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Data Collection Plan for Evaluating the Greenhouse Gas Impacts of High-Occupancy Toll Lane Projects

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Data Collection Plan for Evaluating the Greenhouse Gas Impacts of High-Occupancy Toll Lane Projects

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16. Abstract

This report presents a data collection plan for evaluating the greenhouse gas (GHG) impacts of high-occupancy toll (HOT) lane projects implemented under Caltrans' Carbon Reduction Strategy. Because HOT lanes can affect route choice, departure time, vehicle occupancy, and destination choice beyond the managed lane corridor, the report recommends evaluating impacts across the regional travel shed. We recommend two approaches for reliable before-and-after estimates of vehicle miles traveled (VMT) by speed bin. The household-based survey approach uses OBD-II, GPS, or smartphone-based tools to observe a representative sample of households within the travel shed, yielding the most detailed evidence on regional VMT and how impacts vary across the population. The infrastructure-based approach combines continuous freeway sensor data with sampled counts and speeds on arterials, local roads, and ramps; it is less costly and easier to implement but offers less insight into the travelers behind observed changes. For each approach, the report describes what data to collect, where and when to collect it, and how to validate and integrate it with EMFAC. The report also includes order-of-magnitude cost estimates for the two alternatives.

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Executive Summary

Executive Summary

This report presents a data collection plan for empirically evaluating the greenhouse gas (GHG) impacts of high-occupancy toll (HOT) lane projects implemented as part of Caltrans' Carbon Reduction Strategy. Because HOT lanes can affect not only conditions on the priced facility but also route choice, departure time, vehicle occupancy, trip length, and travel activity throughout the surrounding travel shed, the report recommends a regional before-and-after evaluation framework. The central measurement objective is to estimate vehicle miles traveled (VMT) by speed bin, and, where feasible, by vehicle type, so that the resulting data can be used as inputs to California's EMFAC emissions model.

The report identifies two options for collecting the data needed for this evaluation. The first, and recommended, option is a household survey-based approach in which a representative sample of households in the HOT lane travel shed is recruited, and their vehicle travel is measured before and after HOT lane implementation using OBD-II, GPS-enabled devices, smartphone traces, or similar automated technologies. This approach can produce detailed trajectory data, support estimates of VMT by speed bin and vehicle type, and link travel changes to household, traveler, and vehicle characteristics. It therefore provides the strongest basis for understanding regional GHG impacts and distributional patterns across the traveling population.

The second option is an infrastructure-based approach that combines existing traffic sensor data, especially from freeway monitoring systems (i.e., PEMS), with sampled field observations on arterials, local roads, ramps, and other facilities that are not continuously monitored. This approach can also generate VMT by speed bin for EMFAC, particularly when the same roadway locations are observed before and after HOT lane implementation and when sensor data are carefully validated. Its main advantage is that it can rely on existing infrastructure and targeted field deployment, making it less expensive and easier to administer than a large household survey. Its main limitation is that it provides less direct insight into who changed travel behavior, why they changed it, and how changes vary across household groups.

As always, there is a tradeoff between cost and quality across the two methods, and within each method. Larger samples, longer collection windows, more precise devices, more extensive geographic coverage, and stronger validation procedures improve data quality but increase cost. The household survey-based approach is expected to provide the highest-quality evidence for regional GHG evaluation because it captures observed travel trajectories and connects them to household and vehicle attributes. However, if the available budget is insufficient to support the recommended approach at an adequate scale, the infrastructure-based approach remains a viable and worthwhile option. It can still support a credible before-and-after evaluation, particularly if it is designed around a well-defined travel shed, includes both freeway and non-freeway facilities, and applies consistent pre- and post-implementation sampling.

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Introduction

Study Scope

Caltrans is developing a comprehensive, evidence-based Carbon Reduction Strategy (CRS), with road pricing as a central component, to reduce transportation-related greenhouse gas (GHG) emissions. A key focus of this strategy involves implementing priced managed lanes—specifically high-occupancy toll (HOT) or express lanes.

The purpose of this Task 4 report is to present a detailed data collection plan to support empirical before-and-after evaluations of HOT lane projects. The plan outlines data collection, data processing, and procedures for estimating GHG emissions using modeling tools. The proposed framework is designed to be consistent and scalable across HOT lane projects in California, enabling standardized measurement of their impacts on GHG emissions.

Conceptual Framework

Before we present the evaluation and data collection plans, it is useful to clarify the mechanisms through which HOT lanes may affect transportation-related GHG emissions. Transportation emissions are driven by how much people travel, where and when they travel, which modes and vehicles they use, and the speeds at which those vehicles operate. Therefore, changes in travel behavior or transportation system performance, stemming from HOT lane implementation, can alter regional GHG emissions.

HOT lane implementation can influence a range of traveler decisions, including lane choice (HOT vs. general purpose), route choice, mode choice, vehicle occupancy, departure time, destination choice, and activity participation. HOT lanes may alter these decisions because they affect tolls, travel time, reliability, and other features of travel alternatives. Appendix A provides additional behavioral context on how adding an HOT lane may affect different traveler decisions.

Because roadway capacity is limited, the decisions of some travelers can affect congestion, speeds, and reliability for others. For example, if some drivers shift into an HOT lane, change routes, or change departure times, traffic conditions may also change on general-purpose lanes, ramps, parallel routes, and nearby arterials.

