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Exploring the Induced Travel Effects from Minor Arterials, Auxiliary Lanes, and Interchanges

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16. Abstract

A robust body of empirical research demonstrates that as roadway supply increases, vehicle miles traveled (VMT) generally does, too. The evidence is particularly strong with respect to major roadways, like interstate highways (class 1), other freeways and expressways (class 2), and principal arterials (class 3). However, previous literature reviews have found limited empirical evidence as to the relative magnitude of the induced travel effect of expanding minor arterials, collector streets, and local roads. Previous reviews have similarly not reported empirical research on the induced travel effects of other types of roadway facilities, such as auxiliary lanes, ramps, or other types of interchanges. In this project, the authors conducted a systematic literature review on the induced travel effects of minor arterials, auxiliary lanes, and interchanges (including simple on/off ramps). The authors found that the empirical literature remains limited with respect to auxiliary lanes and interchanges. They found eight studies that include minor arterials in their empirical estimates of induced travel, which collectively indicate that the induced travel elasticity for class 4 minor arterials could be similar to that of class 1-3 facilities. However, none of the studies isolated the induced travel effect from minor arterials specifically. Going forward, the report suggests avenues for future research to help close these research gaps. For example, the authors recommend using case studies of individual roadway expansions to better understand the induced travel effects specific to ramps, interchanges, minor arterials, and auxiliary lanes within specific contexts, especially where larger studies (across multiple facilities, geographies, etc.) have not yet been done.

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Exploring the Induced Travel Effects from Minor Arterials, Auxiliary Lanes, and Interchanges

A National Center for Sustainable Transportation Research Report

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Executive Summary

A robust body of empirical research demonstrates that as roadway supply increases, vehicle miles traveled (VMT) generally does, too (Volker & Handy, 2022). The evidence is particularly strong with respect to major roadways, like interstate highways, other freeways and expressways, and principal arterials. While minor arterials, collector streets, and local roads are also likely to induce VMT, previous reviews have found limited empirical evidence as to the relative magnitude of the effect (Volker & Handy, 2022). Previous reviews have similarly not reported empirical research on the induced travel effects of other types of roadway facilities, such as auxiliary lanes, ramps, or other types of interchanges.

The goal of this project is to further investigate the induced travel effects of minor arterials, auxiliary lanes, and interchanges (including simple on/off ramps). We first describe the studied facilities and explore relevant differences in definitions, design characteristics, and classification criteria. We then summarize our literature review methods and synthesize our findings with respect to the induced travel effects of the studied facilities. We conclude by discussing the challenges and gaps in current research and suggest directions for future studies.

Overall, we found that the empirical literature remains limited. We found no studies that directly analyzed the induced travel effects of adding auxiliary lanes or of adding or widening ramps or other types of interchanges. We did identify eight studies that include minor arterials in their empirical estimates of the induced travel effect of roadway capacity expansions. Those studies report short-run elasticity from 0.07-0.90, and longer-run elasticity estimates from 0.26-0.99. However, none of the studies isolated the induced travel effect from minor arterials specifically. Going forward, our report suggests avenues for future induced travel research. For example, case studies of individual roadway expansions can provide valuable empirical evidence to understand the induced travel effects specific to ramps, interchanges, minor arterials, and auxiliary lanes within specific contexts, especially where larger studies (across multiple facilities, geographies, etc.) have not yet been done.

Introduction

Induced travel is a well-documented phenomenon in which expanding capacity on a roadway – either by widening an existing road, extending a road, or building an entirely new road – increases the average travel speed on the roadway (at least in the short term), improves travel time reliability, makes driving on the roadway perceptibly safer or less stressful, or provides access to previously inaccessible areas, all of which reduce the perceived "cost" of driving and thereby induce more driving (Deakin et al., 2020; Handy, 2015; Noland & Hanson, 2013). In the shorter term, the reduced cost of vehicle travel can cause people to substitute driving for other travel modes (like transit or active travel), drive solo instead of carpooling, make longer trips (by taking longer routes or choosing farther destinations), or make additional trips. These behavioral responses can affect both personal and commercial driving (Duranton & Turner, 2011; Milam et al., 2017). In the longer term, it can lead people to live farther away from where they work (or vice versa) and even spur commercial or residential growth in the region (Duranton & Turner, 2011; Milam et al., 2017).

The phenomenon of induced travel has been theorized and anecdotally observed for more than a century. Anthony Downs popularized the concept when he suggested the "fundamental law of highway congestion" in a seminal 1962 paper and follow-up work (Downs, 1962, 1992, 2004). But Ladd (2013) documents numerous examples of planners and engineers bemoaning the futility of roadway capacity expansions for reducing congestion in the early 1900s. For example, Ladd (2013, p. 17) quotes one official in Los Angeles who observed in 1928 that "'a newly opened . . . or widened street immediately becomes glutted by the access of cars that hitherto have reposed more in their garages than they have utilized the streets.'"

Despite having been theorized and anecdotally observed for decades, however, the first empirical research on induced travel did not appear until the 1940s and 1950s (Ladd, 2013; Cervero, 2002). Most of the early empirical research consisted of facility-specific studies. Those studies typically compared the growth in average daily trips on an expanded facility to either the projected traffic volumes on the facility without an expansion or the traffic volume trends on an unexpanded comparison facility or the area as a whole (Cervero, 2002).

Starting in the 1970s researchers began conducting area-wide studies (Cervero, 2002), which are better able to capture the net effect of capacity expansions on vehicle miles traveled (VMT) across the roadway network than facility-specific or corridor-level studies (Anderson et al., 2021; Handy & Boarnet, 2014; Hymel, 2019). They also tend to produce more generalizable results. However, using an area-wide unit of analysis (e.g., counties, urbanized areas, metropolitan areas, or states) does not by itself guarantee a study's internal validity. That depends on how well the studies control for both the exogenous factors besides roadway capacity that affect VMT as well as the endogenous (bidirectional) relationship between VMT and roadway capacity—the possibility that VMT growth can cause roadway capacity expansion and not just the other way around. The earliest area-wide studies ran simple ordinary least squares (OLS) regressions using cross-sectional data (Cervero, 2002). These studies typically controlled for numerous exogenous variables, but could not control for unmeasured region-specific effects, time-specific effects, or the endogeneity of roadway capacity. Researchers began addressing the first two of these limitations in the 1990s by using cross-sectional time-series data and including fixed-effects variables to capture the effects on VMT of unmeasured variables associated with a specific region or time period, but they were unable to overcome the endogeneity problem (Hansen & Huang, 1997; Noland, 2001). Noland and Cowart (2000) and Fulton et al. (2000) were the first two studies to also attempt to correct for endogeneity. Many others have done so since then, most commonly by using instrumental variables (IV).

