BUILDING AND IMPLEMENTING A RESEARCH AGENDA ON TRANSPORTATION DECARBONIZATION

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TABLE OF CONTENTS

INTRODUCTION

The transportation sector is the fastest-growing contributor of global CO_2 emissions and is considered one of the most urgent to decarbonize. To align with the Paris Agreement goal of limiting global warming to 1.5C above pre-industrial levels, the global average carbon intensity of land-based transportation will need to be reduced to approximately half its 2014 level of 104 gCo_2/pKm by 2030 and reach nearly zero by 2050 (Boehm et al. 2021). In the United States, individual ground transit generates over 80 percent of transportation sector emissions and accounts for about 30 percent of overall energy related CO_2 emissions (EPA 2023; EIA 2023). Abating individual, land-based transportation emissions requires urgent action and systemic changes to the current transportation status quo.

Transportation access and emissions are inextricably linked to climate change and economic and environmental inequities. Technology developments and infrastructure shifts, such as decarbonizing the electric grid and building battery capacity, will be critical for long-term sector-wide decarbonization. However, there is an urgent need to identify policies that shift individual transit modes away from internal combustion engine vehicles (ICEs) and toward low or zero-carbon transport options. Understanding how to effectively leverage policy-driven behavior change to support transportation decarbonization can lead to multiple co-benefits by addressing the inequitable distribution of pollution and improving transportation systems for all users.

Historic levels of federal funding and support for equitable transportation decarbonization present a critical window to address both climate change and its disproportionate impacts on communities. To capitalize on this moment, policymakers need more information on which actions to prioritize. While there is extensive literature on transportation as a driver of climate change, there is limited experimental evidence or impact data on which policies most effectively drive equitable transportation decarbonization.

PAPER SCOPE

This paper synthesizes experimental evidence on policy-driven, individual behavior shifts that underpin a transition to decarbonized transit modes. This research does not address medium and heavy-duty transportation or decisions around travel related to passenger rail or aviation. We focus on behavior shifts at the individual consumer level, though more research is needed to understand how transportation decarbonization policies impact commercial and firm behavior. Informed by a systematic literature review and a series of informal conversations with state and county transportation policymakers, this paper identifies gaps in transportation decarbonization evidence in North America and outlines a research agenda for governments and researchers to advance equitable transportation decarbonization through randomized evaluations.

This paper is organized as follows: an overview of transportation legacy systems and transportation equity; a summary of federal funding opportunities and local transportation decarbonization priorities and challenges; literature review methodology and findings; and a research agenda outlining existing research gaps and recommendations.

BACKGROUND

LEGACY TRANSPORTATION SYSTEMS

Historically, transportation investments in North America have prioritized motorized transportation and personal vehicle use. The interstate highway system and land use policies (e.g., zoning laws) dictated where transportation infrastructure was developed and which populations were prioritized (Wesseler 2023). Through this process some communities benefited from increased infrastructure and access while others were subject to underinvestment, transportation insecurity, and higher exposure to pollution from motorized travel. Decarbonization and addressing economic and health inequities are joint priorities for many policymakers. In this paper, we consider both challenges simultaneously to elevate solutions that have the potential to achieve multiple co-benefits (Advani et al. 2024).

Motorized transport still largely relies on ICEs, which run primarily on fossil fuels. Rising vehicle miles traveled (VMT), ongoing car dependence, and large vehicle sizes make the carbon intensity of passenger transport in the United States high relative to other industrialized countries (Boehm et al. 2021; EPA 2021). The negative impacts of transportation emissions disproportionately impact overburdened and historically underserved communities. These groups include low-income communities, communities of color, tribal nations, and other groups that have been consistently excluded from transportation planning processes and continue to face barriers in accessing transportation resources to meet their daily needs (DOE 2023; CEJST 2024a). This paper also refers to these groups as impacted communities.

Reducing transportation emissions will require a broad set of policy actions including decarbonizing the electric grid and public transit fleets, lowering the cost of lithium-ion batteries, and scaling up technologies like hydrogen fuel cell vehicles (EPA 2021). Momentum in these areas is growing—a record number of electric vehicles (EVs) were sold in the United States in 2023 and the fleet of electric buses deployed grew from 3,297 in 2021 to 5,480 in 2023 (Slowik and Isenstadt 2024; CALSTART 2023). However, these technological and structural changes alone will not be enough to meet US decarbonization targets. Reducing transportation emissions will require fundamental changes to how we think of transportation and mobility. Shifting individual travel behavior from ICEs to lower-carbon transit modes such as public transit, EVs, walking, and cycling will be critical in achieving this goal (IEA 2017).

TRANSPORTATION INEQUITIES

Transportation systems reflect the political and economic context in which they were established (US DOT 2023a). Legacy infrastructure and policies have resulted in a transportation status quo that facilitates inequities in how individuals and groups access low-carbon transportation and are exposed to transportation emissions.

Fossil fuel-based ground transportation contributes to poor air quality and toxins that are responsible for cancer, asthma, and other negative health effects. In the United States, transportation contributes 45 percent of total NOx emissions and 10 percent of PM2.5 and PM10 emissions (EPA 2024d). Historical urban and economic development patterns—such as redlining—have perpetuated housing, income, and mobility inequality. As a result, low-income communities and communities of color in the United States are more likely to live or work near highways and experience higher exposure to transportation-related emissions (ALA 2023b). These trends have been reinforced over time, as transportation corridors and industrial plants are increasingly concentrated in low-income neighborhoods (Rentschler and Leonova 2023). Communities of color also have higher rates of chronic conditions that can exacerbate the impacts of transportation-related air pollutants (ALA 2023a).

Current policies to reduce transportation emissions often don't consider disadvantaged groups. Strategies such as public EV charging and bikeshare systems tend to target more affluent areas and the build-out of public transit hubs can drive up housing prices in the area, crowding out low-income residents (Hess 2020; Heilmann 2018). While many state-level climate action plans address the need for low carbon transit options, these plans often fail to consider and expand access for impacted communities.

Low-income households, communities of color, and rural communities are more likely to experience transportation insecurity and a higher transportation cost burden (EPA 2024b). Segregation-era public transit systems in the United States were designed to exclude Black communities. Additionally, transit networks have faced chronic underinvestment and have been operating in a net deficit since the late 1960s (Shen 2024). These trends have increased reliance on personal car ownership and resulted in transportation deserts in some communities, particularly for individuals who cannot afford the high costs associated with personal vehicles. On average, transportation represents 16 percent of annual household spending in the United States. However, low-income households may spend up to 35 percent of their after-tax income on transportation with costs driven mostly by car ownership (US DOT 2023a). This leaves these households with little financial flexibility to address unexpected maintenance or accident-related expenses (US DOT 2023a; The Federal Reserve 2022).

Replacing ICEs with EVs can have immediate benefits for low-income communities by improving air quality and reducing household fuel expenses (Kane et al. 2022). However, many fleet transition strategies, most notably EV subsidies, can be regressive. Until 2023, for instance, EV buyers in the United States need an income of over $66,000 per year to receive the full tax benefit designed to incentivize adoption of zero-emission vehicles (Osaka 2021). Though recent changes outlined in the Inflation Reduction Act help address this limitation, these changes will roll out slowly, and it is unclear how many households would have utilized this benefit had they been able to access it earlier (Dow 2023).

Transit access disparities compound existing inequities, leaving impacted groups particularly vulnerable to transit system disruptions. Reduced public transit services throughout the Covid-19 pandemic have disproportionately impacted communities with multiple social vulnerabilities such as those with high poverty rates, lower vehicle ownership rates, high percentages of low-income workers, and neighborhoods with a high percentage of black residents (Kar et al. 2022).

Addressing the uneven distribution of benefits and burdens across transportation systems can create welfare and environmental benefits while improving economic outcomes. While there are multiple dimensions of transportation disparities, this paper focuses on transportation access and distribution of burdens.

FEDERAL FUNDING OPPORTUNITIES TO DRIVE EQUITABLE TRANSPORTATION DECARBONIZATION

The Biden Administration has highlighted transportation decarbonization as a national priority, allocating historic levels of federal funding to support state and city governments in creating sustainable, equitable transportation systems.[1]

Through Executive Order 14008, the administration launched the Justice40 (J40) Initiative in 2021, a government-wide program which directs 40 percent of the overall benefits of certain federal investments to disadvantaged communities. Disadvantaged communities are identified based on a score across 36 indicators including energy, housing, health, legacy pollution, workforce, and transportation related burdens (DOE 2024b). Programs funded by J40-covered initiatives must demonstrate that they have engaged community stakeholders and are required to report on how the program impacts disadvantaged communities. J40 applies to three major infrastructure spending legislations: the American Rescue Plan Act (ARP), passed in 2021, the Bipartisan Infrastructure Law (BIL), passed in 2021, and the Inflation Reduction Act (IRA), passed in 2022.

The BIL allocates $1.2 trillion to transportation and infrastructure spending through dozens of programs to improve EV charging infrastructure, reduce traffic congestion, and support environmental justice efforts. This includes the first ever federal investment in EV charging through the National Electric Vehicle Charging Formula Program (NEVI) and Discretionary Grant Program for Charging and Fueling Infrastructure, which together provide over $7 billion in funding over five years (The White House 2022). Through the Carbon Reduction Program, the BIL also provides competitive grants for cities to develop innovative and multimodal projects to reduce traffic congestion (US DOT 2022). The IRA builds on BIL investments, allocating $5.6 billion through DOT programs to catalyze the EV market via rebates and tax credits, develop EV charging infrastructure, and improve public transit access (US DOT 2023a; Chyung and Ricketts 2022).

The BIL and IRA center equity, emphasizing the need to assess and address the distributional impacts of both new policies and legacy systems. This includes establishing competitive grants to support transportation equity directly. The Rebuilding America's Infrastructure with Sustainable and Equity (RAISE) program, for instance, allocates $1.5 billion in grant funding through 2024 to support state, local, tribal, and county governments in completing local locally-significant freight and passenger transportation projects that are difficult to fund through other federal channels. At least $15 million in funding from the RAISE program is guaranteed for projects located in Areas of Persistent Poverty or Historically Disadvantaged Communities and projects in these areas are eligible for 100 percent federal cost share. The Strengthening Mobility and Revolutionizing Transportation (SMART) program also provides over $100 million in funding through 2024 to support transportation safety and efficiency (US DOT 2022; 2023b). In total, the BIL and IRA include over $27 billion in funding for programs that address transportation and community design and $3 billion for projects that address equity and environmental justice initiatives (Dix et al. 2023).

Though many subsidies for decarbonization technologies are means-tested, historically most benefits have been utilized by wealthier households. Between 2006 and 2021, 90 percent of green energy tax credits for heat pumps, solar panels, and EVs in the United States were allocated to households in the top two income quintiles (Borenstein and Davis 2024). The 2023 DOT Equity Action Plan outlines a strategy to address this

[1] While there are multiple definitions of transportation equity that vary slightly across sources (Bruzzone, Cavallaro, and Nocera 2023), this paper uses the US Department of Transportation (DOT) definition of equity and equitable transportation. Equity refers to the "consistent and systematic, fair, just, and impartial treatment of all individuals, including individuals who belong to underserved communities" and equitable transportation "considers the circumstances impacting a community's mobility and connectivity needs" in a way that is safe, efficient, and sustainable (FHWA 2024).

disparity and aims to bridge the gap between federal funding and equitable transportation goals. The plan includes key performance indicators and strategies at federal and local levels to address equity in transportation planning. The plan outlines five key focus areas, including "proactive intervention, planning and capacity building," to ensure impacted communities benefit from new investments, and "expanding access" to increase social and economic opportunity for disadvantaged groups through affordable, multimodal transportation. The DOT also highlights gaps in how institutional impacts of transportation are measured. Public responses to the Equity Action Plan emphasized the need for more performance measures for equity-focused initiatives and increased availability of data that can be used to compare programs and disaggregate impacts at the community level (US DOT 2023a). New programs, including the Charging and Fuel Infrastructure Grant program, leverage these frameworks and J40 guidelines to channel funding directly to rural and low-income areas with low ratios of private parking or high ratios of multi-unit dwellings (US DOT 2024a).

STATE AND LOCAL EQUITABLE TRANSPORTATION DECARBONIZATION PRIORITIES AND CHALLENGES

While current funding opportunities for transportation decarbonization flows through federal channels, applying for funding and implementing policies falls to states and counties. Local jurisdictions are ultimately responsible for most road transportation infrastructure and have significant discretion in how they prioritize policies and resources based on local needs (GAO 2023). Though most jurisdictions are broadly aligned with federal climate goals, specific strategies and policies are often driven by local context.

Policy priorities

The BIL requires states to establish carbon reduction plans and work closely with local metropolitan planning organizations (MPOs) to reduce road transport emissions. These plans were due in November 2023 and must be updated every four years (US DOT 2024b). States have outlined a variety of approaches in their Climate Action Plans, emphasizing different priorities based on geographic and economic factors (Kane et al. 2022). Most plans are cross-cutting, outlining strategies by sector with targets around transportation, land use, buildings, waste reduction, agriculture, and environmental justice.

Transportation goals include structural and behavior-related targets such as installing EV chargers and improving road materials, phasing out ICEs, improving access to sustainable public transportation for Black, Indigenous, and people of color (BIPOC) communities, and reducing commercial and agricultural transportation emissions (City of Portland 2022; King County Climate Action Team 2020). Transportation decarbonization is incorporated into different focus areas across plans including goals for energy efficiency and electrification, land use, and built environment priorities.

While strategies to accomplish transportation goals vary, most state plans include prioritizing EV infrastructure, increasing public ridership and access, and expanding access to alternative transit options such as walking and biking (US DOT 2024b). Climate Action Plan transportation themes include:

- **First and last mile transit access:** In response to reduced public transit ridership, many cities, including Detroit, MI, Los Angeles, CA, Seattle, WA, Columbus, OH, Houston, TX, Jacksonville, FL, and Grand Rapids, MI, have deployed micro-mobility (e.g., public bikes, electric scooters) as a complement to existing transportation services (APTA 2024).

- **Mobility hubs:** Cities aim to make low-carbon transit more accessible by building out mobility hubs—transit centers that integrate multiple transport modes such as public transit, walking paths, and bikeshare docks (Urban Design Studio 2023). Cities including Los Angeles, CA, Seattle, WA, Pittsburgh, PA, Miami, FL and Salt Lake City, UT are leveraging mobility hubs to increase transit access and decrease VMT (Crowther 2022).

- **Electrification of public transit fleets and personal vehicles:** Local jurisdictions are working to increase EV adoption, build out EV charging infrastructure, and electrify public transit bus and school bus fleets (Kane et al. 2022). States including Arkansas, Connecticut, and Iowa have highlighted EV sales and alternative fuels as transportation priorities. Washington, West Virginia, and Nevada have also made significant investments in electric bus and school bus fleets (Dougherty and Grimshaw 2022).

- **Reducing VMT through behavior change:** To reduce traffic congestion, cities and counties are implementing tolls and other transportation demand management strategies. States including Texas, Minnesota, Georgia, and Texas are leveraging new pricing schemes, including fuel taxes and dynamic congestion pricing. California and Oregon are also exploring mileage-based fees as a replacement for fuel taxes (Byars, Wei, and Handy 2017).

- **Universal basic mobility initiatives:** Cities including Portland, OR, Oakland, CA, Los Angeles, CA and Pittsburgh, PA are testing programs that provide free access to transportation to qualifying residents. While specific strategies and amounts vary across locations, programs typically include prepaid debit cards that can be used for transportation-related expenses such as transit passes, bikeshare services, or rideshares (Bliss 2021).

- **Addressing systemic barriers to transportation equity:** Local climate action plans prioritize bottom-up, locally-led, equitable decarbonization. A review of fifty city-level climate action plans found that nearly all plans incorporated equity as a key priority and 94 percent tracked at least one metric related to community engagement. While most plans at minimum recognize the importance of equity in decarbonization, there is significant room for growth—few regions have taken the additional step to embed equity into their metrics and sector specific plans (Kane et al. 2022). Jurisdictions working to integrate equity comprehensively have leveraged a variety of approaches. King County, WA has established a Mobility Equity Cabinet that brings together leaders from historically underserved groups to advise on transportation planning efforts to ensure public transit investments align with community needs (King County 2024). To better measure progress on transportation equity, the Minnesota Department of Transportation partnered with the Texas A&M Transportation Institute to conduct a transportation equity assessment and develop equity-focused strategic actions and assessment methods throughout the state (MnDOT 2024).

Policy Challenges

As states plan for and implement transportation decarbonization policy, six common challenges present barriers to climate and equity action.

- **Incentivizing EV adoption and equitably installing charging infrastructure:** Jurisdictions are experiencing barriers to meeting EV sales targets. Some state DOTs feel that they do not have the tools to help incentivize EV purchases, such as the authority to regulate fuel composition and consumer vehicle choice (GAO 2023). Jurisdictions also worry that charging infrastructure is not developing rapidly enough to keep pace with EV adoption mandates. Specific charging installation challenges vary by location. Montana DOT officials, for instance, said that adding EV infrastructure may be more challenging or take longer to implement in rural states (GAO 2023). In states that have built out charging infrastructure, there are significant inequities. A California study found that majority Black and Hispanic census block-groups were half as likely to have access to public charging stations relative to reference areas with no demographic majority (Hsu and Fingerman 2021). This is a common trend across the country (Fitzpatrick, Muller, and Davis 2023).