Key Data Collection Principles

Principle 1: Estimate net before-and-after changes. Given the broad range of travel behaviors affected by HOT lane projects, this report recommends an empirical, reduced-form evaluation framework focused on regional changes in VMT and GHG emissions. In plain terms, this means measuring what changed before and after implementation, without trying to model every individual behavioral pathway that caused the change.

A more detailed structural modeling approach would require extensive behavioral data and many assumptions about how travelers make decisions. For Task 4, a reduced-form approach is more practical because it can be standardized across projects and used to estimate the overall size and direction of HOT lane impacts on emissions-related outcomes.

Principle 2: Evaluate impacts at the regional scale. In this report, "regional" refers to the broader travel shed likely to be affected by the HOT lane project, not necessarily an entire metropolitan region. HOT lane implementation may change travel patterns beyond the managed-lane facility itself by affecting route choice, departure time, destination choice, mode choice, and overall travel demand. As a result, facility- or corridor-level analysis may miss offsetting or reinforcing effects elsewhere in the network. For example, reduced congestion on the HOT facility could be accompanied by route shifts, longer trips, or traffic changes on nearby arterials. Regional evaluation is therefore necessary to assess changes in total VMT and GHG emissions, rather than only changes in speed, VMT, or emissions on the facility with HOT lanes.

Principle 3: Measure VMT by speed bin for use in EMFAC. Direct measurement of GHG emissions across an entire metropolitan region is not practical. Modeling GHG emissions using measurements of vehicle travel is a practical alternative. The vehicle travel measurements necessary to estimate GHG emissions are VMT by speed bin, and, where feasible, by vehicle type. VMT by speed bin is important because emissions per mile vary by speed; the same amount of VMT can produce different GHG estimates depending on congestion and operating conditions. Vehicle type data can further improve estimates but may be difficult to collect consistently.

Prior HOT lane impact studies have often focused on the facility scale. For example, Xu et al. (2017) found that peak-hour air pollutant emissions on Atlanta's I-85 may have increased by up to 11% after conversion when controlling for calendar-year effects. Although informative, facility-level analyses do not capture the broader regional impacts needed to understand total GHG effects.

Consistent with our review of the academic literature, Manville (2024) did not find any empirical evidence that measures the impact of HOT lane implementation on regional VMT. As such, the direction and magnitude of HOT lane impacts on regional VMT and GHG emissions remain open empirical questions. Collecting standardized before-and-after data across new HOT lane projects, as outlined in this report, will enable analysts to estimate the size and direction of these impacts (likely for the first time). Such estimates would be valuable for policymakers in California and other jurisdictions considering priced managed lanes as part of broader carbon-reduction strategies.

For analysts, the practical implication is that the data collection plan should prioritize consistent regional measurements of VMT, speeds, and (if possible) vehicle types before and after implementation, rather than only monitoring the HOT lane facility itself.

Task 4 Objectives

The objective of Task 4 is to develop a comprehensive and scalable data collection framework for empirically evaluating the GHG impacts of HOT lane projects. The framework is intended to help analysts decide what data to collect, where to collect it, when to collect it, and how to process it for emissions estimation. This report identifies suitable data sources, collection methods, and processing procedures for before-and-after analysis of individual projects. The framework specifies how key metrics, including VMT and speeds, are derived and used as inputs to emissions modeling tools such as California's EMFAC model.

To support regional-level evaluation, rather than only corridor- or facility-level analysis, the framework adopts two alternative data collection approaches: (1) tracking the vehicles of a sample of households in the travel shed, referred to as the **household-based approach**, and (2) installing sensors on a sample of roadway infrastructure throughout the travel shed, referred to as the **infrastructure-based approach**.

Report Outline

The remainder of this report is organized as follows. Section 2 translates the conceptual framing in Section 1 into a methodological framework for evaluating the GHG impacts of HOT lane projects. Section 3 operationalizes that framework and the key data collection principles in Section 1 by describing proposed data collection procedures for both household-based and infrastructure-based approaches, including data validation and integration with emissions models.

Methodological Framework for Evaluating HOT Impacts on GHG Emissions

Although this Task 4 report focuses on data collection, that work is most useful when embedded in a broader framework for evaluating the GHG impacts of HOT lane projects. Effective evaluation of infrastructure projects, including HOT lanes, should (i) align clearly stated goals with performance metrics, (ii) establish a data-collection strategy to support rigorous analysis of the impact of a project or multiple projects of the same type, and (iii) produce findings that can inform future infrastructure investment decisions. **Figure 1** summarizes the proposed methodological framework, and the following subsections describe each step and its role in a credible before-and-after evaluation.

The framework begins by defining project goals and translating them into an evaluation plan. It then turns to data collection, validation, and integration with an emissions model, followed by before-and-after analysis and reporting. Because this report emphasizes implementation of the data-collection component, Section 3 provides more detailed guidance on data collection, validation, and model integration.