A robust body of empirical research now demonstrates that as roadway supply increases, VMT generally does, too. Volker and Handy (2022) synthesized the empirical literature and found that a roadway capacity expansion of 10% is likely to increase VMT by 3% to 8% in the short-run and 8% to 10% or more in the long-run (within three to 10 years). The studies they reviewed mostly focused on major roadways including interstates, other freeways and expressways, and principal arterials. They found that minor arterials, collector streets, and local roads are also likely to induce VMT, though the empirical evidence as to the relative magnitude of the effect is limited. Volker and Handy (2022) did not report any empirical research on the induced travel effects of other types of roadway facilities, such as auxiliary lanes, ramps, or other types of interchanges.

The goal of this project is to further investigate the induced travel effects of minor arterials, auxiliary lanes, and interchanges (including simple on/off ramps). Our literature review identified eight studies that include minor arterials in their empirical estimates of the induced travel effect of roadway capacity expansions. Those studies report short-run elasticity from 0.07-0.90, and longer-run elasticity estimates from 0.26-0.99. We found no studies or reports that directly analyzed the induced travel effects of adding auxiliary lanes. We similarly found no peer-reviewed empirical studies of the induced travel effect of adding or widening ramps or other types of interchanges, though a couple facility-level analyses assess the effect of ramp metering on traffic flow-related outcomes.

The remainder of the report is structured as follows:

- **Description of the Studied Facilities**
  This section provides brief descriptions of ramps and interchanges, minor arterials, and auxiliary lanes. It also compares their definitions, design characteristics, functional roles, and classification criteria between Caltrans and/or federal transportation agencies.

- **Literature Review Findings**
  This section presents the findings from the reviewed literature on the induced travel effects of ramps and interchanges, minor arterials, and auxiliary lanes. Each subsection discusses the empirical evidence, methodological approaches, and key findings related to the induced travel effects of these three facilities.
- **Summary and Recommendations for Future Research**
  This section discusses the challenges and gaps in current research and suggests directions for future studies.

Description of the Studied Facilities

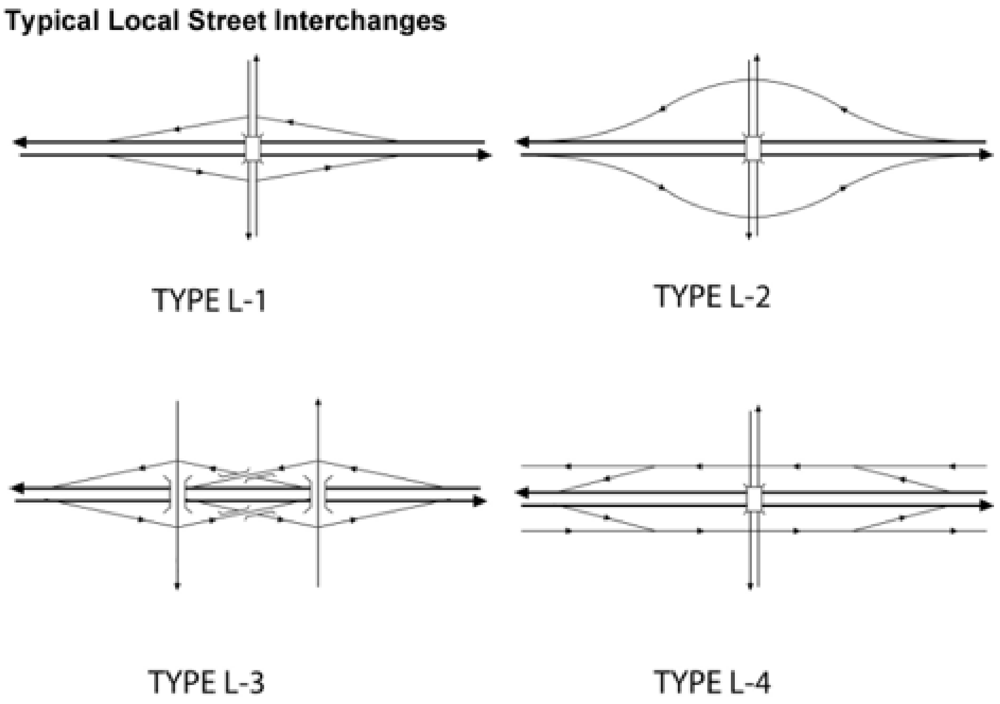
Ramps and Interchanges

Definitions of ramps and interchanges can vary due to regional differences in standards, guidelines, functional classifications, legal contexts, and technical specifications. Different countries or regions use unique terminologies based on their road network designs and traffic patterns, influenced by local transportation agencies and engineering manuals, such as those from the American Association of State Highway and Transportation Officials (AASHTO). Design guideline reports, such as those from AASHTO (2018), Brian et al. (2011), Caltrans (2015), and the Transportation Research Board (2022), highlight factors affecting the definitions of highways and highway facilities. The context, whether urban or rural, also impacts these definitions, reflecting varying design constraints and traffic volumes (Brian et al., 2011; Caltrans, 2015; Federal Highway Administration, 2023b; Transportation Research Board, 2022).

Functional roles and design features contribute to the variability in definitions. While on-ramps (or entry ramps) and off-ramps (or exit ramps) are foundational elements of highway systems, ramps for freeway-to-freeway connections may be defined differently from those for arterial-to-freeway connections. Interchanges also vary by type (e.g., cloverleaf, diamond) based on design and functionality (Transportation Research Board, 2022). Legal and regulatory definitions add complexity, as traffic laws and planning documents may include specific definitions for enforcement and funding purposes. Geometric configuration and context play crucial roles in defining ramps and interchanges. The number of ramps, their shapes (e.g., loops, straights), and the resulting weaving distances impact overall traffic flow. Urban areas tend to favor compact layouts, while rural areas may use different configurations (AASHTO, 2018).

The Caltrans Highway Design Manual (CHDM) (2015) defines ramps and interchanges and mentions their key attributes and roles within California’s highway networks. Instead of defining it separately from an interchange, the CHDM defines ramps as a component of a traffic interchange attached with grade separations connected to the mainline highways (Caltrans, 2015:Topic 500.1). The CHDM provides geometric design features of ramps for various traffic operational projects. Ramps come in various configurations depending on the traffic volume, type of movement, and local conditions. The manual outlines the design considerations for ramp metering, including the provision of High-Occupancy Vehicle (HOV) lanes and adequate queue storage lengths to prevent spillback onto local streets (Caltrans, 2015; Topic 504.3). Ramps can influence induced travel demand by improving accessibility and reducing travel times, which may encourage more people to use the freeway system. The manual addresses this by recommending designs that accommodate current and future traffic volumes, ensuring that ramps can handle increased demand without compromising safety or efficiency. For example, the provision of auxiliary lanes and ramp metering can help manage increased traffic volumes by smoothing the flow of vehicles entering and exiting the freeway (Caltrans, 2015:Topic 504.3 (2) & 504.5).

