Free workplace parking	Commute mode choice	20.7 percentage point increase in drive alone mode share
Khordagui (2019)	California (26 counties)	6,793 work trips (varies between statistical models)	Parking price at workplace location	Commute mode choice	1.3% to 2.6% reduction in probability of driving alone with a 10% increase in parking price (-0.13 to -0.26 elasticity)
Peng et al. (1996)	Portland, Oregon (urban core and suburbs)	1,288 persons	Parking price at workplace location	Commute mode choice	Urban core residents: 1.2% to 13.5% reduction in probability of driving alone with a 10% increase in parking price, depending on baseline parking price (-0.12 to -1.346 elasticity) Suburban residents: 0.9% to 11.5% reduction in probability of driving alone with a 10% increase in parking price, depending on baseline parking price (-0.091 to -1.151 elasticity)
Su & Zhou (2012)	King County, Washington (all areas within the county, including urban, suburban, and rural)	462,346 persons	Parking price at workplace location	Commute mode choice	2.3% reduction in probability of driving alone with a 10% increase in parking price (-0.23 elasticity)

Study	Study area	Sample Size	Parking Treatment	Effect Type	Effect Size
Yan et al. (2019)	University of Michigan (Ann Arbor, Michigan)	2,861 persons (faculty and staff commuters to the University of Michigan)	Parking permit price at workplace location (four permit options)	Commute mode choice	2.1% to 18.9% reduction in probability of using a given parking permit with a 10% increase in the cost of that permit (-0.21 to -1.89 elasticity), but the probabilities of using another parking permit type correspondingly increased (positive cross-elasticities)
Lehner & Peer (2019)	Global (meta-analysis that includes 15 studies in the U.S.)	50 studies (with 193 total elasticity estimates)	Parking price at destination (non-residential only)	Parking space demand (volume)	Elasticities of parking volume with respect to parking price (95% confidence interval in parentheses): Commute trips: -0.52 (-0.41 to -0.63; revealed preference studies) -1.07 (-0.90 to -1.23; stated preference studies) Non-Commute Trips: -0.32 (-0.18 to -0.45; revealed preference studies) -0.87 (-0.75 to -0.98; stated preference studies)
Krishnamurthy & Ngo (2019)	San Francisco, California (urban core)	59,340 daily vehicle counts (over 109 Census blocks)	Dynamic parking pricing program (SFpark)	Daily vehicle counts (in Census blocks with treatment or control blocks)	6% reduction in average daily weekday vehicle count per Census block (not statistically significant) 12% reduction in average daily weekend vehicle count per Census block (statistically significant)

Study	Study area	Sample Size	Parking Treatment	Effect Type	Effect Size
Miller & Wilson (2015)	Chicago, Illinois (focuses on travel to the central business district)	7,555 hourly vehicle counts	Parking tax that applied to all parking providers charging >$12/day and some providers charging >$240/month. In general, the tax increased parking costs between $1-$2 per day.	Commute-period vehicle counts (on roads commonly used to access the district during commute hours)	3.1% reduction in vehicle trips (-0.3 point-slope elasticity)
Shoup (1997, 2005)	Los Angeles County, California (eight businesses in urban areas with ≥120 employees)	1,694 persons (employees at one of the eight studied businesses)	Parking cash-out programs	VMT per employee	12% reduction in commute VMT per employee (weighted result from seven of the eight studied businesses)

6.2 Parking restrictions

We focused our review of parking restrictions on the two measures included in the CAPCOA GHG Handbook: residential parking supply and minimum parking requirements, and unbundling residential parking costs from property costs. "Bundled" parking means that the cost of off-street residential parking is included in the cost of housing (rent or purchase price), while "unbundled" parking means that the parking is paid for separately only by those who want it—unbundling makes the cost of residential parking both more visible and discretionary.

We started with the literature cited in previous reviews on the two subtopics of interest, and then searched Google Scholar for relevant articles that have been published since those reviews using the following search terms:

- ("residential parking" OR "minimum parking" OR "parking minimum") AND ("VMT" OR "ownership" OR "volume" OR "demand") (with >8,000 search results)
- ("unbundling" OR "unbundle" OR "residential parking cost" OR "residential parking price") AND ("VMT" OR "ownership" OR "volume" OR "demand") (with >59,000 search results)

The ten most relevant results that isolate the effect of parking supply on VMT or a VMT-related outcome (like parking space demand, commute mode choice, or vehicle ownership) are summarized in Table 34. Only two studies directly estimated the effect of off-street residential parking supply on VMT, with both finding substantial reductions in VMT for households with no or limited off-street parking. The first study, Guo (2013a), used data from a 1998 survey of households in the New York City metropolitan area to examine the effect of home parking convenience on mode choice, vehicle trip generation, and VMT. The study estimated that households who only had access to on-street residential parking had much lower odds of choosing to drive for a given trip, made fewer vehicle trips, and drove approximately 14.3 fewer kilometers on a typical weekday (about a 10% reduction) than households who also had access to off-street residential parking.