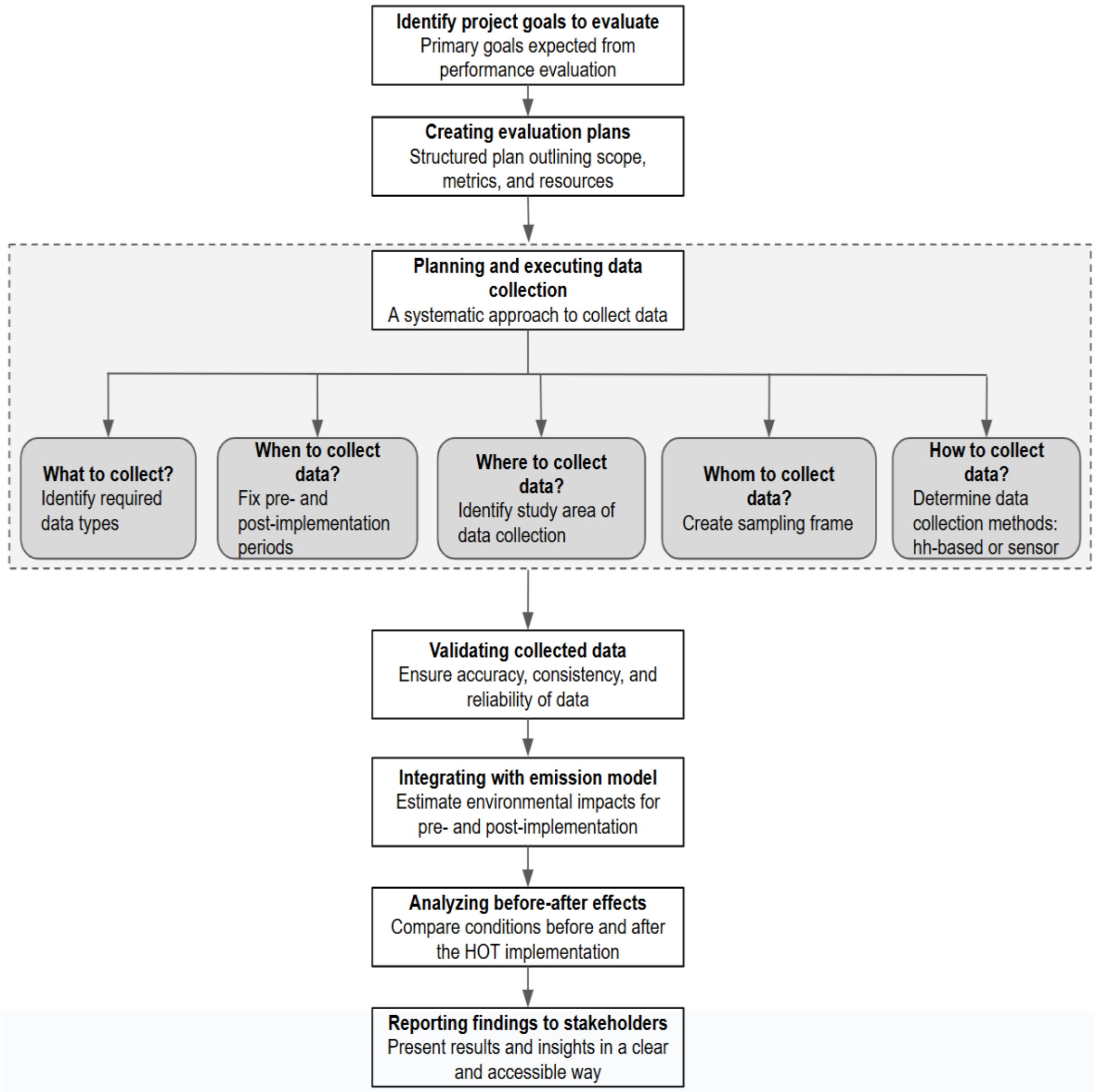


Figure 1. Proposed Methodological Framework for Evaluating HOT Impacts on GHG Emissions

Identify Project Goals to Evaluate

The first step in evaluating an HOT lane project is to identify the goals and objectives the evaluation is meant to assess. Fortunately, Caltrans is quite clear that one of their central goals is reducing GHG emissions, and they want to determine how HOT lane implementation affects GHG emissions. Other objectives for implementing HOT lanes may include improving mobility and travel-time reliability, encouraging higher vehicle occupancy, maintaining or improving safety, and, in some cases, generating toll revenue to support transportation investments.

Creating Evaluation Plans

Once the goals are defined, the next step is to develop an evaluation plan. For practical implementation, the plan should specify: the HOT lane facility under study; the travel shed or geographic scope of the analysis; the pre- and post-implementation periods; the performance metrics tied to each goal/objective in Section 2.1; the data sources; the data processing steps; the emissions-model inputs; and the methods used to compare before-and-after conditions. In this report, the primary performance metric is GHG emissions, and we recommend estimating GHG emissions by (i) measuring VMT by speed bin and vehicle type and (ii) inputting these measurements into EMFAC, a GHG emissions estimation tool.

The evaluation plan should also describe data gaps, assumptions, potential sources of bias, quality-control procedures, and other limitations that may affect interpretation of the results. These limitations may include unavailable data, uncertainty about the appropriate travel shed, simplified data-processing assumptions, incomplete sensor coverage, or differences between the before and after periods that are unrelated to HOT lane implementation.

A strong evaluation plan also identifies the staff, equipment, modeling tools, budget, schedule, and quality-control procedures required to carry out the evaluation. Addressing these issues in advance helps ensure that the analysis is feasible, internally consistent, and useful for decision-making.