The Caltrans manual defines a traffic interchange as “a combination of ramps and grade separations at the junction of two or more highways to reduce or eliminate traffic conflicts, improve safety, and increase traffic capacity” (Caltrans, 2015; Topic 500.1). Caltrans identifies several types of interchanges based on their geometric configurations and specific traffic needs. Figure 1 illustrates the types of interchanges based on the basic shapes of ramps—diamond, loop, directional, hook, or variation of these types as defined in the Caltrans Highway Design Manual (2015)—and their location (i.e., local street interchanges and freeway-to-freeway interchanges).



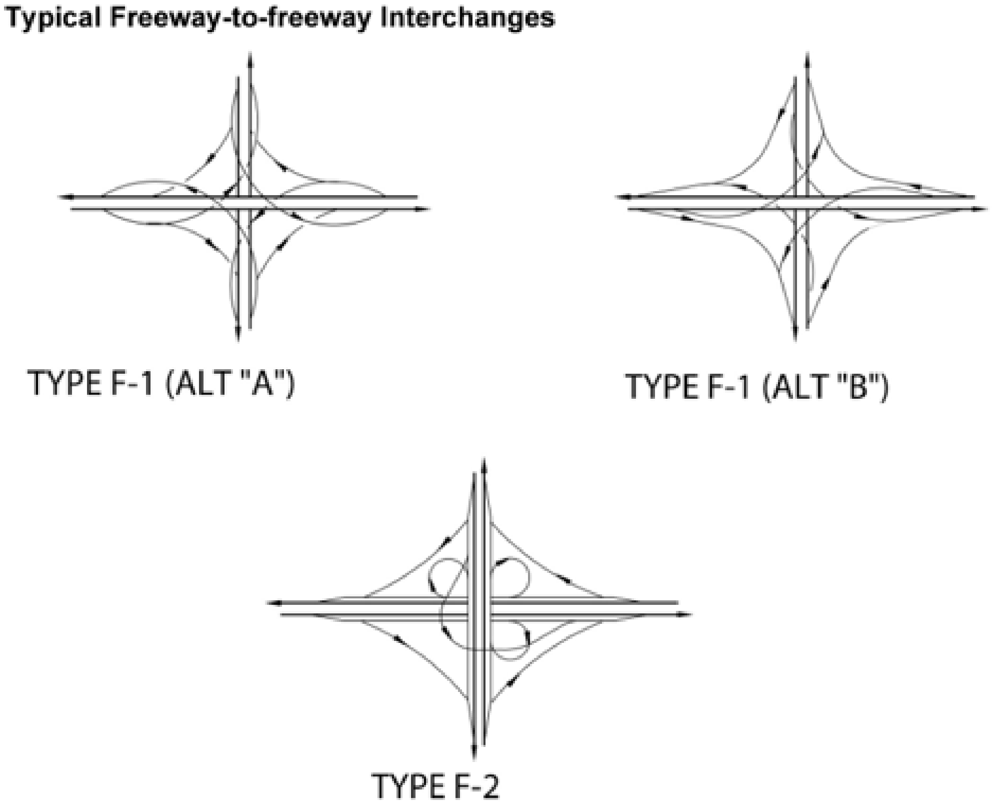


Figure 1. Examples of typical local street interchanges (top) and typical freeway-to-freeway interchanges (bottom).

Source: Caltrans Highway Design Manual (2015), pp. 500-3 and 500-9.

The diamond interchange is the simplest form, featuring high standards of ramp alignment and direct turning maneuvers at crossroads, making it adaptable to a wide range of traffic volumes. However, its capacity is often limited by the intersection of the ramps at the crossroads. A cloverleaf interchange includes loops that allow for continuous traffic flow in all directions, eliminating the need for left turns. The four-quadrant cloverleaf with collector-distributor roads separates weaving conflicts from through freeway traffic, making it suitable for handling large traffic volumes. The trumpet interchange design is used when a crossroads terminates at a freeway, efficient for handling traffic at such terminations but should be avoided if future extensions of the crossroads are anticipated. Freeway-to-freeway interchanges include several design configurations, such as the four-level interchange, which provide direct connections, and combination interchanges, like the three-quadrant cloverleaf with one direct connection. These designs aim to balance high traffic volumes with operational efficiency and cost considerations. Local street interchanges are designed to accommodate both motorized and non-motorized traffic, including pedestrians and bicyclists. The alignment of ramp termini is often perpendicular to local roads to reduce vehicle speeds and enhance safety for all users (Caltrans, 2015).

The fundamental definitions and goals of ramps and interchanges are largely consistent across state and federal agencies, focusing on reducing traffic conflicts, improving safety, and increasing traffic capacity. However, there are some differences in the specifics of design speed ranges, lane width flexibility, and the detailed implementation of ramp metering. For instance, the Caltrans manual provides specific design speeds and detailed criteria for ramp widening and shoulder widths. For example, it specifies a design speed of 50 mph or greater at exit noses and a minimum of 25 mph at intersections where all traffic makes a turning movement. It also mandates a minimum lane width of 12 feet for ramps and typical shoulder widths of 4 feet on the left and 8 feet on the right (Caltrans, 2015). Federal guidelines from the Federal Highway Administration (FHWA) and AASHTO, by contrast, may provide a broader range of acceptable values or more flexibility based on local conditions and constraints. For instance, AASHTO's “Green Book” suggests a range of design speeds for ramps between 30 and 50 mph, depending on the context and connecting roadways. It also allows for narrower lane widths in constrained urban environments, down to 10 feet in certain cases (AASHTO, 2018).

Minor Arterials

Under the FHWA classification, minor arterials serve as arterials for moderate trip length, are smaller than their major arterial counterparts, and offer increased access to other arterial systems while providing community connectivity. Minor arterials are also usually designed to carry out proportionate travel speeds to minimize interference through movement (Federal Highway Administration, 2023a). The range of length of a minor arterial varies depending on its location: A typical minor arterial in urban areas (e.g., minor arterials in a central business district) ranges from 0.125 to 0.5 miles, while a minor arterial in suburban areas tend to have a range between 2 to 3 miles (Federal Highway Administration, 2023a). FHWA’s Highway Functional Classification manual also compares the characteristics of minor arterials in urban and rural areas. From a traffic congestion or travel demand management standpoint, urban arterials connect and amplify higher-level arterials, such as major arterials, and distribute traffic to smaller road levels that support minor arterials, like collectors. By contrast, rural minor arterials tend to connect cities and major trip attractions (i.e., malls, schools, grocery store centers), these rural minor arterials aid in connecting different interstates and offer increased interconnectivity within their respective county. They also play a vital role in ensuring that individuals in rural areas have access to roads connecting them to the higher-level classes, such as interstates and highways (Federal Highway Administration, 2023a).