- **Balancing and understanding tradeoffs between decarbonization and equitable access:** Equity and decarbonization goals can often be in tension with each other. One example of this is the rollout of electric buses and EVs, which are heavier than their gas-powered alternatives, causing tires to break down more quickly (Krantz 2023). This turnover produces water and soil pollution that jurisdictions need to consider as they increase electric bus use and incentivize EV adoption, particularly when these vehicles are deployed in impacted communities. Many jurisdictions are not equipped to track, measure and understand these tradeoffs. While most state and regional climate action plans do incorporate equity, just 6 percent of State DOTs and 20 percent of Transportation Management Areas[2] have implemented an equity screening component that includes meaningful public involvement, data-driven analysis, quantifies equity impacts, and integrates equity measures (US DOT 2023a).

- Overburdened or disadvantaged communities also may not have the local expertise or capacity to navigate the complexities of federal grant opportunities, such as building out a comprehensive cost-benefit analysis. This can exclude these communities from accessing discretionary funds directly (US DOT 2023a).

- **Increasing public transit ridership amid a ridership crisis:** Transit ridership, which decreased sharply during the Covid-19 pandemic, has failed to rebound to pre-pandemic levels (Zipper 2023). This has left transit agencies in a funding hole, without the resources needed to upgrade infrastructure or improve the rider experience (Kar et al. 2022). Ridership patterns have also changed as a result of new working norms. Transit systems are experiencing smaller peaks during rush hours, more trips at other times of day, and increased demand for intra-neighborhood transit routes (Rose 2023). Transit agencies are grappling with ongoing questions of how to increase public transit demand, manage public perception around safety, and attract higher-income riders while meeting the needs of low-income or transit-dependent groups (Rose 2023).

- **Siloed regional climate action planning:** Climate action does not happen in a vacuum and requires coordination across county, city, and departmental levels. Regional transportation systems are connected by a mix of infrastructure components such as highway networks, power grids, and transit fleets. These may be managed by different entities within each jurisdiction, leading to inconsistencies in how decarbonization targets are prioritized within each department and ambiguity about who is responsible for which action (Kane et al. 2022). Department decisions can also be siloed. For instance, DOTs and Metropolitan Planning Organizations[3] often have little say in local

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[2] A Transportation Management Area (TMA) is an urbanized area with a population over 200,000 as classified by the United States Secretary of Transportation (FTA 2024).

[3] Transportation Management Organizations (MPOs) are designated by agreement between state governors and local governments to manage transportation planning in urban areas with a populations between 50,000 and 200,000 (FTA 2024).

land use decisions, which can greatly impact individual transportation needs, VMT, and ultimately GHG emissions (GAO 2023).

- **Gaps between climate ambition, evaluation, and action:** A review of fifty city decarbonization plans found that fewer than 30 percent had detailed benchmarks and reporting strategies, and 61 percent set detailed interim emission reduction goals (Kane et al. 2022). In a 2022 survey, The National Cooperative Highway Research Program found that only six of forty state DOTs set system-wide goals for reducing transportation GHG emissions. Data collection is also a challenge. DOTs have limited resources, data like VMT benchmarks are collected infrequently, and transit agencies have expressed a need for better tools and guidance to incorporate GHG emissions into existing travel demand models (GAO 2023).

- **Challenges prioritizing funding and contextualizing policy decisions.** Jurisdictions struggle to prioritize which climate policies to pursue while managing competing priorities across departments, political changes, and conflicts between private and public stakeholders involved (Kane et al. 2022). To meet climate goals and break out of the current transportation status quo, local jurisdictions are testing new and multifaceted strategies to advance equity and decarbonization simultaneously. However, it can be challenging to build support for programs without an established evidence base and demonstrated cost efficacy. The Minnesota DOT, for instance, has struggled to gain support for a multimodal plan to reduce transportation GHG emissions, as these projects can be expensive and require long-term investment (GAO 2023).

METHODOLOGY

This systematic literature review includes 45 journals across the economic, environmental, and transportation space (see Appendix A for information on journals included). Journals were searched using a set of fixed terms and the first 200 results of each search were reviewed.[4]

Research included in the final set of studies meet the following criteria:

- **Study bounds:** Studies conducted in North America (United States, Canada, Mexico), published between January 2000 and September 2023, use data collected after 2000, and are peer reviewed.

- **Methodology:** Included studies use a credible identification strategy such as a randomized evaluation or regression discontinuity design (RDD) in a field or natural experiment setting. Studies that do not have a defined counterfactual and cannot draw causal impact conclusions (e.g. observational analysis, stated-choice preference surveys, bivariate analysis) are excluded.

- **Transit mode:** This research focuses on land-based individual transport behavior. The decision to focus on this policy area is due both to the emissions generated by individual transportation and the potential for behavior change to effectively drive decarbonization progress in this area. Because of this constraint, we do not include studies on heavy or medium duty transport, aviation, or shipping.

[4] Search terms: transit; transport; electric vehicle; public transit; random; quasi, natural experiment; field experiment; emissions; decarbonization; public utility; regression discontinuity; vehicle charging.

- **Outcome of interest:** This literature review focuses on transportation behavior shifts that relate to decarbonization. Included studies address the impact on policies related to travel demand and variables that are directly tied to traffic congestion (e.g. VMT, traffic volume, parking demand), fleet shift (e.g. EV registration, fuel economy of new vehicles purchased), and public transit (e.g. variables measuring public transit ridership rates). Studies that address transportation behaviors that do not have a direct decarbonization link are not included. These include studies on transit centers and crime, DUI arrests, and cell phone related accidents. Studies focusing on transportation factors outside of behavior shifts, such as technology developments (e.g. lithium-ion battery range, MPG improvements), are not included regardless of methodology.

- **Policy feasibility:** The ultimate goal of this research is to inform how governments can prioritize and implement policy-driven behavior changes to accelerate equitable transportation decarbonization. In line with this objective, we limit studies to those that analyze policies that can directly inform or be replicated in other locations (e.g. taxes, subsidies, information schemes). This literature review does not include studies that examine one-time events such as temporary transit shutdowns and short-term impacts of crisis scenarios (e.g. the impact of Covid-19 lockdowns on transportation emissions or the impact of natural disasters on mobility).

LITERATURE REVIEW RESULTS

LITERATURE OVERVIEW

The literature review found 29 studies that met the criteria outlined the methodology. The identified evaluations address individual passenger transportation behavior shifts across three themes: fleet shift, public transportation, and traffic congestion (Table 1). Studies address ten types of transportation policies (Table 2), and 25 of the 29 studies are focused in the United States (Table 3).

The following sections describe the literature review results by theme, outlining trends, gaps, and equity implications. We also highlight trends in how papers measure the cost efficacy of policies and quantify welfare and environmental impacts. For the purposes of this literature review, we define welfare impacts as any quantified benefit specified in studies, including the marginal value of public funds, value of time saved, benefits of reduced traffic congestion, or value of pollution reduction. Environmental benefits are classified as tonnes of CO2 reduced or abated as a result of the policy.

Table 1: Literature review results by topic

TOPIC	COUNT
Fleet shift	11
Public transit	8
Traffic congestion	10

Table 2: Intervention area

INTERVENTION	COUNT
EV or hybrid purchase incentive	7
Tolls/congestion pricing	3
Public transit complement/ substitute	3
Real-time information	3
Air quality alert	3
Fuel economy information	3
Driving disincentive	2
Infrastructure	2
Public transit pricing	2
EV off-peak charging incentive	1

Table 3: Geographic region

LOCATION	COUNT
United States	26
Nationwide	7
California	6
Illinois	2
New York	2
Minnesota	2
Texas	2
DC	1
Florida	1
Maine	1
Pennsylvania/ New Jersey	1
Massachusetts	1
Mexico	2
Canada	1

FLEET SHIFT

Trends

Experimental evidence on fleet transitions focuses on three areas: evaluating how fuel economy information impacts purchasing decisions, shifting EV charging times to reduce grid demand, and EV purchase incentives such as rebates or "Cash for Clunkers" trade-in programs (Table 4).

Fuel economy information

Imperfect consumer information has been discussed extensively in previous literature. Evidence shows that consumers tend to undervalue vehicle fuel economy (Leard, Linn, and Zhou 2023; Gillingham, Houde, and van Benthem 2021). One study found that changes in gasoline prices impacted hybrid vehicle purchase rates, particularly when paired with other incentives. The authors estimated a discount rate of 14.6 percent on future savings (Gallagher and Muehlegger 2011). Two studies in the literature review found that fuel economy information had limited impacts on buyer decisions (Allcott and Knittel 2019; Siriwardena et al. 2012). While studies suggested improving fuel economy could have welfare impacts, studies did not quantify the equity or welfare impacts of policies evaluated.

EV charging

As the EV fleet grows, managing energy demand during peak charging hours will be critical (Powell et al. 2024). One evaluation in the literature review tested the effects of an information campaign and financial incentive on charging behavior. Bailey et al. (2023) found that a financial incentive was highly effective in shifting EV charging from peak to off-peak hours, suggesting that price elasticity for vehicle charging is much larger than household price elasticity for other electricity uses. However, this shift in charging behavior was not sustained once the financial incentive ended. The cost-efficacy of this strategy is highly dependent on local peak and off-peak electricity prices. Because this study included only participants with EVs living in a metropolitan area, authors noted that the findings may not be generalizable to larger populations. These results are supported by a study in Austin, TX (not included in our formal literature review) which found that consumers responded strongly to electricity peak pricing and shifted EV charging demand to off-peak periods (Burkhardt, Gillingham, and Kopalle 2023).

Low-emission vehicle purchase incentives

Experimental studies on low-emission vehicle purchase incentives focus on direct rebates, subsidies, and trade-in programs (e.g., Cash for Clunkers). Studies find mixed results on the efficacy of these programs. Across policy evaluations, results indicated that consumers who utilize these incentive programs would have purchased relatively fuel-efficient vehicles in absence of the program (Clinton and Steinberg 2019; Li, Linn, and Spiller 2013; Muehlegger and Rapson 2022; Gallagher and Muehlegger 2011).

Muhlegger and Rapson (2023; 2022) analyzed data from California's Enhanced Fleet Modernization Program (EFMP) pilot, targeting low- and middle-income households by zip code. They found that while the program did not have a significant impact when comparing similar zip codes inside and outside of EFMP pilot regions, consumers in lower-income zip codes purchased vehicles that were more fuel efficient than the California average over the study period.

In an evaluation of the 2009 Cash for Clunkers program, Li, Linn, and Spiller (2013) found that the program increased vehicle sales by 370,000 vehicles and that most rebate spending went to buyers who would have purchased new vehicles anyway. These results are aligned with West et al. (2015) and Hoekstra, Puller, and

West (2017), who evaluated how the Cash for Clunkers program impacted the purchasing behavior of households in Texas. Hoekstra, Puller, and West (2017) found that the program increased short-term spending over the two-month program period, but that eight months after the program ended households who were barely eligible and barely ineligible for the rebate were equally likely to have bought a new vehicle since the start of the program. Further, the study found that Cash for Clunkers had a negligible impact on the average fuel economy of new vehicles purchased and ultimately reduced overall spending on new vehicles. West et al. (2015) evaluated the implications of Cash for Clunkers incentivizing low-income groups to make tradeoffs between fuel economy and performance. The study found that although Cash for Clunkers program participants in Texas did not respond to improved fuel efficiency by driving more, they did downsize household vehicles.

Four of the seven studies evaluating purchase incentive programs quantify the environmental costs and benefits of associated policies. Studies found that the cost per Mt $CO2$ avoided or reduced by rebate or subsidy incentive programs was quite high. Clinton and Steinberg (2019) estimated that the overall cost per Mt $CO2$ avoided for EV purchase incentives nationally ranges from $73–$78 to $894–$958 depending on EV charging behavior and vehicle lifespan. Based on analysis of the EFMP, Muehlegger and Rapson (2022) estimated total costs would exceed $12–$18 billion for California alone to reach its 2025 EV sales target. The environmental impacts of EV incentive programs are also highly context dependent and can be negative depending on local grid composition (Gallagher and Muehlegger 2011; Clinton and Steinberg 2019). Li, Linn, and Spiller (2013) estimated the implied cost per MtCO2 abated by the Cash for Clunkers program nationally was between $92 and $288. Using estimates from the Interagency Working Group on Social Cost of Carbon, Hoekstra, Puller, and West (2017) estimated that Cash for Clunkers cost taxpayers over $4,000 and generated $252 in environmental benefits per subsidy.

Data and outcome variables

Studies measuring EV adoption or the fuel economy of new vehicles purchased draw predominantly on state vehicle registration and transaction data. This data is often combined with fuel economy information from another source such as the EPA fuel efficiency models, social cost of carbon estimates, and CO2 per gallon of gasoline estimates from Holland et al. (2016) (Li, Linn, and Spiller 2013; Siriwardena et al. 2012; Muehlegger and Rapson 2022; 2023; Clinton and Steinberg 2019; Gillingham, Houde, and van Benthem 2021; Hoekstra, Puller, and West 2017). West et al. (2015) and Hoekstra, Puller, and West (2017) also draw on household survey data and data from the Department of Motor Vehicles. Other data collection strategies include surveys (online and in person) to track consumer attitudes and purchasing decisions and EV charging sensors to measure kWhs/hour (Allcott and Knittel 2019; Bailey et al. 2023).

Research gaps

Studies note that more work is needed to assess the welfare impacts of EV sales as overall adoption increases and market conditions change (Clinton and Steinberg 2019). Similarly, more work is needed to understand the welfare costs and benefits of ICE trade-in programs in which both new and used vehicle markets are considered (Li, Linn, and Spiller 2013). Authors also emphasize the need for more experimental research to better understand the generalizability of study findings related to EV charging and consumer preferences (Bailey et al. 2023; Gillingham, Houde, and van Benthem 2021).

Fleet transition summary of findings

Table 4: Fleet transition studies

AUTHOR	METHOD	INTERVENTION	SUMMARY OF RESULTS
Allcott and Knittel (2017)	RCT	Fuel economy information	Fuel economy information had no impact on average fuel economy of vehicles purchased.
Bailey et al. (2023)	RCT	EV off-peak charging incentive	Financial incentive was effective in shifting charging to off-peak times, but behavior change did not persist after the financial incentive ended.
Clinton and Steinberg (2019)	Quasi-experiment (DID)	EV purchase incentive	State-level financial incentives increased battery EV adoption on the margin, but were an inefficient CO2 reduction strategy.
Gallagher and Muehlegger (2011)	Regression	Hybrid purchase incentives	Sales tax incentives and fuel savings were positively associated with hybrid vehicle purchases. HOV lane access and income tax credits were less effective.
Gillingham, Houde, and van Benthem (2019)	RDD	Fuel economy information	Vehicle EPA ratings and fuel economy had little impact on consumer purchase decisions.
Hoeskstra et al. (2017)	RDD	EV purchase incentive	Most individuals who utilized Cash for Clunkers subsidies would have purchased new vehicles during the purchase period anyway. Ultimately, the program decreased cumulative spending.
Li, Linn, and Spiller (2013)	DID	EV purchase incentive	The Cash for Clunkers program did not have a significant impact on EV purchases.
Muehlegger and Rapson (2022)	Field experiment (DID)	EV purchase incentive	California's Enhanced Fleet Modernization Program (EFMP) had a small but significant effect on EV adoption among low- and middle-income households.
Muehlegger and Rapson (2023)	Field experiment (DID)	EV purchase incentive	Subsidized buyers of EVs would have, on average, purchased relatively fuel-efficient cars without the subsidy. Environmental benefits of EV rebate programs are likely overstated.
Siriwardena et al. (2012)	Quasi-experiment - nested logit	Fuel economy information	Eco-marketing campaign had a small, short-term positive effect on green-car sales.
West et al. (2015)	RDD	EV purchase incentive	Households did not respond to improved fuel economy vehicles by driving more.

See Appendix B for summaries of fleet transition studies.

PUBLIC TRANSPORTATION

Trends

Experimental evidence on public transit falls into three categories: the impact of real time information (RTI) on ridership levels and rider attitudes, how other transit modes (e.g., bike or car share programs) impact ridership, and public transit price elasticity (Table 5).

Real time information

RTI systems provide transit users with up-to-date information on arrival, departure, and delay times through public platforms such as websites, mobile apps, and displayed signs (Canales 2016). Literature posits that RTI enables users to make more informed transit choices, improves perception of wait time and public transit safety, and positively impacts attitudes toward public transit systems overall, leading to an increase in transit ridership (Harmony and Gayah 2017; Tang and Thakuriah 2011).

Three studies included in the literature review examined the impacts of RTI. Findings were consistent across all three, demonstrating that RTI had a small (1-2 percent) but significant impact on ridership (Brakewood, Barbeau, and Watkins 2014; Tang and Thakuriah 2012; Brakewood, Macfarlane, and Watkins 2015). These studies build on previous ex-post analysis, which suggested RTI reduced acute and perceived wait times (Watkins et al. 2011; Ferris, Watkins, and Borning 2010; Gooze, Watkins, and Borning 2013).

Public transit compliments and substitutes

Three studies in the literature review leveraged phased implementation of bikeshare and rideshare programs to evaluate the interaction between these offerings and existing public transit. Campbell and Brakewood (2017) and Wang and Lindsey (2019) analyzed bikeshare roll out in New York and Minnesota respectively. Campbell and Brakewood (2017) found that bikeshare access coincided with a significant decrease in bus ridership, suggesting people used bikes as a substitute for buses. Wang and Lindsey (2019) evaluated how proximity to a bikeshare station changed bikeshare member use, comparing riders in dense and less dense bikeshare areas. They found that members in less dense areas used bikes as a complement to public transit while those in dense bikeshare areas were more likely to treat bikes and public transit as direct substitutes. In a similar study on phased implementation of Uber across markets, Hall, Palsson, and Price (2018) found that public transit ridership typically increased when Uber entered a market, but that city-level impacts were highly dependent on city population, transit system size, and transit ridership prior to Uber entering the market. The study found that Uber most strongly complemented small transit systems in large cities.