Planning and Executing Data Collection

A credible evaluation of HOT lane impacts on GHG emissions requires a deliberate data-collection strategy that defines the relevant variables, geographic scope, sampling frame, and timing. Useful data sources may include traffic sensors, toll transaction records, travel-time probes, incident logs, and traveler surveys that track vehicle movements. These data should be collected at sufficient spatial and temporal resolution to estimate GHG emissions and, where feasible, to help explain observed changes in travel behavior.

As noted previously, we recommend a data collection plan to measure VMT by speed bin and vehicle type at the regional level, before and after HOT lane implementation. Two data-collection approaches are promising. The **household-based approach** captures vehicle trajectories and can link travel changes to household and traveler characteristics. The **infrastructure-based approach** captures traffic volumes and speeds at selected roadway locations. The approach combines permanent sensors on freeways throughout California with temporary instrumentation to obtain vehicle counts and speeds on arterials, local roads, freeway ramps, etc. Data products from mobility analytics firms that use large-scale mobile-phone or connected vehicle data can help define the relevant travel shed and support the design of both household and infrastructure samples.

For household-based surveys, address-based sampling informed by origin-destination data can support stratified random sampling and oversampling of groups particularly relevant to the evaluation, such as likely HOT lane users. OBD-II devices or alternative technologies that provide detailed trajectory data can then be used to estimate VMT by speed bin.

Infrastructure-based surveys should combine permanent freeway sensor data with sampled observations on roadways that are not continuously monitored, including arterials and local roads. Sampling these roads helps analysts estimate regional VMT and GHG emission changes more accurately than would be possible from freeway sensors alone.

Section 3 provides more detailed guidance on sampling design, sample size, and pre- and post-implementation data collection for both approaches.

Validating Collected Data

After data collection, the data should be validated to ensure that it is accurate, internally consistent, and sufficiently complete for analysis. This step is essential because measurement errors can bias estimated changes in VMT, speeds, and emissions. Validation also provides a structured basis for correcting errors, documenting limitations, and determining whether additional data collection is necessary.

Validation of household-based travel data is especially important because this approach captures detailed trajectories but often relies on relatively small samples. One useful strategy is to calibrate household-based estimates against infrastructure-based counts wherever overlapping observations are available. In practice, this means converting household trajectories into estimated flows on specific roadway segments and comparing those estimates with observed sensor counts on the same facilities.

Validation of infrastructure-based data should focus on sensor health and data quality. Loop detectors, radar systems, and video-based sensors are susceptible to equipment failures, communication problems, weather-related distortion, occlusion, and other known sources of error. Daily quality checks and rule-based filters can provide a practical basis for identifying malfunctioning sensors and retaining only data that meet acceptable performance thresholds.

Section 3 provides detailed recommendations on data validation techniques.

Integrating Data with the Emission Model

Direct measurement of GHG emissions across an entire metropolitan region is not practical. Therefore, this framework recommends using an emissions model. In California, EMFAC is the most appropriate tool because it is designed for on-road emissions analysis and requires traffic activity inputs such as VMT by speed bin. EMFAC also allows VMT to be differentiated by vehicle type, which can improve estimation accuracy. Vehicle type data are valuable where available, but analysts may still conduct a simplified analysis when consistent vehicle type data are not available.

For household-based data, vehicle trajectory records are processed into short time intervals, with VMT and average speed stored for each interval. Each interval's VMT is then assigned to a speed bin. The resulting VMT by speed bin, and by vehicle type where available, is entered into EMFAC to estimate regional GHG emissions.

For infrastructure-based data, interval-level traffic counts and speeds should be converted into VMT by speed bin across monitored roadway segments, with sampled observations scaled as needed to represent full-day and network-wide conditions. Aggregating these results across roadway classes produces the regional VMT-by-speed-bin inputs required by EMFAC.

Section 3 provides a more detailed discussion of the required data-processing steps and emissions-model inputs.

Analyzing Before-After Effects and Collecting Data for Stronger Evidence on HOT Lane Impacts

The core analysis should compare GHG emissions and VMT before and after HOT lane implementation. Depending on the household survey design, this comparison may rely on paired observations for the same vehicles or households, or on repeated cross-sections drawn from the same region. Section 3 discusses these two options in more detail. We recommend repeated cross-section data collection for the household-based approach and paired sampling for the infrastructure-based approach.

A single before-and-after analysis of an HOT lane project can show what changed for that project, but it is difficult to know whether the observed change was caused by the HOT lane or by other factors. Stronger conclusions about the impact of HOT lane implementation on GHG emissions can be drawn when a consistent data-collection framework is applied across multiple projects over time.

Even with multiple evaluations, analysts should collect data on other conditions that may affect travel and emissions at the same time as the HOT lane project. These conditions, often called confounding factors, may include fuel prices, macroeconomic conditions, population and employment changes, seasonal effects, transit service changes, nearby construction, incidents, or other network disruptions. Where feasible, VMT by speed bin and vehicle type data should also be collected for comparison areas where HOT lanes were not opened during the same time period, along with data on the same confounding factors in those areas.