Caltrans uses the FHWA classification guideline to determine the classification of the various road networks in California. Caltrans' Highway Design Manual defines minor arterials as arterials that interlink major arterials while regulating speed and accessibility with 2-3 lanes that include turn lanes to allow through traffic to flow smoothly (Caltrans, 2015).

Auxiliary Lanes

According to the Caltrans Highway Design Manual, an auxiliary lane is a portion of the roadway—usually a freeway—designed for various purposes supplementary to through movement. These purposes include weaving, truck climbing, speed changes, or other functions intended to improve overall traffic flow. Auxiliary lanes are commonly used where an entrance ramp onto a freeway is closely followed by an exit ramp, with the acceleration and deceleration lanes being joined by an auxiliary lane. These lanes can also facilitate the orientation of traffic at two-lane ramps or branch connections and be used in areas with high truck volumes to allow these vehicles to accelerate to a higher speed before merging with mainline traffic. The length and number of auxiliary lanes in advance of two-lane exits are based on percentages of turning traffic and a weaving analysis. Additionally, auxiliary lanes are considered on all freeway entrance ramps with significant truck volumes, where the grade, volumes, and speeds are analyzed to determine the necessity (Cheng et al., 2021). An auxiliary lane allows entrance ramp traffic to accelerate to a higher speed before merging with mainline traffic or simply provides more opportunities for merging (Caltrans, 2015).

The definitions of auxiliary lanes at the federal transportation agencies—such as FHWA and AASHTO—are similar to those of Caltrans. The FHWA Freeway Management and Operations Handbook defines auxiliary lanes as "the portion of the roadway adjoining the traveled way for speed change, turning, weaving, truck climbing, maneuvering of entering and leaving traffic, and other purposes supplementary to through-traffic movement" (Federal Highway Administration, 2017). The AASHTO Policy on Geometric Design of Highways and Streets similarly defines an auxiliary lane as "the portion of the roadway adjoining the traveled way for speed change, turning, weaving, truck climbing, and other purposes supplementary to through-traffic movement" (American Association of State Highway and Transportation Officials, 2018).

Literature Review Findings

We completed the literature review in three phases. We first reviewed the definitions of each facility type studied—minor arterials, auxiliary lanes, and interchanges (including simple on/off ramps). We then perused prior induced travel literature reviews, including Volker and Handy (2022) and the other syntheses cited therein, to identify research potentially relevant to the three facility types examined in this report. Finally, we searched Google Scholar and the Transportation Research International Documentation (TRID) database to identify additional relevant resources. We focused on empirical research on the induced travel effect of the three facility types, including both peer-reviewed academic studies and high-quality "gray" literature.[1] However, we also reviewed other relevant sources, including regulatory or analytical guidance documents. We focused on studies and other literature in the United States but broadened our search where we could not find US-based studies.

For ramps and interchanges, we searched Google Scholar and the TRID database using various combinations of these key terms: "ramps," "interchange(s)," "induced travel," "traffic volume," "vehicle miles traveled," or "VMT," and "elasticity(ies)" (see Table 1 for more specifics). Our searches returned over 1,000 results. We then employed the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) procedures to screen the search results systematically—removing redundant and irrelevant literature from the initial literature collection after reading the abstract and titles of each record and selecting either academic journal papers or professional/project reports that directly analyzed the induced travel effects of ramps and interchanges. This rigorous screening process identified 11 somewhat relevant publications. No academic studies or professional reports that directly analyzed the induced travel effects of ramps and interchanges were identified in our literature search.

For minor arterials, we searched Google Scholar using various combinations of the key terms shown in Table 1. Our searches returned over 700 results. We then employed the PRISMA procedures to screen the search results systematically—removing redundant and irrelevant literature from the initial literature collection after reading the abstract and titles of each record. We identified 21 publications that directly addressed our research questions concerning the effects of minor arterials on induced travel outcomes, including traffic volume, VMT, and traffic speed.

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[1] "Gray" literature studies include government reports, academic reports that have not (at least not yet) been published in a peer-reviewed journal, and reports by other entities. Despite not being published in a peer-reviewed journal, many gray literature studies have still been peer reviewed as part of the internal quality control procedures employed by the publishing entity.

For auxiliary lanes, we searched Google Scholar and the TRID database using various combinations of the key terms shown in Table 1. We found only one empirical study that attempted to analyze the impacts of adding auxiliary lanes on induced travel outcomes—a case study in Tokyo, Japan. From our literature search, the research team could not identify any project reports or academic studies conducted before-and-after analyses to explore the induced travel effects of adding auxiliary lanes using observed traffic flow data in the US.

Table 1. Search terms used for the literature review.

First key terms	Second key terms	Third key terms*
• (“ramps” AND “interchanges”)	• “induced travel” • “traffic volume” • “travel time” • “vehicle miles traveled” OR “VMT” OR “VKT”	• “elasticity”
• (“minor arterial” OR “arterial” OR “class four facilities” OR class 4 facilities” OR “class four facility)	• (“induced travel” OR “induced demand” OR “induced VMT” OR “induced driving)	• (“elasticity” OR “elasticities”)
• “auxiliary lanes”	• (“induced travel” OR “induced VMT” OR “vehicle miles traveled” OR “VMT” OR “VKT”) • “traffic volume” • “travel times” OR “travel costs”	• “elasticity”

Note: The third search term was used depending on the first and/or second terms included for the literature search.

We report our findings from the literature review in the following three subsections about ramps and interchanges, minor arterials, and auxiliary lanes.

Induced Travel Effects of Ramps and Interchanges

Overview of Literature Review Findings

We identified no studies or reports that directly analyze the effects of adding or widening ramps (or ramp lanes) or other types of interchanges on induced travel outcomes, like VMT or traffic volume. Only a few academic studies or professional reports briefly mention or hypothesize the induced travel effects of ramps and interchanges. A few studies attempt to theorize the possible induced travel effects of ramps and interchanges, such as reduced air emissions (Bae et al., 2012; Shaheen & Lipman, 2007) and accident rates in the short term (Feknssa et al., 2023; McCartt et al., 2004; L. Wang et al., 2019), while others indicate the risk of worsening congestion and increased vehicle travel over time (Federal Highway Administration, 2005; He & Guan, 2012). Recent research has highlighted the importance of accurately modeling ramp traffic, particularly in dynamic traffic assignment models, to better predict traffic flow and congestion. However, the relationship between ramps and other types of interchanges and induced travel remains complex and understudied.