More recently and more relevant to California, Currans et al. (2023) analyzed 2017 National Household Transportation Survey data from about 2,000 households from the California add-on sample and estimated a two-step model of vehicle ownership (first level) and VMT (second level). They found that constrained off-street parking (≤1 parking space per dwelling unit) was associated with a statistically significant decrease in vehicle ownership, which in turn was associated with a statistically significant increase in both total and home-based work VMT. They then conducted a scenario analysis for typical households in Los Angeles County, using a hypothetical 100-unit development. They estimated that constraining off-street parking (to ≤1 parking space per dwelling unit) accounted for between a 10 and 21 percentage point reduction in VMT compared to modeled VMT that does not account for parking constraints, depending on the place type and type of VMT (total or home-based work VMT).

Two other studies estimated the effect of off-street residential parking on vehicle trip generation, with both finding statistically significant increases in trip frequency associated with increased off-street parking availability. Currans et al. (2020) studied 35 multifamily affordable housing developments in Los Angeles and San Francisco, using project-level parking data and counts of vehicles entering and exiting the projects. They estimated that a 10% increase in parking spaces per dwelling unit increased vehicle trips by 7.8% in the morning peak period and 7.0% in the afternoon peak period (elasticities of 0.78 and 0.7, respectively). Millard-Ball et al. (2022) analyzed survey data from 779 households in San Francisco and found that a one-standard deviation increase in parking spaces per dwelling unit caused about a 20% increase in the likelihood that a household will drive more frequently.

With respect to more indirect measures of VMT, multiple studies have found that the availability of off-street residential parking correlates with increased vehicle ownership (or related measures, such as overnight occupancy of off-street spaces). That includes studies in California (Cervero et al., 2010; Currans et al., 2023; Millard-Ball et al., 2022) and elsewhere in the U.S. (Cervero et al., 2010; Chatman, 2013; Guo, 2013b; Rowe et al., 2013; Weinberger, 2012). Multiple studies outside of California have also found that the availability of off-street residential parking correlates with higher automobile mode shares (Chatman, 2013; Guo, 2013a; Weinberger, 2012; Weinberger et al., 2009).

Overall, the studies provide strong evidence that off-street parking availability affects VMT, either directly or indirectly through parking demand, vehicle ownership, or automobile mode share.

Table 34. Summary of literature review for residential parking supply.

Study	Study area	Sample Size	Parking Measure	Effect Type	Effect Size
Cervero et al. (2010)	San Francisco, California & Portland, Oregon (near rail transit stations)	31 transit-oriented development projects	Off-street parking supply	Parking space demand (occupancy)	2.2% increase in peak parking demand with a 10% increase in parking spaces per dwelling unit (0.22 elasticity)
Chatman (2013)	Northern New Jersey (within 2 miles of a rail transit station)	1,143 households	Off-street parking supply	Vehicle ownership Commute mode choice	13% reduction in vehicle ownership for households with scarce off-street parking (<1 off-street space per adult in the household) 43% lower odds of driving alone for those with scarce off-street parking
Currans et al. (2020)	San Francisco, California & Los Angeles, California (urban areas)	35 multifamily affordable housing projects (nine used only for validation of the models)	Off-street parking supply	Vehicle trip generation	7.8% increase in vehicle trips (counts coming to and leaving from the housing developments) during the morning peak period with a 10% increase in parking spaces per dwelling unit (0.78 elasticity) 7.0% increase in vehicle trips during the afternoon peak period with a 10% increase in parking spaces per dwelling unit (0.70 elasticity) Increasing the number of parking spaces per dwelling unit from one to two was estimated to increase vehicle trips per dwelling unit by 0.26 trips in the morning peak period and 0.18 trips in the afternoon peak period

Study	Study area	Sample Size	Parking Measure	Effect Type	Effect Size
Currans et al. (2023)	California (all areas and housing types)	~2,000 households	Off-street parking supply	Vehicle ownership VMT	Constrained parking (≤1 parking space per dwelling unit) was associated with a statistically significant decrease in vehicle ownership Vehicle ownership was associated with a statistically significant increase in both total and home-based work VMT A scenario analysis for Los Angeles County indicated that constrained off-street parking accounted for a 10-21 percentage point reduction in VMT compared to modeled VMT that does not account for parking constraints, with the exact reduction varying between place types and type of VMT (total or home-based work VMT)
Guo (2013a)	New York City region (Brooklyn, Queens, Bronx, North Manhattan, 10 municipalities along the Hudson River in New Jersey)	840 households	Off- and on-street parking supply	Vehicle trip generation Mode choice VMT	Having only on-street parking was associated with statistically significant reduction in vehicle trips Having access only to on-street (and not off-street) parking reduced the odds of choosing to drive for a given trip by about 50% Having access only to on-street parking was associated with 14.3 fewer kilometer miles traveled (KMT) on a typical weekday than households with off-street parking (about a 10% reduction)