To support stronger evidence about project impacts and inform future investment decisions, analysts should also document key attributes of each HOT lane project and its implementation. These attributes include: the number and type of lanes before and after implementation; the number of general-purpose, HOV, and HOT lanes; access design and spacing; eligibility rules for carpools, transit, and exempt vehicles; pricing approach, such as static, time-dependent, or real-time demand-responsive pricing; pricing objectives, such as revenue, service quality, or system performance; construction duration; opening date; and major concurrent roadway, transit, or land-use changes in the travel shed.

Reporting Findings to Stakeholders

The final step is to communicate the findings in formats useful to different audiences. Technical documentation should report methods, assumptions, validation results, emissions estimates, data-processing steps, and limitations in sufficient detail for analysts and partner agencies. Recommended reporting outputs include a concise executive summary, a technical memorandum, a data dictionary, a validation summary, emissions-model input and output tables, a discussion of uncertainty and limitations, and clear visual summaries of key before-and-after results. Decision-makers and the public will often benefit from concise summaries, clear visualizations, and plain-language explanations of what changed, how confident the analysts are in their findings, and what the results imply for future HOT lane policy and investment decisions.

Data Collection Procedures for Evaluating HOT Impacts on GHG Emissions

This section is the core of Task 4 as it covers the data-collection procedures for measuring VMT by speed bin and vehicle type before and after HOT lane implementation. We include two complementary data-collection approaches: sampling and surveying households (Section 3.1) and sampling roadway infrastructure (Section 3.2). The primary emphasis is on household-based surveys, which capture detailed travel behavior and link it to demographic, socioeconomic, and geographic characteristics.

Household-Based Survey Data

We recommend sampling and surveying households within the travel shed of an HOT lane project as the primary method for evaluating the effect of HOT lane implementation on VMT and GHG emissions. This approach involves obtaining a representative sample of households that travel within the HOT lane travel shed and collecting detailed information on their VMT by speed bin and vehicle type, as well as information on travel purpose, travel time, mode choice, etc. Surveying households also enables the capture of demographic and socioeconomic characteristics to analyze the heterogeneous impacts of HOT lanes across the population.

Collecting data before and after HOT lane implementation, either from the same households or from separate representative samples, supports direct comparison of changes in travel behavior, VMT, and emissions. **Figure 2** summarizes the recommended data-collection workflow.