The Induced Travel Effects of Ramps and Interchanges: General Findings

Adding or expanding ramps and interchanges along mainline highway segments is frequently proposed as a way to alleviate traffic congestion through improved connectivity, but its actual induced travel-related effects are complex and understudied. One early study on the induced travel effects of highway facilities was conducted using driver survey data that included the drivers' self-reported responses to changes in travel times before and after additional ramps or interchanges were built (Dowling & Colman, 1995). However, the study did not produce a generalizable association between the addition of ramp lanes or interchanges and induced traffic volumes and/or travel time. Other studies have explored indirect effects potentially related to induced travel, such as housing sales premiums near ramps and high-density residential land use development patterns (Boarnet & Chalermpong, 2000) and ramp- and interchange-related crashes (Chen et al., 2009; Feknssa et al., 2023; Lord & Bonneson, 2005; McCartt et al., 2004). Still, we found no empirical studies that directly analyze the impacts of various physical layouts and attributes of ramps and interchanges on induced travel and predict changes in traffic volume, travel times, and VMT in response to the addition of ramp lanes or construction of interchanges.

Beyond the presence and physical attributes of ramps and interchanges, ramp operation can also affect traffic volumes, travel times, and VMT, though the effects are likewise understudied in the empirical literature. For instance, Gillen and Cooper (2004) evaluated various intelligent transportation systems investments in California, including ramp metering, and found that ramp meters effectively maintained or increased VMT without exacerbating congestion. A field study by Haj-Salem and Papageorgiou (1995) in Paris, France found that the application of ramp metering strategies on Paris' outer ring road increased traffic speeds across the network (the outer ring road, inner ring road, and connecting radials), while VMT remained steady (Haj-Salem & Papageorgiou, 1995). Two additional case studies of ramp metering projects in California are highlighted in the next section of this report. A few studies have also analyzed the effects of ramp metering systems on changes in accessibility to highways and speed delay (Bhouri et al., 2013; Yang et al., 1994; Zhang, 2010). A recent study by Haule et al. (2022) found that ramp metering improves traffic safety and efficiency. Their study on I-95 in Miami, Florida, indicated that ramp metering reduces the crash risk downstream of entrance ramps, leading to a more stable and predictable traffic flow (Haule et al., 2022).

In addition to the lack of empirical evidence about the induced travel effects of ramps and interchanges, there is also a lack of consensus and clarity about how to forecast the effects of ramps and interchanges on traffic volume, travel times, and VMT (e.g., Milam et al., 2017). For example, while the California life-cycle benefit and cost analysis model (Cal-B/C) offers "off-model" analysis adjustment options depending on interchanges, connectors, on- and off-ramps, auxiliary lanes, and ramp metering when estimating user benefits in terms of travel speed, traffic volume, and collision rates using the number of lanes, the basis for the adjustment factors is unclear (Williges & Mahdavi, 2008). Marshall (2018) attempted to develop a dynamic traffic assignment (DTA) model for the prediction of ramp traffic and validated the forecast outcome against actual ramp traffic in the Portland, Maine region. The study assumed that ramp traffic had been underestimated in most travel demand models, which often led to incorrect predictions of traffic flow, congestion time, and VMT from highway expansion projects. Unlike static traffic assignment (STA) models, the study found that DTA considered variations in traffic flow, demand, and network conditions, and reflected temporal variations in traffic patterns that allowed for more optimal ramp designs and/or operations like ramp metering. Ramps are generally short in length and their volumes are generally low, so they do not present a large share of the VMT, vehicle hours traveled or vehicle hours of delay. Because of this, STA models can over-assign ramps. This can happen because even a small reduction in mainline travel time can offset the negative effects of increased ramp travel time. Overall, the study concludes that the DTA model is better suited for planning purposes than STA models because it can more accurately account for ramp traffic. Despite its attempt to model ramp traffic, the study did not clearly separate the induced travel effects of ramps and interchanges from the expansion of the mainline highway segments themselves and interchanges (Marshall, 2018).

The Induced Travel Effects of Ramps and Interchanges: Metering Case Studies

Mauch and Skabardonis (2021) and the Mineta Transportation Institute (2020) both evaluated the coordinated ramp metering (CRM) installed in two corridors—I-80 in the Bay Area and SR-99 in Sacramento, both shown in Figure 2. The CRMs were implemented by Caltrans along these two corridors as an advanced traffic management strategy that calculates optimal metering rates in real-time for each ramp along a corridor, aiming to improve freeway flow and reduce congestion. Mauch and Skabardonis (2021) assessed the effects of the CRMs using various performance measures, including traffic volume on the corridor, VMT, vehicle hours traveled (VHT), VHD-35 (delay from vehicles traveling below 35 miles per hour), travel time, planning time index (PTI), travel time index (TTI), and on-ramp volumes.