Findings in these studies suggested that both bikeshare and rideshare programs can benefit public transit systems and improve transit access, but more research is needed on the welfare and environmental impacts of these shifts. Campbell and Brakewood (2017), for instance, indicated that decreased bus ridership in response to bike share programs could have either positive or negative impacts on transit systems. Fewer bus riders may decrease crowding, but may ultimately reduce transit revenue. Authors highlighted the need for additional research on the long term impacts of bike share systems and their distributional equity impacts on transit access. Similarly, Hall, Palsson, and Price (2018) emphasized the ambiguous welfare and environmental impacts of Uber entering a market. In cities with smaller transit networks, the study found that Uber increased ridership by filling a first and last mile access gap. The opposite was true in areas with more expansive transit networks, where ridership decreased when Uber became available. In both circumstances, Uber may increase overall traffic congestion, though this was not directly evaluated in the study. None of the studies captured in the literature review quantified welfare or environmental impacts, or directly analyzed the equity implications of bike or rideshare programs.

Transit price elasticity

Implementing peak pricing schemes can improve transit service and lead to overall welfare gains (Mohring 1972). However, the impact of subsidies and dynamic pricing on transit systems is mixed; ex post research suggests that, in some cases, subsidies can incentivize governments to increase geographic reach of transit lines rather than improve the quality and frequency of existing routes (van Reeven and Karamychev 2016). Two studies in the literature review capture experimental evidence on pricing schemes and ridership. In a natural experiment and natural field experiment, Hahn, Metcalfe, and Tam (2023) found that peak pricing generated significant welfare gains for Bay Area Regional Transit riders by decreasing congestion and shifting demand patterns. Davis (2020) evaluated the impact of exogenous fare changes in three Mexican cities. Findings suggested that the overall price elasticity for transit was high and that temporary fare reductions did not lead to higher baseline ridership.

Data and outcome variables

Studies of public transit use ridership as the primary outcome variable. Data is collected directly from transit agencies via boarding and fare collection tracking, train weight, or bikeshare use data (Brakewood, Barbeau, and Watkins 2014; Campbell and Brakewood 2017; Hahn, Metcalfe, and Tam 2023; Tang and Thakuriah 2012; Brakewood, Macfarlane, and Watkins 2015; Wang and Lindsey 2019). Two studies used national databases on ridership (Davis 2020; Hall, Palsson, and Price 2018). Attitudes about transit were tracked via survey (Brakewood, Barbeau, and Watkins 2014).

Research gaps

Authors highlight several areas for future research on public transportation. First, authors noted that their sample sizes and research setting was often limited and that more behavioral research is needed to generalize findings on bikeshare and transit use to diverse populations. Brakewood, Barbeau, and Watkins (2014) specified that their study population was transit dependent before the study began, limiting findings on how RTI changed transit use, and Campbell and Brakewood (2017) noted that New York City has a significantly different public transit profile than any other North American city. Second, studies emphasized the need for more research on the distributional and equity impacts of transit use policies, quantified welfare impacts, and cost efficacy analysis (Davis 2020; Hall, Palsson, and Price 2018; Hahn, Metcalfe, and Tam 2023; Wang and Lindsey 2019). More specifically, Hahn, Metcalfe, and Tam (2023) outline the need for more research that delineates key elasticities related to transit pricing schemes and more research on how to target subsidies to specific populations. Finally, authors noted the limited availability of experimental evidence in the public transportation space. Suggestions for additional research include further studies on RTI that control for additional exogenous variables and segment ridership data based on peak and off-peak travel periods and testing models other than MVPF to capture non-marginal changes (Tang and Thakuriah 2012; Brakewood, Macfarlane, and Watkins 2015; Hahn, Metcalfe, and Tam 2023).

Public transportation summary of findings

Table 5: Public transportation studies

AUTHOR	METHOD	INTERVENTION	SUMMARY OF RESULTS
Brakewood, Macfarlane, and Watkins (2015)	Natural experiment with panel regression	Real time information	Implementing RTI had a small but significant impact on transit ridership
Brakewood, Barbeau, and Watkins (2014)	RCT	Real time information	RTI decreased average wait time and improved feelings toward waiting
Campbell and Brakewood (2017)	Natural experiment (DID)	Public transit complement/substitute	Bikeshare system coincided with a significant decrease in bus ridership
Davis (2020)	RDD	Public transit pricing	Public transit demand is highly elastic, but temporary fare reduction could lead to higher baseline ridership
Hahn, Metcalfe, and Tam (2023)	Natural experiment, natural field experiment (RCT)	Public transit pricing	Implementing a peak pricing scheme decreased public transit congestion and had positive welfare benefits
Hall, Palsson, and Price (2018)	Natural experiment (DID)	Public transit complement/substitute	Uber complemented public transit ridership in most regions studied.
Tang and Thakuriah (2012)	Natural experiment (RCT)	Real time information	Implementing RTI had a small but significant impact on public transit ridership
Wang and Lindsey (2019)	Quasi-experiment (DID)	Public transit complement/substitute	The impact of new bikeshare stations on bike use and public transit varied based on service density

See Appendix C for summaries of public transportation studies

TRAFFIC CONGESTION

Trends

Literature on traffic congestion falls into four categories: air quality alerts, driving disincentives, infrastructure shifts, and tolls or congestion pricing (Table 5).

Air quality alerts

The goal of air quality alerts is to elicit prosocial behavior by encouraging low-emission travel. Experimental studies in the literature review examined the impact of these alerts on both traffic congestion and public transit ridership. Cutter and Neidell (2009) and Sexton (2012) employed an RDD to evaluate the impacts of air quality alerts in the San Francisco Bay Area. Cutter and Neidell (2009) found a small but statistically significant decrease in traffic volume on days alerts were issued. Sexton (2012) built on this study, investigating how the program effects changed when free transit fare was offered on some alert days. This study found that air quality alerts alone had no impact on traffic volume, but that both traffic volume and public transit demand increased on alert days when free transit fare was offered. The study did not evaluate how transit demand and traffic volume shifted if free fare was offered in absence of an air quality alert. Welch, Gu, and Kramer (2005) examined a similar alert program without free transit fare offerings in Chicago, finding that it did not impact overall traffic congestion or public transit demand. None of the included studies analyzed the distributional or equity implications of alert programs directly.

Driving disincentives

Both studies in the literature review that evaluated driving disincentives produced null results. Guerra and Millard-Ball (2017) analyzed "Hoy No Circula," an air quality improvement program in Mexico that restricts vehicles from driving on certain days of the week based on license plate number. The study found that "Hoy No Circula" did not reduce overall VMT, but that households did adopt low-cost behavioral modifications to avoid the driving restriction. Rosenfield, Attanucci, and Zhao (2019) conducted a randomized evaluation testing information campaigns and monetary incentives to shift commuting behavior among Massachusetts Institute of Technology (MIT) employees. The study included three treatment arms aimed at reducing driving to and parking on the MIT campus. One group received information on MIT transportation benefits, one received monetary rewards for not using on-campus parking, and one group received both interventions. The study found no statistical difference in on-campus parking use between treatment and comparison groups.

Infrastructure

Traffic congestion studies addressed infrastructure in two ways: by evaluating the effects of additional road capacity and by examining the impact of new low-carbon transit modes. Duranton and Turner (2011) confirmed the "fundamental law of road congestion," that traffic volume increases in proportion to road availability. Hamilton and Wichman (2018) found that implementing a bikeshare system in Washington, DC was a highly effective way to curb traffic congestion, finding that bikeshare stations reduced annual congestion costs for Washington Area Commuters by $182 million in total. Though this study did not quantify distributional impacts, the authors highlighted that bikeshare stations are typically installed in higher income areas.

Tolls and congestion pricing

Overall, studies in the literature review found that congestion pricing and tolls effectively reduced traffic volume and associated emissions. Two of the four studies that evaluated highway pricing schemes found that implementing tolls led to health benefits (Currie and Walker 2011) and decreased traffic volume significantly (Foreman 2016). In contrast, Janson and Levinson (2014), found that dynamic pricing for express lanes actually increased demand during some hours.

Data and outcome variables

Studies measuring traffic congestion used freeway monitoring data from a variety of sources such as universities, county records, or state DOT databases (Cutter and Neidell 2009; Foreman 2016; Janson and Levinson 2014; Sexton 2012; Duranton and Turner 2011). Selected studies also used data from toll transponders and VMT data from household surveys and state or county travel statistics (Janson and Levinson 2014; Guerra and Millard-Ball 2017; Welch, Gu, and Kramer 2005). Currie and Walker (2011) leveraged health and birth outcome data from the Vital Statistics Natality records. Rosenfield, Attanucci, and Zhao (2019) used parking garage gate entrance data to track MIT on-campus parking use among study participants.

Research gaps

Across studies, authors noted the need to better understand the welfare impacts of policies such as air quality alerts, driving bans, and infrastructure changes (Cutter and Neidell 2009; Duranton and Turner 2011). Other studies highlighted the need for more research on travel substitution behaviors in response to different policies (Guerra and Millard-Ball 2017; Hamilton and Wichman 2018). Rosenfield, Attanucci, and Zhao (2019) suggested further randomized evaluations of individualized travel planning (e.g., providing additional information on carpooling or location-specific commute options) and Welch, Gu, and Kramer (2005) noted gaps in the research around how new work patterns such as remote work shift travel needs. Finally, there is little research available on the distributional welfare impacts of tolling strategies across income distributions.

Summary of traffic congestion findings

Table 6: Traffic congestion studies

AUTHOR	METHOD	INTERVENTION	SUMMARY OF RESULTS
Currie and Walker (2011)	Natural experiment (DID)	Tolls/ congestion pricing	Incidence of premature births fell in areas within 2km of toll plaza; NO2 levels also reduced
Cutter and Neidell (2009)	RDD	Air quality alerts	Spare the Air (STA) alerts led to small but significant reduction in traffic volume
Duranton and Turner (2011)	Instrumental variable	Infrastructure	Vehicle kilometers traveled increased proportionally to lane kilometers
Foreman (2016)	Quasi-experiment (DID)	Tolls/ congestion pricing	Tolls were associated with lower traffic volume during peak hours
Guerra and Millard-Ball (2017)	RDD	Driving incentive/disincenti ve	License plate-based driving restrictions did not impact VMT
Hamilton and Wichman (2018)	Quasi-experiment (case matching)	Infrastructure	Implementing a bikeshare system decreased traffic congestion and created welfare gains
Janson and Levinson (2014)	Field experiment	Tolls/ congestion pricing	Express lane use increased when prices were higher
Rosenfield, Attanucci, and Zhao (2019)	RCT	Driving incentive/disincenti ve	Incentives and transit information did not impact parking demand for MIT employees
Sexton (2012)	RDD	Air quality alerts	Free transit on STA days was associated with both increased traffic volume and more public transit trips
Welch, Gu, and Kramer (2005)	Fixed effects regression	Air quality alerts	Ozone Action Day air quality alerts had no significant effect on overall transit ridership, but did shift travel timing away from peak travel hours

See Appendix D for summaries of traffic congestion studies.

DISCUSSION AND RESEARCH AGENDA

Local policymakers are at the forefront of transportation decarbonization policy development and implementation, working to break historical patterns by testing strategies to advance equity and decarbonization. Currently, there is an evidence gap at the intersection of behavior change mechanisms and equitable transportation decarbonization at scale, leaving policymakers with little data to guide their decision-making.

Twenty-nine studies captured in our systematic literature review of 45 journals employ experimental evaluation strategies to quantify the causal impact of policies on behavioral changes related to transportation decarbonization. While select studies point to effective strategies to advance fleet shift, public transportation, and traffic congestion policies, studies are limited in their generalizability, few quantify welfare and environmental benefits, and there are no standardized metrics to report welfare or equity impacts.

Of the studies captured in the literature review, only 14 percent (4/29) quantified the welfare impacts of transportation policies. These studies did so using various metrics including the marginal value of public funds, value of improved infant health outcomes, and quantified benefits of reduced congestion.

Twenty percent (6/29) of studies in the literature review addressed the cost efficacy of transportation decarbonization policies. Three of these studies used cost per ton of CO2 avoided and included large ranges of possible CO2 savings based on local context. This underscores the need for additional research on environmental benefits of policies in different settings.

Fifty percent (14/29) of studies discussed equity in some capacity, though there was a wide range in how it was addressed. Three studies in the literature review integrated equity by delineating distributional impacts or by focusing on means-tested programs. Five studies addressed inequities or demographic characteristics within the study pool. The remaining studies called out equity as a research gap or discussed equity as a relevant consideration, but did not relate it directly to the policy evaluation.

There are misalignments between the existing evidence and current policy priorities in the United States. The research topics covered most frequently in the literature review (those with over three studies) are EV purchase incentives and tolls and congestion pricing. Other frequently evaluated interventions (three studies) include fuel economy information, air quality alerts, public transit complements and substitutes, and real time information for public transit. This leaves an evidence gap around many government priorities including increasing public transit ridership and optimization of EV charging infrastructure.

Based on these findings, we have identified areas for further research to address the evidence gap within government priorities. We propose three recommendations to our audience: align research questions to meet the most pressing policy needs; integrate equity and standardized measurement into data collection frameworks; and design research using credible identification methods and standardized welfare metrics. State and local jurisdictions have a momentous opportunity to drive progress by embedding evaluation in innovative policies to quantify emission abatement, delineate distributional impacts, and identify high-impact strategies that are cost-effective, replicable, and equitable.

RECOMMENDATION 1: ALIGN RESEARCH QUESTIONS WITH POLICY PRIORITIES

There is momentum within the federal and local government to advance equitable transportation decarbonization policy. While existing research provides insights into the efficacy of select interventions, more data is needed across several policy areas. The following section outlines priority research areas based on existing evidence and climate action plan trends.

Fleet transition

Many states are working to incentivize EV adoption and equitably develop EV charging infrastructure in a way that is responsive to regional geography, existing infrastructure, and demand.

Nine out of the ten fleet transition-focused studies captured in the literature review examined EV adoption, fuel economy information campaigns and EV rebates. Key results from these studies found that information had limited impact on consumer behavior and that EV rebates were an inefficient carbon reduction strategy. The findings have implications for further research. Muehlegger and Rapson (2023; 2022) found that low-income groups had fundamentally different vehicle purchasing preferences and were more likely to purchase more fuel efficient vehicles relative to higher-income groups regardless of the EV subsidy available. This can help inform how EV uptake strategies are targeted in the future. Similarly, West et al. (2015) found that low-income households made tradeoffs between fuel efficiency and vehicle performance, an important consideration when calculating distributional welfare costs and benefits.

While there is a small evidence base on EV adoption, there is limited experimental evidence addressing EV charger placement and its distributional impacts. Only one study in the literature review discussed EV charging behavior at the household level, however, findings are not generalizable to public charging development.

Priority areas for future research:

- **EV charging placement:** To address EV charging deserts in low-income areas, states are considering co-locating chargers in places where community gatherings take place, such as churches and community centers. More information is needed on how these strategies impact EV uptake and how charger build-out impacts neighborhood factors such as traffic and parking (Unterluggauer et al. 2022). Research is also needed on how to efficiently expand charging access for multi-dwelling housing units. Around 30 percent of US households reside in multi-dwelling residences such as condominiums, apartments, and duplexes. Expanding charging access to these populations is critical to supporting equitable access to EV charging and driving EV uptake in the long term, beyond high-income early adopters (Pierce and Bui 2024). This issue is not currently well addressed in the literature or federal funding programs.

- **Incentives for EV charger installation:** EV charging deployment is uneven across and within regions; charging stations tend to be concentrated in urban, high-income areas. Programs like the California Electric Vehicle Infrastructure Project incentivize regional installation of EV chargers through partnership with municipalities and local utilities (DOE 2022; 2024b). Randomized evaluation can help identify which incentives are most effective and delineate the social, economic, and demographic factors relevant to EV charger placement.

- **Distributional impacts of EV adoption policies:** To further advance research on EV incentive programs such as rebates and Cash for Clunkers, additional research is needed to understand how low-income households make vehicle purchasing decisions, the tradeoffs households make when considering fuel economy, and the impact of the used vehicle market on ICE retirement rates (West et al. 2015; Li, Linn, and Spiller 2013).

- **Consumer preferences:** Studies captured in the literature review highlight the need for more experimental research to better understand the generalizability of charging and consumer preference study findings (Bailey et al. 2023; Gillingham, Houde, and van Benthem 2021).

- **Validate existing policy estimates:** Evaluations quantifying the impacts of EV incentives or subsidies may overstate their efficacy (Muehlegger and Rapson 2023). EV technology and adoption is accelerating rapidly and changing market conditions challenge the external validity of previous estimates. For instance, the efficacy of EV adoption subsidies may decline over time as high-income households purchase EVs. Once the market reaches this early adopter ceiling, other policy mechanisms (e.g., incentives for EV charger installation at the municipal level) may be needed to encourage EV uptake policy among low-income households. Rigorous, policy-relevant research is needed to validate previous estimates as market conditions evolve.

Public transportation

Public transit agencies face fundamentally different challenges today than they did prior to the Covid-19 pandemic. These changes are reflected in the differences between climate action plan priorities and the set of research being conducted on transportation. Specifically, transportation agencies are working to increase ridership while adjusting to new commuting norms, improve the perception of public transit, and balance equitable access with climate goals. Though studies captured in the literature review do point to strategies agencies can use to increase ridership, there is significant misalignment between the research questions being investigated and transit authority evidence needs.