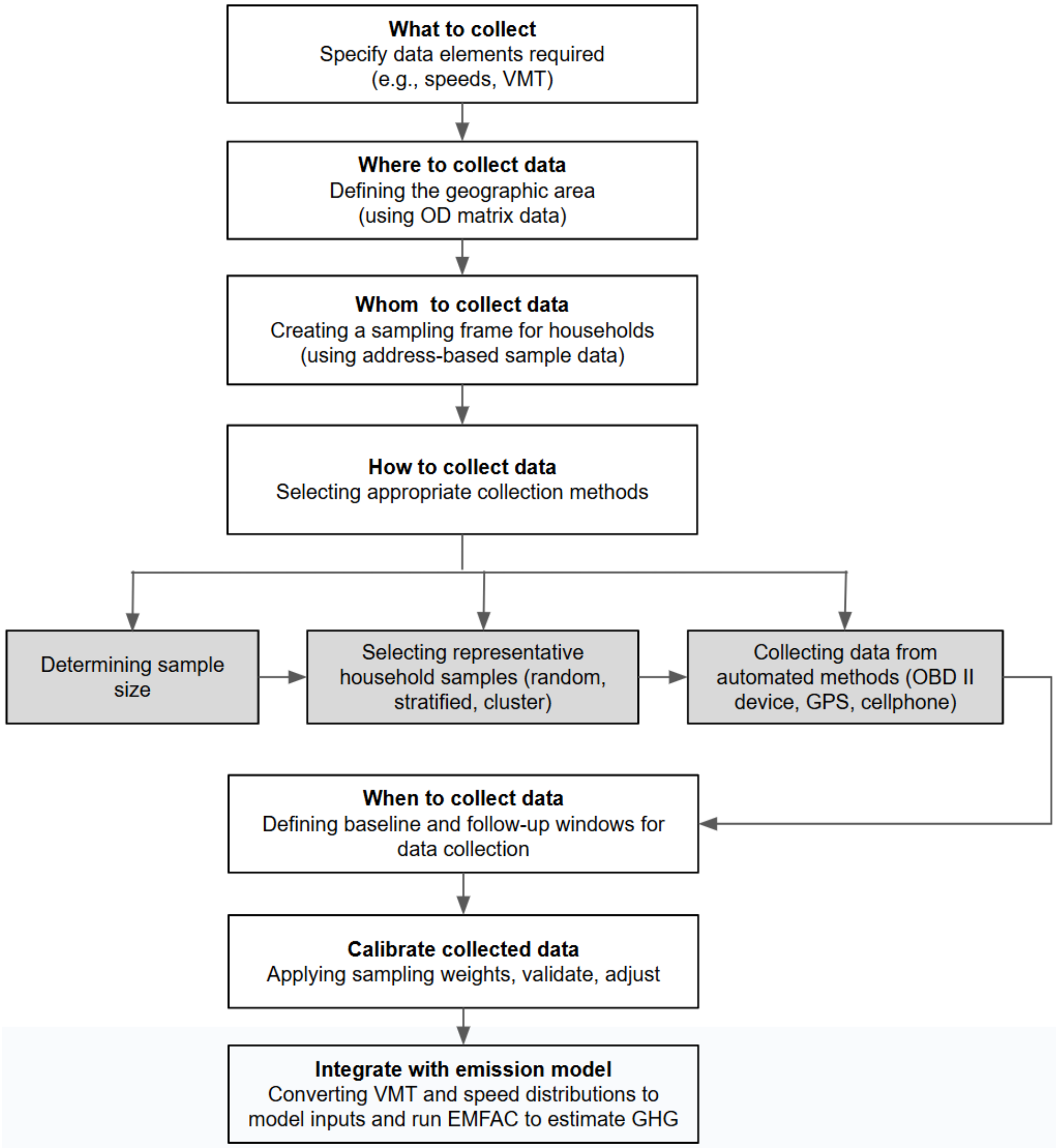


Figure 2. Household Data Collection, Validation, and Integration with Emission Model

What to Collect: Specify Required Data

The overarching methodology for evaluating HOT lane implementation impacts on GHG emissions discussed in Section 2 involves identifying project goals and then performance metrics for those goals. For Task 4, it is clear from Caltrans that their goal is to reduce GHG emissions, and the key performance metric is GHG emissions. However, rather than measuring GHG emissions directly, we recommend measuring VMT by speed bin and vehicle type. VMT by speed bin and vehicle type for the sample of surveyed households can then be expanded to represent VMT by speed bin and vehicle type for the entire travel shed, before being entered into a transportation-based GHG emissions estimation tool, EMFAC.

To collect VMT by speed bin and vehicle type for sampled households, we recommend either instrumenting household vehicles with OBD-II devices and/or GPS or using traveler trace data from smartphones with location information enabled. These technologies enable continuous monitoring of vehicle movements over a defined period, such as one week or one month, and, with existing algorithmic techniques for processing real-time location data, they enable high-accuracy estimation of VMT by speed bin and vehicle type.

For more insights into traveler behavior, survey tools can ask participants about their recent trip to verify mode choice, activity locations, and stop purposes. We also recommend collecting basic sociodemographic characteristics, such as vehicle ownership, income, age, gender, and employment status, to support weighting and additional behavioral insights.

Where to Collect Data: Define the Geographic Area

The next step is to define the geographic area over which HOT lane impacts will be evaluated, i.e., the travel shed. This requires identifying the households and trips likely to be influenced by the new HOT facility.

To define a travel shed around a HOT facility project, we recommend using an origin–destination (OD) trip matrix (see **Table 1**) to obtain a list of origins and destinations with a *reasonable* number of trips that might be *impacted by* the new HOT facility project. Households in the origin and destination zones with a reasonable number of trips that might be impacted by the new HOT facility should then be included in the sampling frame.

Table 1. A Sample OD-Matrix Across Three TAZs

Origins/Destinations	TAZ 1	TAZ 2	TAZ 3	Row Total
TAZ 1	4,000	7,000	9,000	20,000
TAZ 2	2,000	4,000	8,000	14,000
TAZ 3	1,000	5,000	3,000	9000
Column Total	7,000	16,000	20,000	43,000

Determining a “reasonable number of trips” and “might be impacted by” will require some judgment on the analyst’s part. We recommend considering OD pair trips that “might be impacted by” the HOT facility, rather than only the OD pair trips that currently use the facility where the HOT lanes will be added, because of the network effects of an HOT lane project. Section 1 provides the reasoning for this choice—an HOT lane implementation can change a wide range of travel behaviors for people in the travel shed and impact the performance of facilities near and not-so-near the new HOT lane facility.

Regarding “a reasonable number of trips,” the analyst needs to make a trade-off between the cost of surveying households in zones that are increasingly less likely to be impacted by the HOT lane facility and the information gained from surveying these households.

Mobility Analytics providers using big data from smartphones and connected vehicles, such as Streetlight and INRIX, sell OD matrices with flexible zonal resolution. They can filter the OD matrix by time of day, trip purpose, or traveler characteristics. Regional travel demand models also produce OD matrices.

Determining the travel shed is essential as all subsequent sampling and analysis depend on it.

Whom to Collect Data from: Create a Sampling Frame

With the study area defined, the next step is to create a sampling frame of households from which survey participants will be contacted. This frame should cover households in the travel shed and include stratification information derived from two sources: the OD analysis, which identifies where trips likely to be impacted by the HOT lane facility originate and end, and an address-based household database.

Address-based sampling (ABS) is the preferred approach for modern household travel surveys because it provides near-complete coverage and precise geographic targeting. Researchers typically use comprehensive address files such as the USPS Delivery Sequence File to draw random or stratified samples within the study area (Dillman et al., 2014). OD information can then be used to stratify or weight subareas so that higher-demand zones are adequately represented.

Creating the sampling frame involves extracting all residential addresses within the travel shed and tagging each address with attributes useful for stratification, such as census tract or block ID, ZIP code, neighborhood income level, or proximity to high-demand OD pairs. These attributes support the sampling strategies described next.

How to Collect Data: Determine Sample Size, Samples, and Sampling Methods

Sample Size

The sample must be large enough to detect meaningful changes in VMT and GHG emissions with adequate confidence, while remaining feasible within budget and time constraints. Sample size determination should therefore balance statistical precision against the cost of instrumentation for household vehicles or travelers, especially when OBD-II devices are used.