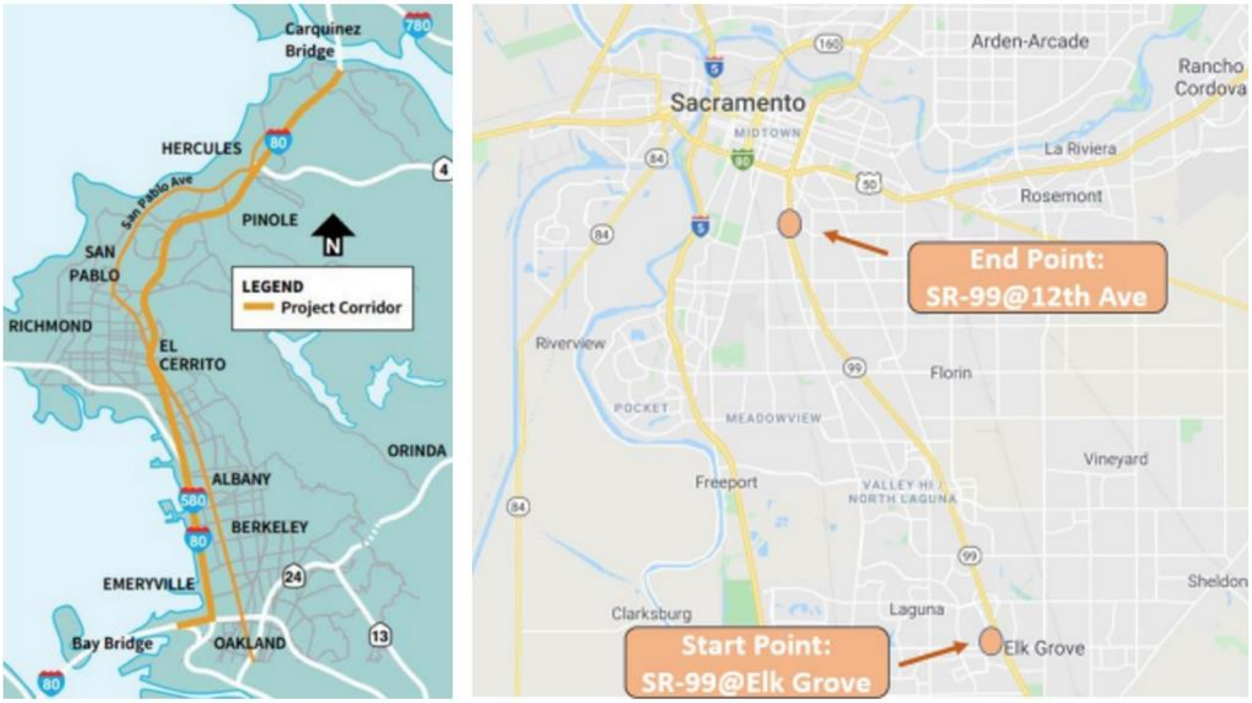

Figure 2. Project maps of the I-80 SMART Corridor (left) in the Bay Area and the SR-99 in Sacramento, CA (right).

Source: Mineta Transportation Institute (2020).

Before and after CRM implementation, daily VMT on the I-80 Eastbound corridor showed negligible changes (-0.24% during AM peak and +0.04% overall). However, the I-80 Westbound corridor experienced a slight decrease in VMT (-5.72% during the AM peak, -11.35% during the PM peak, and -9.66% overall). The SR-99 Northbound corridor remained relatively stable, with a -0.24% change during the AM peak and a +0.04% change overall. VHT decreased significantly across all corridors. The I-80 Eastbound corridor saw a decrease of -8.32% during the AM peak and -5.59% overall. The I-80 Westbound corridor experienced a notable reduction of -8.88% during the AM peak, -11.00% during the PM peak, and -13.40% overall. The SR-99 Northbound corridor showed a decrease of 8.32% during the AM peak and 5.59% overall. VHD-35 reductions were substantial, with the I-80 Eastbound corridor seeing -12.54% during the AM peak and -34.18% overall. The I-80 Westbound corridor's VHD-35 reductions varied, with -97.93% during the AM peak, -12.51% during the PM peak, and -22.57% overall. The SR-99 Northbound corridor significantly decreased by -12.54% during the AM peak and -34.18% overall. Travel time reductions were also observed, with the I-80 Eastbound corridor reducing by -8.51% during the AM peak and -6.50% overall. The I-80 Westbound corridor showed reductions of -3.27% during the AM peak, -11.30% during the PM peak, and -4.59% overall (pages 31 and 32). The SR-99 Northbound corridor decreased by 8.51% during the AM peak and 6.50% overall (See pages 31, 32, and 42 in the report for details about the findings). Finally, on-ramp volumes decreased, with the I-80 Eastbound corridor seeing -15.47% during the AM peak, -17.78% during the PM peak, and -15.39% overall (page 32). The I-80 Westbound corridor experienced decreases of -15.03% during the AM peak, -18.98% during the PM peak, and -17.63% overall (pages 31 and 32). The SR-99 Northbound corridor showed slight decreases, reflecting the overall balanced VMT (page 32).

Overall, Mauch and Skabardonis' (2021) report indicates that CRM implementation led to reductions in VHT, VHD-35, travel time, PTI, and TTI across both corridors, while VMT remained relatively steady. However, the two case studies do not isolate the impacts of CRM from other influencing factors. The authors also caution that consistency and accuracy issues with traffic volume and speed data can affect the results.

Induced Travel Effects of Minor Arterials

Table 2 summarizes the eight empirical studies we identified that estimate the induced travel effects from roadway capacity expansions and include minor arterials in their estimations (though always in combination with at least one other roadway type). All eight studies use area-wide rather than facility-level analyses. All eight studies also measure the magnitude of the induced travel effect as the elasticity of VMT with respect to lane miles, as shown in Equation 1. The elasticity is the percentage increase in VMT in the studied area that results from a 1% increase in lane miles in that area. An elasticity of 1.0 means that VMT will increase by the same percentage as the increase in lane miles.

$$\text{Elasticity} = \frac{\text{\% Change in VMT}}{\text{\% Change in Lane Miles}} \qquad \text{(Eq. 1)}$$

The studies typically obtain elasticity estimates by using the logarithm of both VMT and lane miles in their regression models. Using the logarithmic form, the regression coefficients can be interpreted as elasticities. For example, a 1.0 coefficient on the lane miles variable would indicate a 1.0 elasticity of VMT with respect to lane miles.

The timeframe for the estimated elasticities varies based on the data and regression methods used. Short-run elasticities capture the induced travel effects that occur immediately and within the first couple of years after a capacity expansion, such as substitution of driving for other travel modes, increases in trip lengths (by taking longer routes or choosing farther destinations), or increases in the number of trips. Longer-run elasticities capture a fuller set of induced travel effects, including persistent short-run effects and other effects that take longer to actualize, such as changes in residential and commercial locations and increased growth. We generally use "short run" and "long run" to refer to the periods one to two years and three to 10 years after the capacity expansion, respectively.

The studies summarized in Table 2 consistently find an induced travel effect from roadway capacity expansions, even after controlling for a wide variety of other factors affecting VMT (like population and income) and (for six of the studies) attempting to correct for the endogeneity of roadway capacity. Short-run elasticity estimates range from 0.07-0.90. Longer-run elasticity estimates range from 0.26-0.99. Those elasticity ranges tighten substantially when the lone study that used all road types (including local roads)—Su (2011)—is excluded. Excluding that study, the range of short-run elasticities shrinks to 0.28-0.90. The range of longer-run elasticities narrows to 0.77-0.99. One reason the elasticities estimated in Su (2011) might be outliers is that it includes local roads (the lowest FHWA facility class – class 7).[2] Local roads typically constitute the bulk of the roadway network yet they tend to provide the least per-mile improvement in travel speed or access, as indicated by the fact that they generally have the lowest VMT densities of all roadway classes.[3] As a result, the elasticity of VMT with respect to roadway capacity is likely lower (though not zero) for local roads than for higher road classifications (Noland, 2001).

Apart from Su (2011), two studies estimate a combined induced travel effect of interstate highways, other freeways and expressways, major arterials, minor arterials, major collectors, major collectors, and minor collectors (Duranton & Turner, 2011; Ivanchak, 2022). Another study estimates the combined effect of interstate highways, other freeways and expressways, major arterials, minor arterials, and major collectors (Rentziou et al., 2012). Two studies estimate the combined effect of interstate highways, other freeways and expressways, major arterials, and minor arterials (Graham et al., 2014; Noland & Cowart, 2000). And the last two studies estimate the combined effect of major and minor arterials (Melo et al., 2012; Noland, 2001).