Three of the eight studies on public transit policy evaluated RTI, pointing to welfare benefits such as improved rider attitude and reduced average wait times (Brakewood, Barbeau, and Watkins 2014; Tang and Thakuriah 2012; Brakewood, Macfarlane, and Watkins 2015). There is a general consensus that RTI has a high value for transit riders, and there are many resources transit providers can leverage to roll out comprehensive RTI (MobilityData 2024). Three studies in the literature review examined public transit compliments and substitutes, providing contextual information to governments on how the implementation of bikeshare and rideshare systems impacted transit ridership (Hall, Palsson, and Price 2018; Wang and Lindsey 2019; Campbell and Brakewood 2017). Two studies examined public transit price elasticity, finding that transit ridership was responsive to pricing changes (Davis 2020; Hahn, Metcalfe, and Tam 2023). Hahn, Metcalfe, and Tam (2023) found that a peak pricing scheme was particularly effective in generating welfare impacts and reducing congestion during peak hours in the San Francisco Bay Area. Across studies, authors note their study limitations, including sample size and research setting, calling for more behavioral research to generalize findings.

Priority areas for future research:

- **Micro-transit and mobility strategies:** As cities expand micro-transit and integrate micro-mobility strategies such as bikeshares or electric scooters, more research is needed to understand how new transit offerings impact public transit ridership and the factors that impact access and use of these resources (Price et al. 2021). Data is also needed on the distributional impacts of these new policies, such as increased emissions from micro-transit vehicles.

- **Behavioral shift messaging**: Demand for public transit has fallen dramatically in recent years, particularly among high-income individuals who are more likely to work remotely or have access to personal vehicles (Anderson 2023). More guidance is needed on how best to apply behavioral interventions that shift consumers from ICEs to public transit and other low-emission transportation modes (Whillans et al. 2021).

- **Pricing schemes**: Targeted peak and off-peak public transit pricing has been shown to be a promising strategy to increase welfare and public transit ridership in the long run in specific settings (Hahn, Metcalfe, and Tam 2023). More data is needed on similar programs under different conditions.

Traffic congestion

States and counties are exploring innovative ways to reduce traffic congestion and VMT through holistic strategies such as dynamic toll pricing, app-based behavioral incentives to shift driving times, and universal basic mobility schemes.

Three of the ten traffic congestion studies included in the literature review evaluated toll or congestion pricing schemes and are directly relevant to these efforts. Currie and Walker (2011) quantified the health benefits of reduced traffic congestion near toll plazas while Foreman (2016) and Janson and Levinson (2014) examined the welfare benefits of tolls. Study authors highlight the need to better understand the distributional impacts of these policies in diverse settings, as well as the need to consider structural factors such as housing prices when quantifying welfare impacts.

While there are no peer-reviewed studies on universal basic mobility programs, Hamilton and Wichman (2018) found that bikeshare implementation could be an effective strategy to curb traffic congestion in some metro areas.

Remaining studies on traffic congestion did not show promising results, finding that air quality alerts, driving incentives, and lane expansion did not significantly reduce VMT or overall congestion (Cutter and Neidell 2009; Guerra and Millard-Ball 2017; Sexton 2012; Welch, Gu, and Kramer 2005; Rosenfield, Attanucci, and Zhao 2019; Duranton and Turner 2011).

Given these findings, we suggest the following priority areas for future research:

- **Tolls, dynamic pricing, and behavioral shifts:** Current literature shows that tolls can decrease VMT, shift driving patterns, and have positive welfare benefits. However, results are not consistent across locations. More data is needed across multiple settings and on newer smart-phone based approaches to managing traffic. Cities are also trialing new strategies that support a fuel use or driving tax.

- **Universal basic mobility schemes:** Cities and counties across the United States are piloting mobility wallets or universal basic mobility schemes to reduce emissions and increase transportation access for low-income groups. Programs aim to shift drivers from using ICEs to a mix of low-carbon transit modes including public transit, bikeshares, and EV shares. A pilot of this program is currently underway in Los Angeles and further data will be needed to evaluate the environmental and equity impacts of these strategies (Tu 2024).

RECOMMENDATION 2: INTEGRATE EQUITY INTO STANDARDIZED MEASUREMENT AND DATA COLLECTION FRAMEWORKS

Jurisdictions are required to consider the impacts of a program on historically overburdened groups when applying for federal funding under J40. However, few programs evaluated in the literature review have built equity in as a core component of the policy. To effectively target programs and establish policies that facilitate equitable decarbonization, policymakers must consider the mechanisms that are driving transportation disparities and proactively build infrastructure to measure distributional costs and benefits.

Three studies in the literature review delineated distributional impacts or focused on means tested programs and five studies addressed inequities within the study pool. To integrate equity, it is important to consider both the distribution of benefits and burdens. Beyond focusing on disadvantaged populations, policymakers should also account for how investments often overly favor historically advantaged populations in ways that generate unequal outcomes. Data and indicators that are able to estimate benefits and burdens should be identified and collected at the most disaggregated scale available. Research that centers historical and existing marginalization forces is better positioned to identify, isolate, and address factors that drive transportations system inequities (Advani et al. 2024).

Addressing systemic inequities is critical to improving transportation efficiency and realizing welfare gains for all users. The literature review demonstrates the difficulty in comparing equity implications across studies because of inconsistent definitions, data collection instruments, and measurements. The following research practices can enable governments and researchers to better understand the equity implications of new policies:

- Understand the historical, political, and economic factors that have impacted how state and local transportation conditions are experienced differently across different populations. Identifying mechanisms, such as readlining or gentrification patterns, that have led to transportation access disparities can provide a starting point to better understanding how people engage with transportation systems.

- Disaggregate data by the most relevant indicator associated with the uneven distribution of transportation policy outcomes (e.g., demographic, place-based, and socioeconomic indicators). For instance, if the evaluation is interested in changes in transit ridership, researchers can identify aspects that can influence how accessible the transit system is to people of different genders, physical abilities, and incomes.

- Collect baseline data to bolster analysis of distributional impacts. Evaluating results by quantile could also contribute to our understanding of the variation of treatment effects across different income, ethnicities, genders, for example.

Rigorous research will improve our understanding, identifying, and measuring mechanisms that lead to differential outcomes. The Federal government, through Justice40, has spurred interest in measures that can identify and direct funds toward disadvantaged and overburdened populations. The following table (Table 7) provides an overview of the approaches the different government agencies are taking to measure and identify equity impacts. Research can also play a role in stress testing current measures and identifying new indicators.

Table 7: Measurement tools for policies targeting decarbonization benefits and burdens

TOOL NAME	DESCRIPTION	METHODOLOGICAL LIMITATIONS
Climate Environmental Justice Screening Tool (CEJST 2024a)	Web-based interactive geospatial mapping tool that identifies disadvantaged communities. Uses datasets including indicators of burdens in eight categories: climate change, energy, health, housing, legacy pollution, transportation, water and wastewater, and workforce development. Each measurement of burden includes indicators and definition of disadvantage. (CEJST 2024b). Layers can be toggled on and off to identify dimensions such as power plant emissions or area demographics. This tool was developed by mandate through Executive Order 14008.	Binary indicator of disadvantage. A community is marked as disadvantaged if the census tract meets two criteria. First, it is at or above the threshold for one or more environmental, climate, or other burdens (most often the 90^{th} percentile of exposure). Second, it is at or above the threshold for an associated socioeconomic burden (CEJST uses a 65th percentile threshold to identify disadvantaged communities). Burdens are identified using percentiles (capturing distribution) or binary identification for indicators that are not continuous.
US DOT Equitable Transportation Community (ETC) (DOT 2024c)	Web-based interactive geospatial tool. Designed to complement CEJST with transportation related causes of disadvantage. Measures the cumulative burden communities experience from underinvestment in transportation in the following five components: Transportation Insecurity (DOT 2024a), Climate and Disaster Risk Burden, Environmental Burden, Health Vulnerability, and Social Vulnerability. The identification method focuses on cumulative impacts of transportation disadvantage (DOT 2024b).	Provides an overall disadvantage component score, created by normalizing and summing indicators within each component. The tool displays percentile rankings compared with other census tracts in the state (for state results) or the country (for national results). The ranked component scores are summed across all components to generate an overall score. The Transportation Insecurity component was double weighted. If the overall index score places the tract in the 65 percentile (or higher) of all US census tracts, the tract is considered to experience disadvantage.
Environmental Justice Screening Tool (EPA 2024a)	EJScreen is an environmental justice mapping and screening tool that provides the EPA with a national dataset and systematic approach for combining environmental and demographic socioeconomic indicators. The tool does not identify a community as disadvantaged or not disadvantaged but does include indicators of environmental justice. Authors recommend supplementing	Displays indicators across thirteen environmental indicators; seven socioeconomic indicators; thirteen EJ indexes; thirteen supplemental indexes. The environmental justice indexes combine demographic indicators and indicators for various exposures to environmental burdens (EPA 2024c). Transportation-related indicators include PM 2.5, Ozone, Diesel PM, air toxics cancer risk, air toxics respiratory HI, toxic release to air, and traffic proximity. Other

TOOL NAME	DESCRIPTION	METHODOLOGICAL LIMITATIONS
	with additional data and local knowledge.	indicators less relevant to transportation include lead paint, superfund proximity, rmp facility proximity, hazardous waste proximity, underground storage tanks, and wastewater discharges.
DOE Energy Justice Dashboard (DOE 2024a)	The dashboard identifies disadvantaged communities (DACs) and Tribal land, overlaying information about existing Energy Justice investments. An interactive mapping tool allows users to toggle an equity layer to display. The tool uses indicators from EJScreen to consider pollution-related burden and DOE's Low-Income Energy Affordability Data (LEAD) Tool to evaluate energy-related burden (OEDI 2020).	A census tract is identified as disadvantaged based on measures of cumulative burden using 36 indicators reflecting fossil-fuel dependence, energy burden, environmental and climate hazards, and socioeconomic vulnerabilities. The percentile value for each indicator was identified and summed to develop a score for each tract. The top 20 percent of census tracts in each state were identified into a sample of exposed tracts. Tracts where at least 30 percent of households were below an income threshold were identified as disadvantaged.

RECOMMENDATION 3: DESIGN RESEARCH USING CREDIBLE IDENTIFICATION STRATEGIES AND STANDARDIZED WELFARE METRICS

While the body of evidence on the causal effects of climate policies is growing, policymakers still have limited research to draw from as they operationalize local climate action plans. Even for policy areas that are relatively well covered in the literature review, such as EV incentives and congestion pricing, it is challenging for policymakers to compare results and assess which programs will align best with local conditions. Though seventeen studies in the literature review discuss the welfare or environmental impacts of policy changes in some capacity, few quantify these costs and benefits. Of the studies captured in the literature review, four studies quantified welfare impacts, six studies quantified policy-driven CO2 reductions, and ten studies included information about the public or private costs associated with the policies assessed. Studies that did quantify welfare or environmental impacts did so using a variety of outcome metrics and assumptions, making it difficult to compare across studies. Many studies had sample size limitations and authors highlighted the need for additional research to understand the welfare impacts of climate mitigation policies under a variety of conditions, particularly as climate mitigation technology advances (Clinton and Steinberg 2019; Li, Linn, and Spiller 2013; Cutter and Neidell 2009; Duranton and Turner 2011; Guerra and Millard-Ball 2017; Hamilton and Wichman 2018; Brakewood, Barbeau, and Watkins 2014; Campbell and Brakewood 2017; Davis 2020).

Addressing transportation emissions is a vital component of mitigating climate damage and reducing negative impacts on historically disadvantaged groups. Capitalizing on federal funding opportunities also requires policymakers to make rapid decisions about which actions to prioritize. To address the current research gap in a way that maximizes utility for local and state policymakers, future research should employ credible identification methods and standardize welfare and environmental metrics.

Credible identification methods

Research designs that use credible identification strategies will grow the transportation decarbonization evidence base and enable state and local jurisdictions to better assess effective policies and capitalize on federal funding opportunities. Randomized evaluations, regression discontinuity designs, and other credible research methods enable researchers to isolate a specific causal mechanism and theory of change. Isolating the mechanism behind a behavior shift, such as a reduced transit fare, enables researchers and policymakers to then assess which local factors drove the behavioral response. While it is not feasible to evaluate every policy in every setting, these research methods can enable policymakers to determine how local conditions compare to the tested setting and assess how a policy mechanism may impact transportation behavior (Bates and Glennerster 2017).

Standardized welfare and environmental metrics

Studies quantifying welfare or environmental impacts are challenging to compare due to the range of outcome metrics used. To calculate CO2 emission-related impacts, studies in the literature review combine data sources and base estimates on varying assumptions. Studies base environmental findings on the Social Cost of Carbon as defined by the Interagency Working Group (Hamilton and Wichman 2018; Li, Linn, and Spiller 2013; Hoekstra, Puller, and West 2017), Eisele et al.'s (2013) analysis of the relationship between CO2 emissions and traffic congestion (Hamilton and Wichman 2018), Holland et al.'s (2016) estimates of the environmental benefits of EVs based on location (Clinton and Steinberg 2019; Hoekstra, Puller, and West 2017), and emission estimates based on grid composition (Muehlegger and Rapson 2023). Welfare metrics are also reported on vastly different scales. Currie and Walker (2011) used the social cost of premature births to quantify policy benefits; Hamilton and Wichman (2018) used the personal economic benefit of reduced commute times; Hahn, Metcalfe, and Tam (2023) leveraged the Marginal Value of Public Funds (MVPF). This creates a challenging situation for state and local policymakers as they evaluate which policies are most cost-effective and best align with local climate priorities.

Empirical metrics such as MVPF can address this challenge by standardizing policy costs and benefits, enabling policymakers to make 1:1 comparisons of results across transportation and other climate-focused policies. MVPF is the ratio of beneficiaries' willingness to pay for a policy to the net government cost associated with the policy. A key advantage of the MVPF framework is that it accounts for the costs and benefits of inframarginal transfers, or costs and benefits incurred by individuals who do not change their behavior in response to a policy. For instance, the MVPF incorporates the costs and benefits of providing an EV subsidy to a consumer who would have purchased an EV regardless. This overcomes limitations of using costs per CO2 metrics alone and helps address concerns about how a policy may impact different consumers (Hahn et al. forthcoming).

Government cost can be defined multiple ways and can include the direct government expenditure related to the policy, fiscal externalities or increases in government costs as a result of responses to the policy, and opportunity cost of the spending (Finkelstein and Hendren 2020). In assessing government costs of providing pre-paid transit cards, for example, costs would include the direct cost of the cards, costs incurred from the associated increased demand for public transit services, and lost revenue from highway tolls or gasoline taxes.

Willingness to pay captures the benefits and costs of a policy across beneficiary groups (Hendren and Sprung-Keyser 2020). Collecting the data needed to disaggregate willingness to pay across income, race, gender, and age can help assess the distributional impacts of transportation policies and inform equitable policy implementation. For example, the MVPF of a policy that provides off-peak EV charging incentives may be higher for higher-income groups than for low-income groups.

Hahn et al. (forthcoming) demonstrates how MVPF can be used to compare climate policies, applying the framework across a comprehensive set of rigorously evaluated US climate policies. Notably, they demonstrate how MVPF can account for future benefits and declining prices of new technology over time. This "learning by doing" effect suggests that subsidizing high abatement-cost technology today may create spillover effects and generate environmental and welfare benefits in the future.

To apply this framework across policies, Hahn et al. (forthcoming) translate policy-driven behavior changes (e.g., car purchases) into changes in emissions, applying a dollar value of externality using the social cost of carbon. They construct two MVPF estimates for each policy: an estimate at the year the policy was implemented in the relevant study and an estimate of MVPF as if it were implemented nationally in 2020. This strategy allows for comparison across policy landscapes, time, and place.

As an example, Hahn et al. (forthcoming) apply this framework to the Enhanced Fleet Modernization Program (EFMP) pilot in California evaluated by Muehlegger and Rapson (2022). The EFMP provided means-tested subsidies to incentivize EV adoption. Eligible zip codes included "disadvantaged" households, as defined by the Cal-EPA EnviroScreen tool, in the pilot areas: the San Joaquin Valley and South Coast Air Quality Management (AQMD) zones. Muehlegger and Rapson (2022) found that demand for EVs was relatively elastic and that the subsidy had a high passthrough rate, with consumers receiving about 85 percent of the subsidy. Hahn et al. (forthcoming) combine these findings with analysis from Holland et al. (2016) and data from the EPA Avoided Emissions Generation Tool to calculate lifetime emission savings of an EV compared to a counterfactual vehicle. The analysis determines the overall willingness to substitute toward EVs based on the climate benefits that accrue locally and globally. Hahn et al. also account for "learning by doing" externalities, which in this case relate to the decreasing price of lithium-ion batteries used in EVs. They find that adding these externalities increases the value of the subsidy by around 20 percent. Finally, the analysis considers the rebound effect of the policy on electricity prices and gasoline distributors, determining that the subsidy generates $1.60 per $1 of subsidy spending overall.

Hahn et al. calculate cost of the EFMP by accounting for California and federal EV tax credits, the estimated loss of tax revenue from gasoline consumption, and the estimated impact of climate change-related productivity reduction. The final MVPF of the EFMP is .99, indicating that a $1 increase in government subsidy from 2015–2018 would have led to $0.99 in benefits. However, in this case, the high subsidy drives down the MVPF. When Hahn et al. calculate the value of the California subsidy as if no federal credit is offered, they find that the first $1 of the subsidy has an MVPF of 1.5.

The final component of the Hahn et al. (forthcoming) MVPF analysis estimates the MVPF in 2020 terms, using the same elasticity rates as the baseline 2015–2018 estimate, but with updated environmental emissions and damage estimates, lower EV costs, and a reduced federal subsidy. Analysis finds a higher MVPF of 1.51. This difference is due largely to different subsidy baselines. In 2015, when CEFMP was implemented, average subsidies were around $7,000 in California, whereas the 2020 average was around $604.