Required sample size depends on the variability of the outcome measures and the desired precision. For example, determining an appropriate sample size, n, with a specified margin of error, ME, at a given confidence level, α, requires an estimate of VMT standard deviation, S, from prior surveys or pilot data. A common survey-design formula from Dillman et al. (2014) is shown below.

$$n = \left(\frac{S \times Z_{\alpha}}{ME}\right)^2 \qquad (1)$$

In this expression, S is the standard deviation of the key metric (i.e., VMT in our case), Z_α is the z-statistic from the standard normal distribution for the chosen confidence level, α, and ME is the allowable margin of error.

For example, using data from the 2022 National Household Travel Survey (NHTS), we estimate the standard deviation of household-level daily VMT in the US as S = 24 miles (with a mean of 26 miles). Assuming a 90% confidence level (Z = 1.645) and an allowable margin of error of ME = 0.5 miles, the required sample size is approximately 6,235.

Greater variability in the outcome measure or stricter precision requirements (i.e., a smaller margin of error) lead to a larger required sample size. The margin of error represents the maximum acceptable difference between the sample estimate and the true population value. Because the required sample size grows with the inverse square of the margin of error, so does the cost of the survey; Section 3.1.8 quantifies this relationship.

Select Representative Household Samples

Once the target sample size and frame are established, the next step is to select the households to invite. The sample should be representative of the population within the travel shed to ensure unbiased inferences about travel behavior and HOT lane effects. Common options include simple random sampling, stratified sampling, and cluster sampling; the choice should reflect both study goals and operational constraints.

Simple random sampling gives every household an equal chance of selection and is straightforward to implement. However, simple random sampling can easily fail to include key subgroups if the subgroup sizes are small.

Stratified sampling is therefore often preferable. The frame can be divided into strata based on geography, expected corridor use, or demographic variables, and separate random samples can be drawn within each stratum. With stratified sampling, the sample size can be allocated in proportion to trip generation or adjusted to oversample high-relevance zones, with weights applied during analysis to ensure unbiased population estimates.

Cluster sampling, in which groups of households are sampled by neighborhood, block, or employer, can reduce fieldwork costs when in-person recruitment or device deployment is required. However, it also increases within-cluster similarity and reduces the effective sample size. Unless logistics strongly favor clustering, stratified random sampling is usually more appropriate.

In practice, the preferred approach is likely to be stratified random sampling with proportional allocation and, where justified, oversampling of critical strata. Selected households should be randomized within strata, recruited through standard consent procedures, and checked against population benchmarks such as census data. Any remaining imbalance between the sample and the area's census information can be addressed through weighting, but large deviations may indicate a need for supplemental recruitment.

Collect Data through Automated Methods

After sample selection and recruitment, the core task is to collect detailed data on the movements of each member of a sampled household, or at least the movements of the household's vehicles.

We recommend using OBD-II devices installed in participant vehicles because they can record high-resolution information such as speed, engine activity, and, when paired with GPS, location and trajectory. OBD-II devices provide precise measures of VMT by speed bin (and vehicle type), enabling high-quality estimates of emissions.

Each participating household would be asked to install a plug-and-play OBD-II device in each of their household's vehicles for the data-collection period. These devices can store data locally or transmit it through a cellular connection. Over the study period, the devices can record distance traveled, routes, speed profiles, idling time, and other driving conditions. These devices largely eliminate recall error, and they capture drive-cycle information that can be used for the most accurate emissions modeling.

A brief supplementary survey can collect contextual information such as fuel type, vehicle characteristics, typical routes, carpooling behavior, and attitudes toward toll lanes. These data can help interpret observed changes, but the primary travel measures should come from the automated device records.

California's 2017 and 2024 Road Charge Pilot Programs found that plug-in OBD-II devices were among the most practical and user-acceptable methods for collecting road-use data (California Department of Transportation, 2024, 2017). The pilots highlighted their reliability, ease of use, and potential for large-scale deployment. The key advantages, based on the two reports, are summarized below.

- **Reliability and accuracy**: Unlike GPS or smartphone apps, OBD-II systems directly capture mileage from the vehicle's odometer, ensuring precise and consistent data reporting. Even in tunnels, dense urban areas, or locations with poor connectivity, the devices continued to record accurate mileage.
- **Privacy protection:** One of the most significant concerns with road usage charging is driver privacy. OBD-II devices address this by recording mileage without tracking location. Unlike GPS-based systems, which can reveal detailed travel patterns, OBD-II devices only report the distance traveled.
- **Cost-effectiveness:** Since most vehicles manufactured after 1996 are already equipped with OBD-II ports, the program avoided the need for costly new infrastructure or custom hardware. The plug-in devices were inexpensive to distribute and required no permanent modifications to vehicles, making them a practical choice for large-scale deployment.
- **Universal compatibility:** California's diverse vehicle fleet—ranging from older sedans to newer hybrids—posed no challenge for OBD-II devices. Because OBD-II ports are standardized, the devices worked seamlessly across nearly all participant vehicles. In contrast, GPS devices and smartphone apps would have faced issues with older vehicles lacking modern technologies or drivers with incompatible phones.
- **Ease of use for participants:** Participants only needed to plug in the device once, after which it automatically handled data collection. Unlike smartphone apps, which demand installation, regular activation, and battery management, the OBD-II devices were a true "set it and forget it" solution—minimizing participant effort while maximizing data quality.