The studies we reviewed indicate that the induced travel elasticity for class 4 minor arterials could be similar to that of class 1-3 facilities. However, none of the studies we reviewed estimated the induced travel effect from just minor arterials. Facility-level studies of minor arterial additions or expansions could help provide additional insights.

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[2] When we refer to “local roads,” we mean roadways similar in function to those classified as class 7 by FHWA. This designation is agnostic of roadway ownership and jurisdiction.

[3] For example, Caltrans’ 2019 Public Road Data show that local roads comprised nearly 57% of all lane miles across California but carried only 5% of its VMT (California Department of Transportation, 2020b).

Table 2. Literature review summary: the effects of minor arterials on induced travel.

Authors	Study Years	Roadway Types	Geography	Unit of Analysis	Controls	Controls for Simultaneity Bias	Short-Run Elasticity	Longer-Run Elasticity
Duranton & Turner (2011)	1983, 1993, and 2003	Interstate highway, other highways, principal arterials, minor arterials, collector roads	United States	Urbanized areas	Population, Census divisions, elevation range, terrain ruggedness index, heating degree days, cooling degree days, sprawl index	No	0.66 - 0.90	NA
Graham et al. (2014)	1985 - 2010	Interstate highways, other freeways and expressways, principal arterials, minor arterials	United States	Urbanized areas	Population growth, income per capita, fuel cost, congestion (annual hours of delay per VMT), network composition (freeway lane miles/arterial lane miles), traffic composition (arterial VMT/freeway VMT), mode share (annual public transit passenger miles), metropolitan wage per year, employment level, metropolitan share of manufacturing jobs, year fixed effects	Yes	NA	0.77
Ivanchak (2022)	1980 - 2019	Interstate highways, other freeways and expressways, principal arterials, minor arterials, major collectors, and minor collectors	United States (excluding Hawaii, Delaware, and Washington, DC	States	Population, income per capita, fuel cost, share of population in small metropolitan areas, share of population in non-metropolitan areas, auto and truck registrations per capita, employment per capita, state fixed effects, year fixed effects	No	0.483 (fixed-effects panel data without time effects) 0.334 (fixed-effects panel data with time effects)	NA
Melo et al. (2012)	1982 - 2009	Principal arterials, minor arterials	United States	Urbanized areas	Congestion (total hours of delay per peak-period traveler), gross domestic product per capita	Yes	NA	0.989

Authors	Study Years	Roadway Types	Geography	Unit of Analysis	Controls	Controls for Simultaneity Bias	Short-Run Elasticity	Longer-Run Elasticity
Noland (2001).	1984 - 1996	Principal arterials, minor arterials	United States (excluding Washington, DC)	States	State population, per capita income by state, fuel cost, and state fixed effects.	No	0.491-0.498 (urban) 0.362-0.369 (rural)	0.79 (urban) 0.71-0.72 (rural)
Noland & Cowart (2000).	1982 - 1986	Interstate highways, other freeways, expressways, principal arterials, minor arterials	United States	Urbanized areas	Population density, fuel cost, income per capita, urbanized area fixed effects, year fixed effects	Yes	0.28–0.76	NA
Rentziou et al. (2012)	1998-2008	Interstate highways, other freeways, expressways, principal arterials, minor arterials, major collectors	United States (excluding Alaska and Hawaii)	States	Race, ethnicity, gender, income per capita, share of telecommuters, fuel cost, density, percent congested interstate miles, percent congested minor arterial miles, state fixed effects, year fixed effects.	Yes	0.336 (rural) 0.449 (urban)	NA
Su (2011)	2001-2008	Interstate highways, other freeways, expressways, principal arterials, minor arterials, major collectors, minor collectors, local roads	United States	States	Population, fuel cost, income, vehicles per capita, congestion (annual hours of delay per capita), average vehicle fuel economy, numerous others	Yes	0.07 (only passenger VMT)	0.26 (only passenger VMT)

Induced Travel Effects of Auxiliary Lanes

There has been general consensus that adding or expanding auxiliary lanes along highway routes can be expected to potentially increase VMT. By increasing overall capacity and, at least temporarily, improving traffic flow, auxiliary lanes can incentivize new or longer trips or mode shifts (Sato et al., 2011; Sharma et al., 2023; Yi et al., 2014). However, as with previous literature reviews (Yi et al., 2014), we found almost no empirical research on the induced travel effects of auxiliary lanes. The one semi-relevant empirical study we identified—Moriyama et al. (2011)—examined the effects of temporarily converting an approximately 0.75-mile truck climbing lane into an auxiliary lane along an eastbound section of the interregional Chuo Expressway in Japan. However, the study did not assess the effect of the lane conversion on total traffic volumes or VMT – it focused on the distribution of traffic flow across the three lanes in the studied expressway section. It also did not explain whether and how truck climbing lanes and auxiliary lanes were managed differently (e.g., the types of vehicles allowed to use the lanes), which is critical to understanding any effect on traffic flow and volumes.

Beyond the empirical literature, the Governor's Office of Planning and Research's (OPR's) Technical Advisory on Evaluating Transportation Impacts in CEQA notes auxiliary lanes "would likely lead to a measurable and substantial increase in vehicle travel" (OPR, 2018, 20). However, the advisory also suggests a rule of thumb that the "addition of an auxiliary lane of less than one mile in length designed to improve roadway safety" generally not be considered to have a significant impact on VMT for purposes of CEQA (OPR, 2018, 21). Caltrans' (2020a) subsequent advisory—Transportation Analysis under CEQA: Evaluating Transportation Impacts of State Highway System Projects—echoes OPR's recommendations. In addition to those advisories, Caltrans' Benefit/Cost Model can implement off-model analysis adjustment to account for induced travel effects from auxiliary lanes by adjusting analysis weights. However, it is not clear how that effect is estimated or what it is based on (Williges & Mahdavi, 2008).

Overall, despite some anecdotal or hypothetical expectations and modeled outcomes related to the induced travel effects of adding auxiliary lanes, we found no empirical studies that directly analyze their impacts using before-and-after observation statistics or analyses.

Summary and Recommendations for Future Research

Key Findings from the Literature Review

The systematic literature review in the previous section examines the induced travel effects associated with three types of roadway facilities— minor arterials, auxiliary lanes, and interchanges (including simple on/off ramps).

Our literature review identified eight studies that include minor arterials in their empirical estimates of the induced travel effect of roadway capacity expansions. Those studies report short-run elasticity from 0.07-0.90, and longer-run elasticity estimates from 0.26-0.99. That range shrinks to 0.28-0.90 for short-run elasticities and 0.77-0.99 for long-run elasticities if the lone study that included local roads (which likely have a lower induced travel elasticity) is excluded. Overall, while the studies we reviewed indicate that the induced travel elasticity for class 4 minor arterials could be similar to that of class 1-3 facilities, none of the studies isolated the induced travel effect from minor arterials specifically.