There are multiple advantages of the MVPF framework. First, this analysis is flexible. Researchers and policymakers can vary assumptions such as the type of vehicle displaced by an EV or the makeup of the electric grid. Second, it overcomes limitations of relying on a singular cost of carbon metric by accounting for intramarginal benefits both locally and internationally. Finally, the MVPF framework can incorporate willingness to pay as the sum of multiple subgroups, which can help capture variation in consumer demand (Hahn et al. forthcoming). Incorporating MVPF as an analysis metric when reporting research results enables policymakers to compare strategies directly across welfare, environmental, and cost efficacy metrics to make decisions that align best with local needs.

CONCLUSION

Historic levels of federal investment have created a unique window of opportunity to address both climate and equity crises within transportation systems in North America. Local jurisdictions are at the forefront of policy action, testing new strategies to decarbonize transportation through policy-driven behavior change. However, to create the systematic changes needed to abate transportation emissions and inequities in the distribution of transportation benefits and burdens, policymakers need more data on which policies are high-impact and cost-effective. Through a systematic literature review, this research synthesizes existing experimental evidence on transportation decarbonization policies and proposes a future research agenda.

Local jurisdictions and transit agencies face real constraints around funding, resources, and infrastructure. Individual behavioral changes are not a panacea for climate action and will not alone be enough to address centuries of political, economic, and social factors that impact disadvantaged groups. However, understanding the behavioral mechanisms that support the transition from ICEs to low or zero carbon transit modes is critical to meeting the current funding window to maximize decarbonization progress. By leveraging opportunities to embed randomized evaluation in innovative policies to quantify emission abatement, delineate distributional impacts, and identify high-impact strategies that are cost-effective, replicable, and equitable, state and local jurisdictions are well positioned to drive momentous progress toward a decarbonized and equitable transportation system.

APPENDIX A: LITERATURE REVIEW RESULTS

Table A1 lists journals searched for the literature review and the number of studies included in the final literature review set from each journal.

Table A1: Journals included in literature review

JOURNAL NAME	STUDIES INCLUDED
American Economic Journal: Economic Policy	3
American Economic Review	1
American Economic Review Insights	0
Econometrica	0
Economics of Transportation	0
Energy and Environment	0
Energy and Environmental Science	0
Energy Efficiency	0
Environment and Behavior	0
Environmental and Resource Economics	1
Environmental Health Perspectives	0
Environmental Research Letters	0
Green Energy and Environment	0
Journal of Air Transport Management	0
Journal of Economic Literature	0
Journal of Economic Perspectives	0
Journal of Environmental Economics and Management	4
Journal of Environmental Economics and Policy	0
Journal of Environmental Health	0
Journal of Environmental Management	0
Journal of Political Economy	0
Journal of Public Economics	2
Journal of the Association of Environmental and Resource Economists	1
Journal of Transport Economics and Policy	0
Journal of Travel Research	0

Journal of Urban Economics	1
Nature	0
Nature Communications	0
NBER working paper series	4
Proceedings of the National Academy of Sciences (PNAS)	0
Regional Science and Urban Economics	0
Research in Transportation and Business Management	0
Research in Transportation Economics	0
Science	0
The Review of Economics and Statistics	0
Transport Economics and Management	1
Transportation	1
Transportation Research Part A: Policy and Practice	4
Transportation Research Part B: Methodological	0
Transportation Research Part C: Emerging Technologies	2
Transportation Research Part D: Transport and Environment	3
Transportation Research Part E: Logistics and Transportation	0
Transportation Research Part F: Traffic Psychology and Behaviour	0
Urban Affairs Review	0
Utilities and Policy	0

APPENDIX B: FLEET SHIFT STUDIES

Allcott, Hunt, and Christopher Knittel. 2017. "Are consumers poorly informed about fuel economy? Evidence from two experiments." *National Bureau of Economic Research*, NBER Working Paper, No. 23076 (January). https://doi.org/DOI 10.3386/w23076.	
Location:	US (Nationwide)
Methodology:	RCT/ Field experiment
Result significance:	Null

Study design: This study assessed if providing fuel economy information caused consumers to buy higher fuel-economy vehicles. To address this research question, authors conducted two field experiments. The first provided fuel economy information to consumers via in-person survey at seven Ford dealerships across the US. The second provided similar information to consumers planning to purchase a new vehicle sourced from a nationwide online survey. The study followed up with consumers to record the type of vehicle ultimately purchased. In both experiments, consumers received a baseline stated-choice preference survey and were randomly assigned to treatment and comparison groups. Groups received the following information:

- In person
  - *Treatment group*: participants received additional questions on fuel economy, additional information on MPG, tailored annual and lifetime fuel costs for the participants' current vehicle and the vehicle the participant was considering.
  - *Comparison*: participants baseline stated-choice preference survey only.
- Online
  - *Treatment group 1*: the "Base Only" group received additional information on MPG, tailored annual and lifetime fuel costs for the participant's current vehicle, first and second choice vehicles, and for the highest MPG vehicle in the same vehicle class the first choice.
  - *Treatment group 2*: the "Base + Relative" group received information on potential fuel savings based on self reported weekly mileage for the participant's first and second choice vehicles and the vehicle with the highest MPG in the same vehicle class as the first choice. These savings were compared to fuel savings that would be obtained at the national average mileage of about 12,000 miles per year.
  - *Treatment group 3*: the "Base + Climate" group received information comparing the social damages from carbon emissions for the first and second choice vehicles and for the vehicle with the highest MPG in the same vehicle class as the first choice.
  - *Treatment group 4*: the "Full" group received all information included in treatment groups 1, 2, and 3.
  - *Comparison*: the online experiment included four comparison groups that paralleled treatment arms in length, text and graphics but did not contain fuel economy information.

Sample size: Seven car dealerships (375 vehicle buyers) and online via the ResearchNow market research panel (1,489 vehicle buyers)

Results: In the follow-up surveys for both experiments, the study found no statistically significant effect of information on average fuel economy of purchased vehicles.

Study period:

- *Dealership:* the intervention took place between December 2012 and April 2014. The follow-up surveys were conducted via phone from August 2013 to September 2014.
- *Online:* the baseline survey and intervention were delivered in March 2015. Follow-up surveys were conducted in two rounds; July 2015–November 2015 and August 2016–September 2016.

Data collection method: Survey.

Cost efficacy: N/A

Welfare and environmental impacts: N/A

Equity: N/A

Bailey, Megan R., David P. Brown, Blake C. Shaffer, and Frank A. Wolack. 2023. "Show me the money! Incentives and nudges to shift electric vehicle charge timing." *National Bureau of Economic Research*, NBER Working Paper, No. 31630 (August). https://doi.org/DOI 10.3386/w31630.

Location:	Calgary, Alberta, Canada
Methodology:	RCT
Result significance:	Significant

Study design: Bailey, Brown, Shaffer, and Wolak (2023) conducted a field experiment in Alberta, Canada to assess the willingness of EV owners to shift their charging windows in response to financial incentives and moral information. Participants were randomly assigned to a control group and two treatment groups. The "nudge" group received information on the societal benefits of grid charging in off-peak hours and the "reward" group received a financial incentive of 3.5 cents per kWh (a ~23 percent discount off retail price) on all off-peak charging (10pm–6am). In phase two of the study (August 31, 2022), the "reward" group was randomized again to a "rewards stop" group that no longer received a discount and a "rewards continue" group. The "rewards continue" group continued to receive the 3.5 cents per kWh financial incentive through the conclusion of the study on December 31, 2022.

Sample size: Total 150 households

- Phase one:
  - Reward: 68
  - Nudge: 45
  - Comparison: 37
- Phase two:
  - Rewards stop: 35
  - Rewards continue: 33

Results: The study found that financial incentives were very effective in shifting the timing of EV charging, whereas the nudge treatment did not have a significant effect. The receipt of a 3.5¢/kWh credit led to a 37 percent increase in off-peak at home charging kWhs from a pre-treatment "rewards" group mean of 1.2280 kWhs. Data showed a commensurate decrease in peak at home charging ($P<.05$). The estimated off-peak price elasticity for the "rewards" group was -1.59. This is much larger than estimated price elasticities of household-level consumption from time-of-use price signals, which are estimated in the range of -0.10 to -0.20. When the "rewards stop" group stopped receiving the financial incentive, charging behavior did not differ significantly from the comparison group, suggesting the financial incentive did not create long-term habit changes. The "nudge" group did not change their peak charging post treatment, but the data suggest this group did start charging more away from home.

Study period: February 1, 2022–December 31, 2022

Data collection method: In-vehicle monitoring device to record charging information.

Cost efficacy: The 3.5¢/kWh discount was cost-effective for retailers serving these households. The wholesale market price difference between peak and off-peak hours in Alberta during the time of the study was 8.9¢/kWh.

Welfare and environmental impacts: N/A

Equity: The study noted that the sample of EV owners is not generalizable to the broader population of Calgary or other groups of potential EV buyers. Authors referenced the high average education level among the study pool as one variable representing these differences. Over 80 percent of study participants had a bachelor's degree or higher compared to 37 percent of the Calgary population overall.

Clinton, Bentley C., and Daniel C. Steinberg. 2019. "Providing the spark: Impact of financial incentives on battery electric vehicle adoption." *Journal of Environmental Economics and Management* 98 (102255): 1–18. https://doi.org/10.1016/j.jeem.2019.102255.	
Location:	US (Nationwide)
Methodology:	Quasi-experiment (DID)

Study design: Clinton and Steinberg (2019) leveraged the heterogeneity in subsidy types and vehicle models offered across the United States to evaluate the impact of incentives on vehicle purchasing behavior. The study also examined behavior differences between Tesla buyers and buyers of other EV models. States were classified into two groups: those with incentives active during the full study period and those with incentive levels that change during the study period.

To estimate emission reductions achieved by EV incentives, authors combined state-level incentive effects with spatially detailed emissions damage estimates from Holland et al. (2016).

Sample size: Analysis included 3,864 BEV registrations.

Results: Analysis suggested direct purchase rebates increased EV registrations by 8 percent per $1,000 of incentive offered. This represents an 11 percent increase in total EV adoptions compared to the counterfactual scenario in the absence of state-level incentives ($P<.05$). Incentives offered as state income tax did not have a statistically significant impact on EV registrations. Consumer behavior did not vary based on the type of vehicle (Tesla or other battery EV) purchased.

Study period: Rebate incentives from 2011–2015

Data collection method: Battery EV registration data was compiled from multiple annual snapshots of total vehicle registrations in the United States. States included CA, IL, TX, PA, HI, TN, MA.

Cost efficiency: Cost per Mt CO2 avoided ranged from $73–$78 in an off-peak charging scenario accounting for marginal adopters only. Incorporating the marginal cost of public funds and considering all inframarginal and marginal adoptions, the total cost per Mt CO2 avoided was $447–$479 (assuming ten-year vehicle life). Assuming a five-year vehicle life, estimates were $145–$156 per Mt CO2 avoided for marginal adopters and $894–$958 per Mt CO2 avoided for marginal and inframarginal adopters.

Welfare and environmental impacts: Though the environmental benefits of EV rebates were positive at a national level, this study found that state-level impacts were mostly negative. Many of the states that offered EV incentives were in areas where the emission impacts of EVs are greater than ICEs due to grid composition and the emissions generated by charging. EV subsidies had positive emissions benefits in two of the states that offered rebates: California and Texas. National-level benefits were largely driven by high EV adoption in California. Estimates were determined by combining state-level incentive effects with emissions data from Holland et al. (2016).

Equity: N/A

Gallagher, Kelly Sims, and Erich Muehlegger. 2011. "Giving green to get green? Incentives and consumer adoption of hybrid vehicle technology." *Journal of Environmental Economics and Management* 61 (1): 1–15. https://doi.org/10.1016/j.jeem.2010.05.004.	
Location:	US (Nationwide)
Methodology:	Regression
Result significance:	Significant

Study design: Gallagher and Muehlegger (2011) evaluated how state incentives impacted hybrid vehicle sales in the United States from 2000 to 2006. The study also examined the effects of different incentive types and the impact of gas price on hybrid adoption. State incentives considered in this analysis included income tax credits, sales tax waivers, and single-occupancy HOV lane access. To assess how gas prices impacted hybrid sales, authors calculated the average tax-inclusive gasoline prices for each state in each quarter included in the analysis and estimated hybrid fuel cost savings relative to a comparable ICE vehicle. The primary dataset combined state incentives and state-quarter-vehicle model sales data for the eleven hybrid vehicle models introduced from the first quarter of 2000 to the fourth quarter of 2006. The impact of each incentive was analyzed by regressing the log of per-capita vehicle sales on the value of tax incentives, the presence of HOV access, annual fuel savings, and state demographic characteristics.

Sample size: The sample included 4,781 observations at the state-quarter-vehicle model level.

Results: The study analyzed how state incentives varied by vehicle model. Results showed that incentives were positively associated with hybrid vehicle sales, but that different types of incentives had significantly different impacts. Overall, a tax incentive of $1,000 was associated with a 5 percent increase in hybrid sales (P<.10). Increasing the incentive by 1 percent of the vehicle's manufacturer's suggested retail price (MSRP) was associated with a 1.2 percent increase in sales (P<.10). Sales tax waivers (mean value $1,077) were significantly more effective than income tax credits (mean value $2,011). Authors rejected the hypothesis that sales tax waivers and income tax credits had equal effects (P<.02). A $1,000 incentive increase was associated with a 45 percent increase in hybrid vehicle sales if provided via a tax waiver compared to a 3 percent increase in sales when provided via an income tax credit.

HOV lane access had a significant positive effect in Virginia only. Single occupancy HOV lane access was associated with a 92 percent increase in hybrid sales (P<.01). Authors suggest that this is likely driven by the use of carpool lanes to travel to and from the Washington DC metro area.

The study found that fuel saving was a significant driver of hybrid purchases. A $100 increase in annual fuel savings relative to a comparable non-hybrid vehicle was associated with a 13 percent increase in hybrid sales (P<.05).

Per-capita income was also a significant factor. A one standard deviation increase in per-capita income was associated with a 32 percent increase in hybrid sales (P<.01). Based on these findings, Gallagher and Muehlegger estimate a 14.6 percent discount rate on future fuel savings.

Study period: 2000–2006

Data collection method: This study leveraged quarterly, state-level sales data by model for the eleven hybrid vehicle models sold from 2000 to 2006. Hybrid sales data was sourced from JD Power and Associates' proprietary Power Information Network. State incentives were compiled by contacting each jurisdiction. The analysis included demographic controls from the Current Population Survey.

Cost efficiency: Average state sales tax waivers were much less in value than average income tax waivers, but had a much greater impact on hybrid vehicle sales. The study suggests that transparency and ease of access are important factors in how effective financial incentives are in hybrid vehicle adoption.

Welfare and environmental impacts: N/A

Equity: Demographic controls included for education, income, age, and gender.

Gillingham, Kenneth, Sebastien Houde, and Arthur van Benthem. 2019. "Consumer myopia in vehicle purchases: Evidence from a natural experiment." *National Bureau of Economic Research*, NBER Working Paper, No. 25845 (May). https://doi.org/DOI 10.3386/w25845.	
Location:	US (Nationwide)
Methodology:	RDD
Result significance:	Significant

Study design: Gillingham, Houde, and van Benthem (2019) leveraged an exogenous shift in EPA ratings to analyze how consumers value fuel economy. A 2012 reporting modification changed how fuel economy was reported for 1.6 million vehicles. Authors use the implied changes in willingness-to-pay to quantify behavior shifts.

Sample size: 1.52 million vehicle sale observations.

Results: Results indicated that consumers were indifferent between $1 in future gasoline costs and $0.15–$0.38 in the vehicle purchase price using a 4 percent discount rate. For the 2011–2012 model-year vehicles, consumers were indifferent between a $1 increase in future fuel savings and a $0.38 increase in the upfront vehicle purchase price. The estimate drops to $0.15 for the 2013 model-year vehicles. Conclusions are robust to a wide range of valuation assumptions.

Study period: August 2011–June 2014

Data collection method: Combined dataset on all dealer-reported new vehicle transactions from R.L. Polk from August 2011 to June 2014.

Cost efficiency: N/A

Welfare and environmental impacts: N/A

Equity: N/A

Hoekstra, Mark, Steven L. Puller, and Jeremy West. 2017. "Cash for Corollas: When stimulus reduces spending." *American Economic Journal: Applied Economics* 9 (3): 1–35. https://doi.org/10.1257/app.20150172.	
Location:	Texas, United States
Methodology:	RDD
Result significance:	Significant

Study design: Hoekstra, Puller, and West (2017) evaluated the efficacy of the 2009 Cash for Clunkers program in the United States, exploiting a discontinuity in the eligibility criteria. The Cash for Clunkers program provided rebates to car buyers who traded in eligible vehicles and purchased new, more fuel efficient vehicles. The program was launched as a stimulus program to increase spending on new vehicles in response to the Great Recession. Cash for Clunkers also aimed to improve fleet fuel economy by requiring vehicles purchased as part of the program to comply with stringent fuel economy standards. Vehicles rated at eighteen MPG or lower were eligible for the program. Authors compared purchasing behavior between Texas households with barely eligible and barely ineligible vehicles.

Sample size: The sample included 4.5 million Texas households that purchased new vehicles during the Cash for Clunkers program or in the eight months following the program's conclusion (July 2009 to April 2010). Included households owned no more than seven vehicles in June 2009 and owned a potential "clunker" with an EPA rating between 14 and 23 MPG.

Results: The study found that households with vehicles eligible for the Cash for Clunkers program were significantly more likely to purchase new cars during the two months the program operated (discontinuity $P<.01$). However, the discontinuity disappeared seven to eight months after the program ended and the analysis estimated that nearly 60 percent of vehicles purchased under the program would have been purchased during the two-month purchase period anyway. In the eight months following the program, barely eligible and barely ineligible households were equally likely to have purchased a new vehicle since the beginning of the program.