Study	Study area	Sample Size	Parking Measure	Effect Type	Effect Size
Guo (2013b)	New York City, New York	403 households	Off-street parking supply	Vehicle ownership	The number of off-street parking spaces was associated with a statistically significant increase in vehicle ownership, even after accounting for on-street parking availability
Millard-Ball et al. (2022)	San Francisco, California	779 households	Off-street parking supply	Vehicle ownership Vehicle trip generation	Parking space availability (spaces per dwelling unit) was associated with a statistically significant increase in vehicle ownership. A one-standard-deviation increase in parking spaces per dwelling unit (an increase of about 0.43 spaces/unit) caused households to be about 14 percentage points more likely to own a car Parking space availability was associated with a statistically significant increase in vehicle use. A one-standard-deviation increase in parking space availability caused about a 20% increase in the likelihood that a household will drive more frequently
Rowe et al. (2013)	King County, Washington (urban areas)	208 multifamily developments	Off-street parking supply	Parking demand (occupancy)	Parking space availability (spaces per dwelling unit) was associated with an increase in parking demand (occupied parking spaces per dwelling unit)

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Study	Study area	Sample Size	Parking Measure	Effect Type	Effect Size
Weinberger (2012)	New York City, New York (Bronx, Queens, and Brooklyn)	1,717 Census tracts	Off-street parking supply	Vehicle ownership Commute mode choice	Greater off-street parking availability (spaces per dwelling unit in the Census tract) was associated with a statistically significant increase in vehicle ownership levels Greater off-street parking availability (spaces per dwelling unit in the Census tract) was associated with a statistically significant increase in automobile commute mode share
Weinberger et al. (2009)	New York City, New York (Jackson Heights neighborhood in Queens, and Park Slope neighborhood in Brooklyn)	2 neighborhoods	Off-street parking supply	Commute mode choice	Descriptive data suggested that off-street parking supply was positively associated with automobile commute mode share

Fewer studies examine how unbundling residential parking costs from property costs affects travel behavior, and the results are less conclusive. Table 35 shows the four studies we reviewed, three of which found an association between bundled parking and indirect measures of VMT. Rowe et al. (2013) studied 208 multifamily developments in the Seattle region of Washington, and found that parking price (the monthly price divided by the average rent) was associated with a decrease in parking demand (occupied spaces per dwelling unit). Using national data, both Manville (2017) and Manville and Pinski (2020) also found statistically significant correlations between bundled parking and indirect measures of VMT. For example, Manville (2017) estimated that households with bundled parking had 58-70% lower odds if being vehicle-free (owning no vehicles), while Manville and Pinski (2020) estimated that households with bundled parking spent about $48 more per month on gas than households without bundled parking. However, in both studies, the measure used for bundled parking is imperfect and might overstate its prevalence, which could reduce the magnitude of the reported effects. The fourth study—ter Schure et al. (2012)—surveyed residents of 13 multifamily developments in San Francisco's downtown and other transit-oriented areas and found no statistically significant relationship between bundled parking and either vehicle ownership or commute mode share.

Table 35. Summary of literature review for unbundling of residential parking costs.

Study	Study area	Sample Size	Parking Measure	Effect Type	Effect Size
Manville (2017)	United States	Varies based on sample and model	Unbundling of residential parking costs	Vehicle ownership Commute mode choice	58-70% lower odds of a household being vehicle free if their residential parking is bundled, using the national samples. 63-70% lower odds using the Los Angeles Metropolitan Statistical Area samples. Bundled parking was associated with a statistically significant increase in the percentage of household commuters who drive to work
Manville & Pinski (2020)	United States	>4,500 for all models	Unbundling of residential parking costs	Gas expenditures	Bundled parking was associated with a statistically significant increase in gas expenditures. Households with bundled parking spent about $48 more per month on gas than households without bundled parking.
Rowe et al. (2013)	King County, Washington (urban areas)	208 multifamily developments	Parking price	Parking demand (occupancy)	Parking price (monthly price divided/average rent) was associated with a decrease in parking demand (occupied parking spaces per dwelling unit)
ter Schure et al. (2012)	San Francisco, California (downtown and transit-oriented development districts)	298 persons (across 13 different multifamily developments)	Unbundling of residential parking costs	Vehicle ownership Commute mode share	No statistically significant difference in vehicle ownership between respondents with unbundled parking and those with bundled parking No statistically significant difference in rates of driving alone between respondents with unbundled parking and those with bundled parking

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