We found no studies or reports that directly analyzed the induced travel effects of adding auxiliary lanes. We similarly found no peer-reviewed empirical studies of the induced travel effect of adding or widening ramps or other types of interchanges, though a couple facility-level analyses assess the effect of ramp metering on traffic flow-related outcomes.

Recommendations for Future Research

To address the current gaps in the literature and improve our understanding of induced travel effects from minor arterials, auxiliary lanes, and interchanges, future research should focus on several key areas, as follows.

Context-Specific Case Studies of Individual Expansions

Induced travel effects can vary significantly based on the context, including factors existing transportation infrastructure, land use patterns, and vehicular congestion levels. Therefore, context-specific studies are crucial for understanding how induced travel manifests in different settings. For example, studies should differentiate between urban and rural environments. Case studies of individual roadway expansions provide valuable empirical evidence to understand the induced travel effects specific to ramps, interchanges, minor arterials, and auxiliary lanes within specific contexts, especially where larger studies (across multiple facilities, geographies, etc.) have not yet been done. This section explores the methods for conducting case studies.

Quantitative Approaches

Facility-level case studies can be done quantitatively using traffic flow or VMT data (e.g., from the PeMS database) from the expanded roadway and, if possible, other potentially affected routes. Statistical techniques commonly employed in this context include regression analysis, difference-in-difference (DiD) analysis, and interrupted time series analysis. DiD analysis is particularly useful as it compares changes in traffic volumes and VMT before and after an expansion with a control group that did not experience the expansion. This method helps isolate the impact of the expansion from other external factors. This approach is particularly valuable for studying the induced travel effects of minor arterials and auxiliary lanes.

Interrupted time series analysis involves examining traffic data over a period, identifying trends, and detecting any abrupt changes that coincide with the road expansion. This technique is effective in isolating the impact of the expansion by controlling for temporal trends. Anderson et al. (2021) demonstrated the application of this method in their case studies of express lanes and connectors expansion projects. In the study, the interrupted time-series regression model compared traffic outcomes before and after the lane expansions, with the key parameter measuring the impact of the lane expansion on traffic outcomes like average speed and vehicle flow. The model included control variables for month-of-year, day-of-week, and hour-of-day to account for seasonal, weekly, and daily patterns. The analysis assumed that the indicator for the post-expansion period was uncorrelated with the error term, which is reasonable within a short time frame around the expansion but may become less so over longer periods due to broader trends. Interrupted time series analysis is a valuable method for studying the induced travel effects of minor arterials, auxiliary lanes, and interchanges.

Qualitative Approaches

Qualitative methods can complement quantitative approaches by providing insights into the contextual and behavioral factors influencing induced travel. These methods involve collecting and analyzing non-numerical data through interviews, focus groups, field observations, and documentary analysis, which help capture the nuanced impacts of roadway expansions.

Conducting interviews and focus groups with stakeholders such as commuters, local residents, business owners, and transportation planners shed light on how road expansions affect travel behavior and local communities. For instance, interviews with commuters can uncover their perceptions of the expansion, changes in their travel patterns, and reasons for choosing certain routes, offering valuable qualitative data on how the expansion influences individual travel decisions. Furthermore, focus groups with local residents can provide broader insights into community mobility, access to services, and potential shifts in local development patterns resulting from the expansion.

Field observations at key points along the expanded roadway offer real-time insights into traffic flow, congestion points, and driver behavior. Observing how vehicles merge, exit, and navigate the expanded roadway helps identify specific areas of improvement or new bottlenecks created by the expansion. Additionally, noting how the expansion affects non-motorized road users, such as pedestrians and cyclists, provides a more comprehensive view of its overall impact.

Reviewing planning documents, environmental impact assessments, and policy reports can enrich the case study by providing context and background information. Environmental impact assessments often contain data on expected changes in traffic volumes, pollution levels, and community impacts, which can be compared with actual outcomes to evaluate the accuracy of predictions and the effectiveness of mitigation measures. Planning documents outline the objectives, expected benefits, and projected costs of the expansion, allowing researchers to assess the success of the project against its initial goals.

Challenges and Considerations

Conducting case studies of roadway expansions involves several key challenges, including ensuring data availability and quality, isolating the expansion’s impact from external factors, and accounting for temporal and spatial variability. High-quality data can be gathered through collaboration with local transportation agencies and advanced data collection technologies. Control groups and sophisticated statistical techniques, such as difference-in-difference analysis, help isolate the expansion’s effects from other influences. Longitudinal studies and multi-site analyses are essential for capturing temporal and spatial variations in induced travel effects. Engaging with local communities and stakeholders is necessary to understand broader impacts, incorporate community feedback into study designs, and ensure transparent communication of findings. Addressing these challenges ensures more effective and insightful case studies on induced travel effects.

Analysis of the Induced Travel Demand of Other Facilities on the Entire Roadway Network

Case studies focusing on individual and multiple roadway expansions might not capture the total VMT effect of the facilities (e.g., ramps and interchanges, minor arterials, and auxiliary lanes) on the entire network surrounding the expansion. Capturing the total VMT effects can be difficult, due, e.g., to the unavailability and/or inaccuracy of relevant data for lower-class facilities, which are often underrepresented in traffic data collection efforts. Accurate measurement of network-wide VMT impacts requires integrating data from various sources, including traffic sensors, GPS tracking, and travel surveys, to create a comprehensive picture of travel behavior. Studies should discuss the problems associated with measuring the VMT impact on the total network. Issues such as inconsistent data collection methodologies, temporal mismatches, and spatial resolution limitations can complicate the analysis. For example, the evaluations of coordinated ramp metering (CRM) on the I-80 and SR-99 corridors in California highlighted the difficulties in isolating CRM impacts due to other influencing factors and data consistency issues (Mauch & Skabardonis, 2021; MTI, 2020).

Potential solutions include enhancing data collection infrastructure, standardizing measurement techniques, and employing data imputation methods to fill gaps in the datasets. Addressing these challenges requires a multi-faceted approach, combining empirical data collection with sophisticated modeling techniques. Leveraging big data analytics and machine learning algorithms can enhance the accuracy of VMT estimations across the network. These advanced analytical tools can identify hidden patterns and correlations within large datasets, offering deeper insights into how roadway expansions influence travel behavior at the network level. Engaging with stakeholders, including local governments, transportation agencies, and the public, is also crucial for validating findings and ensuring that the study's conclusions are grounded in real-world contexts.

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