Barely eligible households purchased smaller, less expensive vehicles under the program and spent an average of $8,000 less on new vehicles than they otherwise would have ($P<.01$). While the program did increase short-term spending, it reduced cumulative long-term spending. On average, vehicles purchased under the program were three MPG more fuel efficient than vehicles that would have otherwise been purchased.

Timeline: The Cash for Clunkers program ran from July 1st, 2009–August 24th 2009. The study includes purchase data from July 2009–April 2010.

Data collection method: The study used vehicle purchase records maintained by the Texas Department of Motor Vehicles. Authors used VIN data to determine fuel economy and other vehicle characteristics. The study also uses data from the National Household Travel Survey to control for household characteristics.

Cost efficiency: The Cash for Clunkers Program allocated $3 billion in subsidies toward the purchase of 677,000 new vehicles nationally. This ultimately reduced revenues to the auto industry by $2–$5 billion over eight months.

Welfare and environmental impacts: Hoekstra, Puller, and West (2017) used data from the Energy Information Administration, Holland et al. (2016), the Interagency Working Group on Social Costs of Carbon (2013), and Muller and Mendelsohn (2009) to estimate environmental benefits of the program. The average fuel economy of vehicles purchased under the program was 25.1 MPG compared to 22 MPG for vehicles that would have been purchased otherwise. This three MPG difference reduces lifetime gasoline use by 859 gallons per vehicle. Emission per mile standards for vehicles with 22 and 25 MPG yield no changes in NO_x, PM2.5, and VOCs, but lead to marginal benefits from CO_2 and SO_2 reduction. In total, the average subsidy cost taxpayers $4,210 and generated $253 in environmental benefits.

Equity: National Household Travel Survey data was used to control for income and demographic characteristics. Distributional impacts were not discussed.

Li, Shanjun, Joshua Linn, and Elisheba Spiller. 2013. "Evaluating 'Cash-for-Clunkers': Program effects on auto sales and the environment." *Journal of Environmental Economics and Management* 65 (2): 175–93. https://doi.org/10.1016/j.jeem.2012.07.004.	
Location:	United States and Canada
Methodology:	Quasi-experimental (DID)
Result significance:	Null

Study design: Li, Linn, and Spiller (2011) employed a difference-in-differences method to estimate the effect of the US Cash for Clunkers program on new vehicle sales, using Canada as the comparison group. The Cash for Clunkers program provided eligible consumers with a $3,500 or $4,500 rebate when trading in a qualifying used vehicle and purchasing or leasing a new, more fuel efficient vehicle. The program launched in late July 2009 and was terminated in late August 2009. The study analyzed two behavior changes: shifting from buying a low to high fuel efficiency vehicle and shifting the time of purchase to take advantage of the rebate program. The study also evaluated the cost-efficiency of reducing gasoline consumption and CO2 emission savings with and without the program.

Sample size: The sample included 16,776 transaction observations from the full sample and 13,976 from the pre-program sample.

Results: The rebate program did not have a statistically significant impact on vehicle sales. Analysis showed that the program increased sales by 370,000 during July and August of 2009. However, data shows that the increase in vehicle sales during June to December of 2009 was practically zero. This implies that of 0.66 million vehicles purchased under the program in the sample, 0.29 million would have been purchased anyway during these two months (90 percent confidence interval) and that 45 percent of rebate spending went to consumers who would have purchased a new vehicle anyway.

Study period: 2007–2009

Data collection method: Analysis used a combined dataset of monthly new vehicle sales for all vehicle models in the United States and Canada during the study period. Vehicle MPG data was sourced from the EPA.

Cost efficiency: The program cost $2.85 billion, generated 678,359 eligible transactions, and reduced CO2 emissions between 9 and 28.2 Mt based on lower and upper bounds of the ninety percent confidence interval. The implied cost per MtCO2 saved was $92–$288 after accounting for criteria pollutants. These estimates exceed the estimates from the United States Government Interagency Working Group on Social Cost of Carbon. In 2010, this range was $5–$65 per ton of CO2.

Welfare and environmental impacts: The implied costs of reducing gasoline consumption and CO2 emissions are quite high: the best-case scenario estimates a cost of over $92 in government expenditure for each ton of CO2 avoided and almost $0.90 for each gallon of reduced gasoline consumption. The analysis did not include the costs of scrapping the traded-in vehicles or the environmental costs of manufacturing and shipping new vehicles.

Equity: N/A

Muehlegger, Erich, and David S. Rapson. 2022. "Subsidizing low-and middle-income adoption of electric vehicles: Quasi-experimental evidence from California." *Journal of Public Economics* 216 (104752). https://doi.org/10.1016/j.jpubeco.2022.104752.[5]	
Location:	California, United States
Methodology:	Quasi-experimental (DID)
Result significance:	Significant

Study design: Muehlegger and Rapson (2022) used a quasi-experimental design to study the impacts of the Enhanced Fleet Modernization Program (EFMP), a California program designed to incentivize low- and middle-income households to scrap old vehicles and purchase more fuel efficient vehicles. This study focused on EFMP pilot regions: San Joaquin Valley and the South-Coast Air Quality Management Districts (AQMD). The program used the Cal-EPA EnviroScreen tool to identify eligible zip codes within AQMDs, providing incentives in zip codes classified as "disadvantaged." This eligibility determination considers household income and pollution exposure levels (income threshold was set to below 400 percent of the federal poverty line). Program incentives were offered on a sliding scale based on household income with a maximum of $5,000.

Using difference-in-differences (DID), matched (DID), and triple-differenced models, this study exploits geographic, temporal, and subsidy-exposure variation to compare eligible and ineligible zip codes and estimate three policy-relevant parameters: the rate of subsidy pass-through for the program, the impact on EV adoption, and the elasticity of demand for EVs among low- to middle-income buyers.

Sample size:
OLS
- Difference in differences: 12,495 households
- Matched DID: 16,415 households
- Triple difference: 2,5139 households

Preferred specification:
- Difference in differences: 12,468 households
- Matched DID: 16,415 households
- Triple difference: 25,112 households

Results: Analysis showed small but statistically significant differences in EV adoption between eligible and ineligible zip codes. Zip codes where all buyers were eligible for the subsidy experienced a 26 percent increase in the number of EVs purchased relative to zip codes where no buyers were eligible (P<.01). This suggests that a $1,000 subsidy increased EV adoption by 9 percent and 16 percent in the South Coast and San Joaquin Valley, respectively. Analysis suggests a subsidy passthrough of 73–85 percent. Price elasticity ranged from -3.2 to -3.3. The preferred specifications suggest the demand elasticity is -2.1.

Study period: 2012–2018. This includes three years pre and post program implementation in 2015.

5 Study found in NBER literature search

Data collection method: Combined dataset: (1) disadvantaged community designations available from CalEPA, (2) program rebate data and (3) transaction-level data on the universe of new and used EVs purchased by California buyers.

Cost efficiency: During the two-year pilot period, this program received approximately $72 million in state funding. Based on these findings, authors estimate that the expected subsidy bill required for California to reach its 2025 EV adoption targets would likely exceed $12-$18 billion.

Welfare and environmental impacts: See Muehlegger and Rapson (2023).

Equity: Means tested subsidy.

Muehlegger, Erich and David S. Rapson. 2023. "Correcting estimates of electric vehicle emissions abatement: Implications for climate policy." *Journal of the Association of Environmental and Resource Economists* 10 (1). https://doi.org/10.1086/721374.[6]	
Location:	California, United States
Methodology:	Quasi-experimental
Result significance:	Significant

Study design: Building on Muehlegger and Rapson (2022), this study compares the average fuel economy of vehicles purchased in disadvantaged zip codes inside and outside of participating AQMDs before and after the start of the EFMP pilot. The study uses a difference-in-differences approach leveraging data on California vehicles purchased between 2015 and 2017. The study analyzed emissions savings under the program by comparing EVs and the emissions produced by the counterfactual vehicle that would have otherwise been purchased.

Sample size: 9,230 observations from 2,474 participants in EFMP.

Results: The study found that EFMP increased the average fuel efficiency of the set of vehicles purchased in a zip code, but that subsidized EV buyers would have purchased relatively fuel efficient vehicles in absence of the program. Vehicle buyers in these zip codes also vary from other California buyers. Without the program, EFMP participants would have purchased vehicles with a fuel economy of approximately 35 MPG, compared to the California average of 22 MPG over the study period ($P<.01$). The study also finds that roughly 80 percent of the vehicles purchased under the EFMP were plug-in hybrids, which are significantly less efficient than EVs. This has significant CO_2 pollution abatement implications.

Study period: 2015–2017

Data collection method: Combined dataset aggregating all vehicles purchased and registered in California during the study period.

6 Study found NBER literature search

Cost efficiency: During the two-year pilot period, this program received approximately $72 million in state funding.

Welfare and environmental impacts: The implied CO_2 savings per EV per year are contingent on the charging energy source used. With natural gas, CO_2 savings are approximately 198kg. With a 50/50 mix of natural gas and renewable energy, CO_2 savings are 1934 kg. This finding suggests EV emissions savings may be overstated by six times to fifty percent when compared to an average new car purchased during the sample period.

Equity: Means tested subsidy.

Siriwardena, Shyamani, Gary Hunt, Mario F. Teisl, and Caroline L. Noblet. 2012. "Effective environmental marketing of green cars: A nested-logit approach." *Transportation Research Part D: Transport and Environment* 17 (3): 237–42. https://doi.org/10.1016/j.trd.2011.11.004.	
Location:	Maine, United States
Methodology:	Quasi-experimental
Result significance:	Significant

Study design: Siriwardena, Hunt, Teisi, and Noblet (2012) analyzed how the Maine Clean Car Campaign impacted green vehicle purchasing decisions from 2004 to 2007 using a quasi-experimental design and nested logit model. In control areas, eco-labels were displayed at car dealerships. In treatment areas, radio and news advertisements were administered in addition to eco-labels.

Sample size: The final dataset included passenger vehicles only. The sample included 20,543 individual observations with 543 available makes and models.

Results: Analysis showed that the marketing campaign had short-term impacts on green car sales (as defined by EPA SmartWay designation). The marketing campaign was conducted from January to May 2005. Treatment areas experienced a 16.6 percent increase in SmartWay car purchase in 2006 relative to comparison areas without marketing ($P<.10$). In 2007, there was no variation in consumer likelihood to purchase green vehicles between treatment and control areas, but the overall eco composition in both areas increased. A potential explanation to this finding is the relative increase in the market supply of SmartWaySM cars over the time period; the percentage of SmartWaySM cars increased from 15 percent in 2004 to 74 percent in 2007. Overall, results from this study suggest that eco marketing can be effective, but a continuous campaign is needed to create sustained consumer behavior change.

Study period: The evaluation ran January–May 2005. The study compares data from 2004 (pre intervention), 2005, 2006, and 2007.

Data collection method: Maine vehicle registration data.

Cost efficiency: N/A

Welfare and environmental impacts: N/A

Equity: N/A

West, Jeremy, Mark Hoekstra, Jonathan Meer, and Steven L. Puller. 2015. "Vehicle miles (not) traveled: Why fuel economy requirements don't increase household driving." *National Bureau of Economic Research*, NBER Working Paper, No. 21194 (May). https://doi.org/DOI 10.3386/w21194.	
Location:	Texas, United States
Methodology:	RDD
Result significance:	Significant

Study design: West, Hoekstra, Meer, and Puller (2015) exploited a discontinuity in eligibility requirements for the 2009 Cash for Clunkers program in Texas to assess household driving response to fuel economy improvements. This study tested the theory that improved fuel economy may increase VMT by comparing household behavior for those with a vehicle with an EPA rating of 18 MPG (eligible for Cash for Clunkers) and 19 MPG (not eligible). The program ran for two months and the study uses data from all households who bought a vehicle within one year of the program starting.

Sample size: 153,821 households vehicle purchases.

Results: This study found a meaningful discontinuity in fuel economy of new vehicles purchased by Cash for Clunkers eligible households relative to ineligible. Eligible households purchased more fuel-efficient vehicles that were cheaper, smaller and lower performing. The barely eligible households purchased vehicles with a fuel economy rating 0.87 MPG higher than the barely ineligible. Program eligibility increased the fuel economy of new car purchases by 3.9 percent ($P<.01$). Point estimates indicated that driving decreased by 1-4 percent as a result of purchasing a more fuel efficient and downsized vehicle ($P<.05$). Eligibility for the program induced new vehicle purchasers to reduce gasoline consumption by 44 to 97 gallons per year, depending upon specification analyzed. These figures represent reductions ranging from 3-7 percent ($P<.05$).

Study period: The program ran from July 1, 2009–August 24, 2009

Data collection method: Combined data set on new vehicle purchase data and odometer readings via VIN data.

Cost efficiency: The total cost for the program was $3 billion. Cash for Clunkers spurred 677,000 vehicle purchases nationwide, 44,000 of which were in Texas.

Welfare and environmental impacts: N/A

Equity: The study discussed the equity implications of trade-offs between higher fuel economy vehicles and lower performing vehicles.

APPENDIX C: PUBLIC TRANSPORTATION STUDIES

Brakewood, Candace, Gregory Macfarlane, and Kari Watkins. 2015. "The impact of real-time information on bus ridership in New York City." *Transportation Research Part C: Emerging Technologies* 53 (April), 59-75. https://doi.org/10.1016/j.trc.2015.01.021.	
Location:	New York, United States
Methodology:	Natural experiment (Panel regression)
Result significance:	Significant

Study design: Brakewood, Macfarlane, and Watkins (2015) built on the methodology used by Tang and Thakuriah (2012) to conduct a natural experiment on real-time information (RTI) for the New York City bus system. RTI was rolled out by borough beginning in 2011. The analysis employed a panel regression to evaluate bus ridership over a three year period, controlling for changes in transit services, fares, local socio-economic conditions, and weather.

Sample size: Average weekday route-level unlinked bus trips across 185 routes operated by New York City Transit (NYCT). Weekday averages were compiled monthly for 36 months (January 2011 through December 2013).

Results: Results showed that RTI increased trips per route per weekday by approximately 118. This represents a 1.7 percent increase in weekday route-level ridership ($P<.01$). Additional analysis, dividing RTI coefficients based on quartiles of bus service per route, indicated that ridership increased only on the routes with the highest levels of service, or those with the highest frequency, span of service, and route length. This suggests RTI increased ridership by 340 trips per weekday in the largest quartile of routes, representing a median increase of 2.3 percent. This finding aligns with findings in Tang and Thakuriah (2012).

Study period: January 2011 - December 2013

Data collection method: NYCT weekday ridership data.

Cost efficiency: N/A

Welfare and environmental impacts: N/A

Equity: N/A

Brakewood, Candace, Sean Barbeau, and Kari Watkins. 2014. "An experiment evaluating the impacts of real-time transit information on bus riders in Tampa, Florida." *Transportation Research Part A: Policy and Practice* 69 (November): 409–22. https://doi.org/10.1016/j.tra.2014.09.003.	
Location:	Florida, United States
Methodology:	RCT
Result significance:	Significant

Study design: Brakewood, Barbeau, and Watkins (2014) used a pre-post control group design to investigate how RTI impacted travel behavior using the Hillsborough Area Regional Transit (HART) system in Tampa, Florida. All participants completed a pre-treatment survey on travel behavior and attitudes toward public transit, they were then randomly assigned to treatment and control groups. RTI was provided to the treatment group through a mobile app, OneBusAway. Five OneBusAway interfaces were made available to the treatment group: a website, two mobile websites for internet-enabled mobile devices (one text-only and one optimized for smartphones), an Android application, and an iPhone application. At the conclusion of the study, a post-treatment survey was administered to both treatment and control groups.

Sample size: 268 study participants

Results: Results suggested that RTI decreased wait time for the treatment group by 1.5 minutes relative to the control group. This represents a 16 percent decline in the overall average wait time reported in the pre-treatment survey (P<.01). Riders in the treatment group also reported feeling significantly more productive, less anxious, less frustrated, and safer in the post-treatment survey compared to the pre-treatment survey relative to the control group (P<.05).

RTI did not impact the mean number of trips and transfers per week or affect users' overall satisfaction level with the transit system. This study was limited by time (less than three months) and difficulty with the smartphone application.

Study period: The pre-treatment survey was conducted in February 2013; the post-treatment survey was conducted during the last two weeks of May 2013.

Data collection method: Pre and post treatment surveys; HART bus ridership data.

Cost efficiency: N/A

Welfare and environmental impacts: The study discussed the general welfare benefits of RTI, including shorter wait times and fewer transfers. RTI can also reduce perceived wait time for users.

Equity: Participants were recruited from a pool of HART riders who were largely transit dependent. Over half of the study participants did not have a driver's license and 66 percent of participants live in households without cars. Based on these sample characteristics, changes in ridership and usage were not anticipated and findings may not be generalizable to a larger population.

Campbell, Kayleigh B., and Candace Brakewood. 2017. "Sharing riders: How bikesharing impacts bus ridership in New York City." *Transportation Research Part A: Policy and Practice* 100 (June): 264–82. https://doi.org/10.1016/j.tra.2017.04.017.	
Location:	New York, United States
Methodology:	Natural experiment (DID)
Result significance:	Significant

Study design: Campbell and Brakewood (2017) used phased CitiBike implementation in New York City as a natural experiment to evaluate the causal link between bikeshare availability and bus ridership. Leveraging data on unlinked daily trips, the study divided bus routes into treated and untreated areas based on the number of bike docks located within .25 miles of each bus route. The study period included bus trips per route on buses operated by New York City Transit (NYCT) from May 27th, 2012 to July 26, 2014, excluding a two-month adjustment period after bikesharing opened. Analysis controlled for miles of bus service, roll-out of real-time bus information, and introduction of the Boro Taxi program, which expanded the service area for-hire cabs to pick up passengers with limited restrictions within the five boroughs. To address concerns about bike share accessibility, researchers conducted the same analysis controlling for MetroCard type. Reduced fare MetroCards are available to riders 65 and older and riders with qualifying disabilities, demographics that are less likely to use bikeshare stations regardless of availability.

Sample size: The study analyzed data across two specifications: bus routes covering Manhattan and Brooklyn and bus routes covering Manhattan only.

- *Manhattan and Brooklyn*:
  - Treatment: 45 routes
  - Comparison: 40 routes
- *Manhattan only:*
  - Treatment: 23 routes
  - Comparison: 11 routes

Results: Results indicate that bikeshare implementation was associated with a significant decrease in bus ridership. The decrease was significant with or without controlling for the existence of bike lane infrastructure and in both the combined Manhattan and Brooklyn dataset and the Manhattan only dataset. Every thousand bikeshare docks located along a bus route were associated with a 2.42 percent decrease in daily unlinked bus trips on routes in Manhattan and Brooklyn ($P<.01$). This represents a total daily fall in bus ridership of around 18,100 rides. Controlling for bike lane infrastructure, the study found a lower treatment effect of 1.69 percent, or approximately 12,600 unlinked bus trips per day ($P<.01$). Results suggest that 50-70 percent of bikeshare users substituted bikeshare use for bus trips. Controlling for MetroCard type did not impact results.

Study period: The study period included bus trips per route on buses operated by NYCT from May 27th, 2012 to July 26, 2014, excluding a two-month bikeshare adjustment period from May–July 2013.

Data collection method: Bus ridership data was collected and provided by NYCT. Data included daily unlinked trips per route, daily unlinked bus trips by route disaggregated by fare type, and scheduled revenue miles per route (miles driven on route when a bus is in service).

Cost efficiency: N/A

Welfare and environmental impacts: The study noted potential welfare impacts of lower bus ridership, but these are not quantified. Decreasing bus ridership could decrease operating costs as well as revenue for the NYCT, which could ultimately be positive or negative. Authors noted the welfare impacts of bikeshare implementation as an area for future research.

Equity: Equity implications noted as a research gap and area for future research.

Davis, Lucas W. 2020. "Estimating the price elasticity of demand for subways: Evidence from Mexico." *National Bureau of Economic Research*, NBER Working Paper, No. 28244 (December). https://doi.org/DOI 10.3386/w28244.	
Location:	Mexico
Methodology:	Natural experiment (RDD)
Result significance:	Significant

Study design: Davis (2020) leveraged exogenous changes in public transit fares in three cities in Mexico (Mexico City, Guadalajara, and Monterrey) to evaluate transit price elasticity using a regression discontinuity design. In all three cities fares were changed by a factor of thirty percent or greater.

Sample size: City level monthly ridership across study period.

- Mexico City: 107 months
- Guadalajara: 62 months
- Monterrey: 108 months

Results: In Mexico City, metro prices increased 67 percent (from MX$3–5), resulting in a 12 percent decrease in ridership. In Guadalajara, the light rail system increased prices by 36 percent, leading to a 9 percent decrease. In Monterrey, metro service was offered free of charge for sixty days resulting in a 61 percent increase in ridership. This ridership increase did not persist when metro fares were reinstated, indicating that the temporary price decrease did not lead to lasting behavior shifts. This study does not explore distributional impacts or the equity implications of fare changes.

Study period: Events of interest:

- Mexico City: December 2013
- Guadalajara: July 2019
- Monterrey: May 2009

Data for four years before and after the rate changes was analyzed where possible. Guadalajara ridership data analyzed was through the end of 2019.

Data collection method: Data was sourced from the Mexican Statistics Institute (INEGI), which collects ridership data from the individual urban rail systems. Data after March 2020 was excluded due to ridership changes resulting from the Covid-19 pandemic. Data was also excluded from September 2017 for Mexico City due to an earthquake that damaged several subway lines.

Cost efficiency: N/A

Welfare and environmental impacts: N/A

Equity: N/A

Hahn, Robert W., Robert D. Metcalfe, and Eddy Tam. 2023. "Welfare estimates of shifting peak travel." *National Bureau of Economic Research*, NBER Working Paper, No. 31629. https://doi.org/DOI 10.3386/w31629.	
Location:	California, United States
Methodology:	Natural experiment, natural field experiment (RCT)
Result significance:	Significant

Study design: Hahn, Metcalfe, and Tam (2023) conducted a natural experiment and a natural field experiment to estimate peak and off-peak price elasticities of urban mass transit using the Bay Area Rapid Transit (BART) system. The natural experiment tested off-peak price changes over a six month period and included 17,500 BART riders and over 3.6 million trips. Riders were staggered into the pricing program over the course of six weeks. Prices were reduced an hour before the peak period (6:30am-7:30am) and an hour after the peak period (8:30am-9:30am).

The natural field experiment evaluated the efficacy of targeted price incentive to shift riders from their typical travel time to a less congested travel period. Over a four month period beginning in December 2018, 1,900 BART riders were recruited via direct outreach at four BART stations and randomly assigned to treatment and control groups. Those in the treatment group received a 25 percent fare reduction for the least-congested train within 45 minutes (before or after) of their typical morning or evening departure time. Participants were phased into the program, with all control group participants receiving reduced fare offers by April 2019. Optimal travel windows were determined using a machine learning platform that drew on participant travel history and a predictive crowding model.

Sample size: Natural experiment: 17,500 BART riders over 3.6 million trips. Natural field experiment: 1,900 riders.

Results: The study found that subsidies shifted travel behavior as expected, decreasing travel during the period without the fare subsidy. Findings from the natural experiment suggested own and cross-price elasticities are -0.86 and 0.44 respectively. The treatment group reduced their share of peak hour trips by 2.1 percentage points during the program and increased their share of off-peak trips by 2.6 percentage points relative to the start of the program ($P<.01$). Ridership data also showed that the subsidy increased overall BART ridership by decreasing congestion during peak periods, attracting riders who would have taken alternate transportation modes during these time windows.

Data from the natural field experiment found that the subsidy increased the probability that riders would travel at the subsidized time compared to the control group. Subsidies that shifted riders to an earlier time increased the probability of traveling at the subsidized time by 3.4 percent (standard error 0.009) and reduced the probability of traveling at their usual time by 3.5 percent (standard error 0.016). Subsidies shifting travel to a later time increased the probability that riders would travel at the subsidized time by 2.2 percent (standard error 0.008) and decreased the probability riders would travel at their usual time by 4.6 percent (standard error 0.017). The own and cross price elasticities estimated in the natural field experiment were -0.94 and 0.54 respectively.

Study period:

- The natural experiment began August 23rd, 2016 and ran for six months.
- Enrollment was staggered to compare "late" versus "early" enrollment groups. The natural field experiment lasted from mid-December 2018 to March 2019. The comparison group received the same pricing offer in April 2019.

Data collection method: To measure congestion, both evaluations use train-level data on the weight of the train and Clipper Card data recording the time the rider entered and left a station.

Cost efficiency: A total of $23,000 in subsidies were given during the field experiment. The average net benefit was $.36 per $1 subsidy.

Welfare and environmental impacts: Welfare impacts varied depending on how the subsidy was targeted. In the natural experiment, shifting travel to off-peak periods had a marginal value of public funds (MVPF) of 1.6 (for each additional $1 of net cost to the government, the marginal benefit to all parties is $1.60). The net benefits per $1 of subsidy in the natural experiment was $0.36 per $1 of subsidy expenditure. Results from the natural experiment showed that targeting made a significant difference - targeting riders on the most congested routes increased the average net benefits by 15 percent. However, accurate targeting requires extensive information about riders which may not be captured by crowding data alone.

The MVPF in the natural field experiment was less than one, indicating the willingness to pay associated with the policy is less than the net cost to the government.

The study also estimated the potential environmental benefits of shifting vehicle travel to BART as a result of the subsidy. Assuming all riders respond similarly to the subsidy and that overall miles traveled remain consistent, authors estimated local pollution benefits equivalent to $70,000 million annually and global CO2 reduction benefits equivalent to $250,000 million per year.

Equity: The study noted that MVPF should not be interpreted as a sole indicator of better policy and that additional equity assumptions would need to be made to determine this relationship.

Hall, Jonathan, Craig Palsson, and Joseph Price. 2018. "Is Uber a substitute or complement for public transit?" *Journal of Urban Economics* 108 (November): 36–50. https://doi.org/10.1016/j.jue.2018.09.003.	
Location:	US (Nationwide)
Methodology:	Natural experiment (DID)
Result significance:	Significant

Study design: Hall, Palsson, and Price (2018) use a difference-in-differences approach to estimate Uber's net effect on public transit ridership across all Metropolitan Statistical Areas in the United States. The study exploited variation between and across markets based on when Uber launched and the intensity of Uber's market penetration (measured by relative number of Google searches in the relevant area).

Sample size: 196 metropolitan statistical areas with Uber presence.

Results: The study found that a one standard deviation increase in Uber's market penetration led to a 1.38 percent increase in transit ridership. This increased to 5 percent after two years ($P<.05$). However, analysis found that results varied depending on city size and transit characteristics. In larger cities, Uber increased public transit use by 6 percent while decreasing ridership in smaller cities ($P<.05$). Transit ridership prior to Uber entering the market was also correlated with the impact on ridership. In cities with public transit ridership above the sample median prior to Uber entering the market, Uber decreased public transit use by 2.1 percent ($P<.05$). Authors suggest that Uber most strongly complements small transit agencies in large cities, likely because these systems provide the least flexibility. Authors posit that transit users in large cities have greater variation in income, and the complementary effects might be driven by riders who can afford Uber.

Study period: The study used transit ridership data and Uber market entry over 2004–2015, specifically the 24 months before and after Uber entered a new city market.

Data collection method: Data on transit ridership was sourced from the National Transit Database. This database contains monthly ridership data points for nearly all transit agencies that receive federal funding and reports ridership separately by mode (e.g., bus, train).

Cost efficiency: N/A

Welfare and environmental impacts: The study highlighted the need for more research to understand these causal mechanisms and the welfare impact of Uber. Though Uber can increase welfare by helping to solve the public transit last mile problem and reducing commute time, it can also increase traffic congestion and associated air pollution.

Equity: N/A

Tang, Lei and Piyushimita (Vonu) Thakuriah. 2012. "Ridership effects of real-time bus information system: A case study in the City of Chicago." *Transportation Research Part C: Emerging Technologies* 22 (June): 146–61. https://doi.org/10.1016/j.trc.2012.01.001.	
Location:	Illinois, United States
Methodology:	Natural experiment (DID)
Result significance:	Significant

Study design: Tang and Thakuriah (2012) leveraged phased implementation of RTI throughout the Chicago Transit Authority (CTA) bus system to analyze the effect of RTI on public transit ridership. The study controlled for unemployment levels, gas prices, local weather, and socioeconomic factors throughout the study period.

Sample size: The sample included 14,450 bus ridership observations.

Results: Results found that average weekday ridership for CTA bus routes increased by 126 trips after RTI was implemented. This represents a 1.8–2.2 percent increase in ridership ($P<.05$). The study also found several control variables that significantly impacted ridership including transit fares, gas prices, unemployment rates, and weather conditions. Authors posited possible explanations for the small impact of RTI detected including lack of awareness about RTI rollout, difficulty in accessing RTI, and the accuracy of the model used to capture ridership changes.

Study period: RTI was rolled out in phases from August 2006–May 2009. Ridership data analysis included data from January 2002 to December 2010.

Data collection method: Data on average weekday ridership was obtained from the CTA.

Cost efficiency: N/A

Welfare and environmental impacts: The study discussed general potential welfare benefits of RTI.

Equity: N/A

Wang, Jueyu, and Greg Lindsey. 2019. "Do new bike share stations increase member use: A quasi-experimental study." *Transportation Research Part A: Policy and Practice* 121 (March): 1–11. https://doi.org/10.1016/j.tra.2019.01.004.	
Location:	Minnesota, United States
Methodology:	Quasi-experimental (DID)
Result significance:	Significant

Study design: Wang and Lindsey (2019) used a quasi-experimental, difference-in-differences study design to assess if new bikeshare stations increased member use in the Minneapolis-St. Paul, Minnesota area. The analysis utilized a six-year panel dataset of member bikeshare trips from 2010–2015, using expansion of the bikeshare network (Nice Ride) over time to establish treatment and comparison groups. To understand how bikeshare network expansion impacted users differently, the study divided bikeshare members into two groups based on their proximity to a bikeshare station. Members living within .25 miles of a bikeshare station throughout their entire membership were defined as living in dense bikeshare areas. Members living more than .25 miles away from a bikeshare station were defined as living in a less dense area.

Sample size: Between 2010 and 2015, Nice Ride had 13,569 unique annual members. Analysis was limited to members within the city boundaries of Minneapolis and St. Paul, producing a final dataset of 9,046 users.

Results: The effect of bikeshare proximity on frequency of member use was small but significant. On average, a .01 mile decrease in distance to a bikeshare station increases weekly usage by 0.3 percent ($P<.01$). This result varied across settings. For members living in dense bikeshare service areas, a .01 mile decrease in distance to a bikeshare station increased use by 12.5 percent ($P<.01$). In less dense areas, a .01 mile decrease in distance increased use by .10%

Bike lane length also had a significant impact on ridership. A one unit increase in bike lane length (0.1 mile) increased weekly trips by 2.3 percent for members in denser bikeshare areas. Bike lane length did not change weekly use for members living in less dense areas. In dense bikeshare areas, weekly bike ridership decreased by 26 percent when a light rail station was installed within a quarter mile of the member's home ($P<.01$). In less dense areas, results indicate that a light rail station installation increased weekly bike ridership by seven percent, though this is not statistically significant. One possible explanation for this result is that these members may be more likely to combine two transportation modes to fulfill their daily travel needs (i.e., bike share is complementary to, and not a substitute for, use of the light rail) in lower-density areas.

Overall, results show that in areas with higher bikeshare density, installing a new station increased use. In less dense areas, increasing bike share access had a smaller impact on use. Authors suggest that installing bike share stations in areas with few existing stations without forming or connecting them as part of a dense network system that combines bike and light rail services may not increase bike ridership significantly.

Study period: 2010–2015 panel dataset of Nice Ride member trips.

Data collection method: Nice Ride membership and use data.

Cost efficiency: Authors noted that more cost-benefit analysis is needed to inform local policy makers on bikeshare station placement.

Welfare and environmental impacts: N/A

Equity: This study noted that bikeshare users are more likely to be white, higher income, younger, and more highly educated compared to the average American population.

APPENDIX D: TRAFFIC CONGESTION STUDIES

Currie, Janet, and W. Reed Walker. 2011. "Traffic congestion and infant health: Evidence from E-ZPass." *American Economic Journal: Applied Economics* 3 (1): 65–90. https://doi.org/DOI:10.1257/app.3.1.65.	
Location:	New Jersey and Pennsylvania, United States
Methodology:	Natural experiment (DID)
Result significance:	Significant

Study design: Using a difference-in-differences analysis, Currie and Walker (2009) examined the impact of E-ZPass toll implementation on health impacts related to air quality in New Jersey and Pennsylvania. Electronic toll systems have been shown to decrease traffic congestion. Authors evaluated how this change impacted birth outcomes among those living in close proximity to toll plazas. The analysis compared incidence of premature birth and low birth rate among mothers within 2km of toll plazas to those between 2km and 10km.

Sample size: The study sample included 98 toll plazas along the Atlantic City Expressway and Pennsylvania Turnpike.

Results: The incidence of premature infant births decreased 6.7–9.16 percent among mothers within 2km of a toll plazas relative to those living between 2km and 10km of plazas ($P<.05$). The incidence of low birth weight fell by 8.5–11.3 percent ($P<.05$). Study results also suggested toll plazas were associated with reduced NO2 levels.

Study period: Data analyzed includes traffic and toll records from Pennsylvania (1997–2002) and New Jersey (1994–2003). E-ZPass tollbooths were installed from December 1999 to December 2001 at a rate of approximately one per month.

Data collection method: Data was sourced from the Vital Statistics Natality records from Pennsylvania (1997–2002) and New Jersey (1994–2003.) Vital Statistics data covers all births in NJ and PA.

Cost efficiency: N/A

Welfare and environmental impacts: A 6.7–9.16 percent reduction in the risk of prematurity can be valued at around $9.8–$13.2 million. This statistic is based on a 2007 Institute of Medicine report estimating the social cost of premature infant birth at $15,600 per infant.

Equity: Authors noted the implicit equity considerations in estimating the benefits of air quality improvements, specifically that wealthier households tend to self-select into areas with higher air quality. The analysis found no significant effects of E-ZPass installation on resident characteristics or housing prices during the study period.

Cutter, W. Bowman, and Matthew Neidell. 2009. "Voluntary information programs and environmental regulation: Evidence from 'Spare the Air.'" *Journal of Environmental Economics and Management* 58 (3): 253–65. https://doi.org/10.1016/j.jeem.2009.03.003.	
Location:	California, United States
Methodology:	RDD
Result significance:	Significant

Study design: Cutter and Neidell (2009) used a regression discontinuity design to analyze the impact of Spare the Air (STA) alerts in the San Francisco Bay Area from 2001–2004. Throughout the study period, STA alerts were issued on days when ozone levels were predicted to exceed National Ambient Air Quality Standards. STA alerts aim to induce a voluntary and altruistic response, encouraging commuters to use public transit rather than personal vehicles to minimize pollution. The study compared transport behavior on days just above and just below the ozone threshold at which an STA alert is issued. The study also included a difference-in-differences analysis comparing traffic volume in Los Angeles, which does not have an STA initiative, to the San Francisco Bay Area on days when STAs were issued.

Sample size: The study included 23 days where STA alerts were issued and 44 days when the air quality forecast was within .010 ppm of the trigger rule but no STA was issued.

Results: The study found significant effects in the regression discontinuity analysis only. Data showed that STA alerts reduced total traffic volume by 2.5–3.5 percent with the largest effect during and just after morning commute periods (95 percent confidence interval). STA alerts did not produce statistically significant effects on total daily public transit ridership.

Study period: 2001–2004

Data collection method: Data on ozone forecasts was sourced from Bay Area Air Quality Management District (BAAQMD). Traffic data was provided by the Freeway Performance Measurement System, a joint project between the University of California at Berkeley and various California state agencies.

Cost efficiency: N/A

Welfare and environmental impacts: The study included a general discussion of potential STA welfare and environmental benefits (e.g., improved air quality). These are not quantified.

Equity: Authors discussed potential equity implications of STA alerts, noting that policymakers must also consider the distributional impacts and costs accrued by different groups. Analysis did not address this directly.

Duranton, Gilles, and Matthew Turner. 2011. "The fundamental law of road congestion: Evidence from US cities." *American Economic Review* 101 (6): 2616–52. https://doi.org/DOI: 10.1257/aer.101.6.2616.	
Location:	US (Nationwide)
Methodology:	Instrumental variable
Result significance:	Significant

Study design: Duranton and Turner (2011) used data from across the United States to analyze the effect of changes in lane kilometers on vehicle-kilometers traveled (VKT). The study used average annual daily traffic and road network data provided by the Highway Performance Monitoring System in 228 metropolitan statistical areas (MSAs) for 1983, 1993, and 2003. Analysis used time series and cross-sectional variation, exploring three instrumental variables (planned interstate highway kilometers from the 1947 highway plan; 1898 railroad route kilometers; and the incidence of major expeditions of exploration between 1835 and 1850) to predict incidence of roads in MSAs, controlling for geographic and population demographic differences between cities.

Sample size: The analysis included 228 metropolitan statistical areas.

Results: The study estimated the elasticity of MSA interstate highway VKT with respect to lane kilometers at 1.03 ($P<.01$). This finding confirms the "fundamental law of highway congestion," where the extension of the interstate leads to a corresponding increase in traffic volume and VKT. The study found that availability of public transportation modes had no impact on congestion levels.

Study period: The study used time series data from 1983, 1993, and 2003.

Data collection method: Data was obtained from the Highway Performance Monitoring System.

Cost efficiency: N/A

Welfare and environmental impacts: N/A

Equity: N/A

Foreman, Kate. 2016. "Crossing the bridge: The effects of time-varying tolls on curbing congestion." *Transportation Research Part A: Policy and Practice* 92 (October): 76–94. https://doi.org/10.1016/j.tra.2016.06.033.	
Location:	California, United States
Methodology:	Difference in differences
Result significance:	Significant

Study design: Foreman (2016) utilized a quasi-experimental design to assess the impact of congestion pricing on traffic volume and travel time during peak hours on the San Francisco-Oakland Bay Bridge. The study capitalized on a policy shift that increased tolls on all seven bridges in the San Francisco Bay Area. While six bridges implemented a flat-rate increase, the Bay Bridge implemented non-uniform congestion pricing: $6 per vehicle during weekday peak hours; $4 per vehicle during weekday off-peak hours; $5 per vehicle on weekends. Analysis employed a difference-in-differences approach to compare traffic variation across comparable time ranges before and after the toll was implemented. Using hour-level data, traffic volume was compared to travel time during each hour of the day from 1:00 am to 11:59 pm before and after July 1, 2010 on the Bay Bridge. The midnight hour before and after the policy change was used as a control.

Sample size: Analysis included 10,000 hourly observations per bridge, per outcome variable.

Results: Findings suggest that drivers responded to toll changes by making fewer overall trips and by shifting Bay Bridge trips to off-peak hours. The study also found suggestive evidence that drivers substituted toward the San Mateo Bridge which had a flat rate toll. Traffic volume across the Bay Bridge during peak hours decreased by an average of 312 vehicles per hour, a 4.2 percent change ($P<.01$). Changes during off-peak hours were not statistically significant. Travel time over the Bay Bridge decreased by two to six minutes, representing a 7-20 percent decrease during peak hours (95 percent confidence interval).

Travel time variability also decreased significantly during peak hours. Standard deviation in travel time across the bridge decreased by 4.1–5.6 minutes (7am and 3pm respectively). Travel time variability decreases were statistically significant ($P<.05$) for all hours except 8pm, 9pm, 10pm, 3am, and 11am.

For peak hour travel over the Bay Bridge, the overall own-price elasticity was 0.084, implying that a ten percent increase in the Bay Bridge toll decreased trips across the bridge by less than 1 percent. Overall, findings suggest that a 50 percent increase in toll prices during peak hours decreased peak trips by about 4.4 percent.

Study Period: This study used data from the year before and the year after the toll change, July 1, 2009 to June 30, 2011.

Data collection method: Hourly traffic volume sourced from the San Francisco Bay Area Metropolitan Commission.

Cost efficiency: N/A

Welfare and environmental impacts: The study discussed the potential welfare impacts of toll pricing, including the psychological and time saving benefits of decreased travel time and reduced travel time variability. Foreman (2016) also noted the potential benefits of reducing traffic volume, which can improve vehicle fuel economy, reduce pollution, and lower bridge maintenance needs. The study estimated that a peak pricing strategy leads to a consumer surplus relative to a flat-rate toll increase, but this is not quantified.

Equity: N/A

Guerra, Erick, and Adam Millard-Ball. 2017. "Getting around a license-plate ban: Behavioral responses to Mexico City's driving restriction." *Transportation Research Part D: Transport and Environment* 55 (August): 113–26. https://doi.org/10.1016/j.trd.2017.06.027.	
Location:	Mexico City, Mexico
Methodology:	RDD
Result significance:	Null

Study design: Guerra and Millard-Ball (2017) evaluated the impact of the license plate-based driving restriction program, 'Hoy No Circula,' on vehicle miles traveled and travel behavior in Mexico City. The Hoy No Circula program launched in Mexico City in 1989 to reduce household vehicle miles traveled and improve air quality. The program restricted private vehicles from driving one day per week based on the license plate number. Previous research on this program has found that Hoy No Circula does not reduce overall vehicle travel. This study evaluated the low-cost behavioral shifts that households make in response to driving restrictions, using 2007 data to analyze how the restriction impacted nine-year-old vehicles (mostly exempt from the program) and ten-year-old vehicles (mostly restricted from driving at least one day per week).

Sample size: The study included 37,546 Mexico City Metropolitan Area (MCMA) Household Travel Survey respondents. The sample included households with at least one vehicle.

Results: Consistent with previous literature on travel restrictions and other analyses of the Hoy No Circula program, this study found that the restrictions had no statistically significant impact on household VMT. Behavioral shifts explored in this analysis include changes in car ownership (e.g., purchasing a second car), reshuffling travel (e.g., moving travel to a different day or clustering trips), network effects (e.g., drivers unaffected by the ban might drive more when the ban is in effect and traffic volume is perceived to be lower), shifting travel to other high-emissions modes of transport (e.g., Uber or mini buses), and driving despite the ban. Findings did not support the theory that households would respond to the restriction by purchasing additional vehicles. There was suggestive evidence that households tended to replace older vehicles (over ten years) that were impacted by the restriction. The study also suggested that households did not drive older vehicles every day, making it easy to cluster trips to unrestricted days. Though households may have shifted travel mode, there was no evidence as to whether drivers switched to a lower-carbon option. Authors concluded that it was very easy for single-vehicle households to avoid the ban with low-cost behavior changes.

Study period: The study used household level data from 2007 MCMA household travel survey.

Data collection method: All data was obtained from the 2007 MCMA Household Travel Survey. The survey collected data from over 50,000 households on income, household size, and composition, and data on over 200,000 weekday trips, including origins and destinations, trip purpose, trip duration, trip time of day, out-of-pocket expenses, and mode of travel.

Cost efficiency: N/A

Welfare and environmental impacts: This study did not quantify the direct welfare or environmental impacts of Hoy No Circula, but the authors did acknowledge that most driving restriction programs are designed with air pollution reduction goals. Authors noted that while Hoy No Circula was not an effective VMT reduction strategy, a more "effective" license-plate restriction system might have higher welfare costs and that the economic welfare costs would depend on alternatives available to households.

Equity: The study discussed potential distributional impacts of more restrictive driving programs.

Hamilton, Timothy L., and Casey J. Wichman. 2018. "Bicycle infrastructure and traffic congestion: Evidence from DC's Capital Bikeshare." *Journal of Environmental Economics and Management* 87 (January): 72–93. https://doi.org/10.1016/j.jeem.2017.03.007.	
Location:	US (Washington, DC)
Methodology:	Quasi-experimental (matching)
Result significance:	Significant

Study design: Hamilton and Wichman (2018) analyzed the causal link between bikeshare implementation and traffic congestion using the phased expansion of Washington DC's Capital Bikeshare program from 2011–2012. The study employed propensity score matching by neighborhood, using the presence of a bikeshare station as the treatment and matching on socioeconomic characteristics, traffic congestion prior to bikeshare installation, and public transportation infrastructure.

Sample size: Data included 165 stations located throughout the metropolitan area and 305 block groups.

Results: Results from the unmated sample showed that the presence of a bikeshare station decreased traffic congestion by .34 percent ($P<.01$). Analysis of the matched sample suggested that bikeshare stations reduced congestion by around 4 percent on average and up to 5.4 percent in neighborhood block groups with high congestion levels prior to bikeshare installation ($P<.01$). Authors noted that the findings are limited due to challenges in estimating the impact of bikeshare stations on neighboring areas and the considerable variation in geographic size and shape of block groups.

Timeline: 2010–2013

Data collection method: Traffic data was obtained through a partnership with the Center for Advanced Transportation Technology (CATT) Lab at the University of Maryland. Traffic speed information was sourced through the Vehicle Probe Project (VPP) Suite within the Regional Integrated Transportation Information System (RITIS).

Cost efficacy: Capital Bikeshare's total operating cost in Washington, DC in 2014 was $5.8 million with a 70 percent cost recovery ratio without government intervention.

Welfare and environmental impacts: A 4 percent reduction in traffic congestion among approximately 19.7 percent of block groups with a bikeshare station reduced annual congestion costs for Washington, DC area commuters by $57 per commuter and $182 million total. This estimate considered the social benefits of shorter travel times and lower fuel consumption. A 4 percent reduction in traffic congestion also implies a $1.28 million annual benefit in congestion-induced CO2 emission reduction. Authors calculated this estimate by multiplying the implied reduction in congestion-induced CO2 emissions from Eisele et al. (2013) by the USSCC 2015 social cost of carbon estimate. These estimates did not consider local environmental benefits or health benefits accrued by biking.

Equity: Authors acknowledged selection bias in bikeshare station placement. Bikeshare stations are located predominantly in wealthy areas of metropolitan Washington.

Janson, Michael, and David Levinson. 2014. "HOT or not: Driver elasticity to price on the MnPASS HOT lanes." *Research in Transportation Economics* 44 (June): 21–32. https://doi.org/DOI: 10.1016/j.retrec.2014.04.008.	
Location:	Minnesota, United States
Methodology:	Field experiment
Result significance:	Significant

Study design: Janson and Levinson (2014) conducted three field experiments on the impact of dynamic congestion pricing on MnPASS High Occupancy Toll lanes on two freeway corridors in the Minneapolis-St.Paul area. Analysis focused on how drivers responded to price increases and willingness to pay for perceived time savings. The highways included in the study (I-394 and I-35W) were segmented, with prices posted for each segment. Tolls ranged from $0.25 to $8.00 and were adjusted every three minutes based on density levels measured in MnPASS lanes.

Sample size: All MnPASS subscribers over 2011–2012.

Results: The study found that driver elasticity to price was positive, ranging from .03 to .85 and that drivers paid between $60 and $124 per hour of travel time saved ($P<.05$). Overall, higher express lane prices increased lane use, contradicting the hypothesis that higher tolls would decrease express lane demand. Authors suggest this was due to the fact that drivers may use lane pricing as an indication of downstream congestion.

Study period:

- I-394 field experiment I: October 8, 2012–November 2, 2012.
- I-394 field experiment II: December 7–21, 2012 and January 7–25, 2013.
- I-35W field experiment: October 29, 2012–November 23, 2012.

Data collection method: Frequency of use data from MnPASS transponders.

Cost efficiency: N/A

Welfare and environmental impacts: N/A

Equity: N/A

Rosenfield, Adam, John P. Attanucci, and Jinhua Zhao. 2019. "A randomized controlled trial in travel demand management." *Transportation* 47 (June): 1907–32. DOI: 10.1007/s11116-019-10023-9.	
Location:	Massachusetts, United States
Methodology:	RCT
Result significance:	Null

Study design: Rosenfield, Attanucci, and Zhao (2020) conducted a six-week randomized evaluation to test strategies to shift communing to reduce employee parking demand at the Massachusetts Institute of Technology (MIT). Participants (all MIT parking users) were split into four treatment groups: the first received weekly informational emails highlighting MIT transit benefits, the second received monetary rewards for reducing days parked on campus, the third received information and monetary rewards, and the fourth was used as a comparison, receiving no emails or rewards. The study evaluated the effect of the interventions on parking demand as a proxy for personal vehicle use.

Sample size: 2,000 MIT employees

Results: Results showed that there was not a statistical difference in on-campus parking use between treatment groups or between treatment and comparison groups. A post-treatment survey showed that employee awareness about MIT transit benefits was much higher than at the start of the evaluation, but there was a high discrepancy between self-reported driving and parking behavior and actual parking demand data collected via parking garage gates. Authors noted that this study took place soon after MIT implemented large changes to its commuting benefits, including provision of free public transportation to employees in the Boston Area. This suggests that the remaining drivers, those in the sample, may have been facing additional barriers to switching to alternate modes of travel.

Study Period: 2015

Data collection method: Pre- and post-treatment survey, parking data collected via parking garage gates on the MIT campus.

Cost efficiency: The program cost $16,600 or $8 per participant.

Welfare and environmental impacts: N/A

Equity: N/A

Sexton, Steven E. 2012. "Paying for pollution? How general equilibrium effects undermine the 'Spare the Air' program." *Environmental and Resource Economics* 53 (4). https://doi.org/DOI:10.1007/s10640-012-9577-z.	
Location:	California, United States
Methodology:	RDD
Result significance:	Significant

Study design: Sexton (2012) built on Cutter and Neidell (2009), analyzing the efficacy of STA alerts in the San Francisco Bay Area from 2002–2009. The analysis exploited a 2004 change to the STA program that offered free public transit on some days the alerts were issued. Researchers compared freeway traffic volume and Bay Area Rapid Transit (BART) ridership on STA days with and without free public transit offerings.

Sample size: Sixty STA alerts were issued during the study period. Free public transit was offered on eleven STA days. Analysis included traffic data from 316 traffic monitoring stations across forty randomly selected freeway segments in the Bay Area.

Results: Findings showed that STA alerts alone increased BART demand by 1.5–1.8 percent. Results were stronger when STA alerts were issued on consecutive days. On STA days with free transit, BART demand increased by 3.6 percent, or roughly 12,600 trips ($P<.01$). Without free transit, STAs had no impact on traffic congestion. However, STA days with free fare were associated with a 1.7–1.8 percent increase in traffic volume, or around 300,000 additional car trips ($P<.10$). The increase in both traffic volume and BART ridership on free fare STA days suggests that people did not substitute away from cars to BART on free fare days, but did substitute away from walking, cycling, or other active transit modes to both cars and BART.

Timeline: 2002–2009

Data collection method: Analysis included hourly aggregated traffic data from 316 traffic monitoring stations across forty randomly selected freeway segments in the Bay Area. Data on transit ridership was obtained through a BART public records request.

Cost efficiency: Providing free fare on STA days costs $2.5 million per day.

Welfare and environmental impacts: N/A

Equity: N/A

Welch, Eric, Xiaohua Gu, and Lisa Kramer. 2005. "The effects of ozone action day public advisories on train ridership in Chicago." *Transportation Research Part D: Transport and Environment* 10 (6): 445–58. https://doi.org/doi:10.1016/j.trd.2005.06.002.	
Location:	Illinois, United States
Methodology:	Fixed regression model
Result significance:	Null

Study design: Welch, Gu, and Kramer (2005) used a fixed effects regression model to evaluate the effects of Ozone Action Day (OAD) advisories on Chicago Transit train ridership from 2002–2003. ODA advisories are issued when a high level of ozone pollution is forecasted for the following day with the goal of reducing traffic congestion. There were seventeen ODAs during the two summers in the study period, primarily occurring in July and August. The analysis controlled for adverse weather, gas prices, and holidays.

Sample size: Analysis included seventeen ODA alerts issued between 2002 and 2003.

Results: Results suggest that ODA advisories had no statistically significant effect on overall train ridership, but that hourly shifts did occur. Advisories were associated with 4 fewer riders per station from 6–7am and 6 additional riders from 10–11am. There were also 3 fewer riders per station from 2–3pm, and 8 additional riders from 6–7pm in the evening. Transit ridership on ODA advisory days increased from 9–11am and 5–9pm. Ridership increases during ODAs represent a 0.03–0.13 percent reduction in hourly VMT.

Study Period: 2002–2003

Data collection method: Transit ridership data was sourced from the Chicago Transit Authority (CTA). VMT estimates are based on Cook County Travel Statistics and Illinois Travel Statistics.

Cost efficiency: N/A

Welfare and environmental impacts: The shift in travel times indicate that air quality alerts have potential to impact ozone quality, which could have welfare benefits.

Equity: The study included a breakdown of CTA ridership demographics and use.

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