One advantage observed in the road charge pilots does not transfer to HOT lane evaluation. Those pilots used OBD-II devices in a mileage-only configuration, which is sufficient for road usage charging but not for emissions analysis. The OBD-II devices can also log and report vehicle speeds, meaning that OBD-II devices produce the information necessary to estimate GHG emissions using the EMFAC model. However, OBD-II devices do not provide location information. Given that one of the main benefits of the household-based approach is understanding how travel behavior changes vary before and after HOT lane implementation, OBD-II devices must be paired with GPS, GPS-enabled loggers, or smartphone traces. The validation procedure described in Section 3.1.6 likewise depends on GPS data, because it requires identifying which sampled vehicles traversed specific roadway segments.

Participant consent procedures and data management protocols must accordingly address location privacy directly, including limits on data retention, restrictions on access to raw trajectories, and spatial aggregation of any published results.

In summary, OBD-II devices paired with GPS can provide the high-resolution travel data needed to estimate VMT by speed bin (and vehicle type) and support credible GHG analysis. By relying on observed behavior rather than self-reported travel, this approach strengthens the evaluation's validity.

When to Collect Data: Define Windows of Data Collection

Defining when to collect data is critical to a valid before-and-after evaluation. This requires specifying the before-and-after periods, along with the duration and frequency of data collection within each period.

Pre-Implementation (Before) Period

For California HOT lane evaluations, the baseline period should reflect conditions immediately before implementation and should consider local travel patterns, weather, school schedules, and holiday effects. Ideally, baseline data would cover a full 12 months and avoid atypical conditions such as major construction, wildfire smoke events, or other unusual disruptions. If a facility opens in September, the strongest benchmark would typically span the previous fall through summer. Baseline data collection planning should begin roughly two years before opening to allow time for setup and full data collection (Perez et al., 2011).

Post-Implementation (After) Period

Post-implementation data collection should capture short-term effects and longer-term behavioral adjustments. A useful schedule would involve evaluating travel behavior in the short term (within 1 year of implementation), medium term (after 3 years), and long term (after 5 years).

Paired Before–and–After Samples (Same Households)

A paired before-and-after (also known as panel) sample design follows the same households across waves. Its main advantage is statistical efficiency: each household serves as its own control, reducing the influence of time-invariant factors such as location, vehicle type, and stable travel preferences. With OBD-II or GPS data, panel designs also support fine-grained analysis of changes in speeds, routes, idling, and stop-and-go conditions.

Paired samples also have drawbacks. Attrition can bias results if dropout is associated with key factors related to VMT (by speed bin and vehicle type). Maintaining a panel increases costs because it requires participant retention, device maintenance, and repeated contact. Changes in household composition, employment, residence, or vehicle ownership can also complicate interpretation, and panel data require careful treatment of missing observations and attrition weights. Moreover, given the nature of infrastructure projects, even if the household composition remains the same, all members will have aged at least a few years between pre-implementation and post-implementation, potentially changing their life stages.

Independent Before–and–After Samples (Different Households)

An independent before-and-after sampling design (or, repeated cross-section analysis) involves recruiting new respondents in each wave. This approach is simpler to administer because it avoids panel retention.

It has two main limitations: reduced statistical efficiency and potential bias due to residential relocation. Regarding statistical efficiency, consider the equation below, where Y denotes GHG emissions from a household. In a paired sample, the covariance term $\mathrm{Cov}(Y_{\text{after}}, Y_{\text{before}})$ is almost certainly positive, making the variance on the left side smaller. In an independent-sampling approach, the covariance term is either zero or much closer to zero than in the paired-sample case. The implication of high variance in the independent sampling case is that a larger sample is needed to provide the same precision as a paired sampling approach.

$$\mathrm{Var}(Y_{\text{after}} - Y_{\text{before}}) = \mathrm{Var}(Y_{\text{after}}) + \mathrm{Var}(Y_{\text{before}}) - 2\,\mathrm{Cov}(Y_{\text{after}}, Y_{\text{before}}) \quad (2)$$

Regarding bias from residential relocation, the impact of HOT lane implementation and the time required to implement the HOT lane mean that a sizeable number of households may move into or out of the HOT lane travel shed between the before and after data collections. These residential relocations may be independent of the HOT lane implementation or due in part to it.

Independent samples also provide less insight into within-household changes and require careful stratification and weighting to ensure comparability across waves.

We recommend independent sampling for infrastructure projects, given their long construction times, because under these conditions the shortcomings of paired sampling are more pronounced than those of independent sampling.

Validating Household-Based Survey Analysis with Infrastructure-Based Data

Household-based surveys can capture detailed travel trajectories across all road types, but their main limitation is sample size and representativeness. Because only a sample of households is observed, estimates may be biased if the sampling design or realized sample does not reflect the broader traveling population.

One way to reduce this risk is to verify and validate household-based estimates against infrastructure data such as loop detectors or video image processors. These sensors provide population-level observations of counts, speeds, and related traffic measures on equipped roadways, especially freeways, and therefore offer a useful benchmark for the household sample.

Validation requires converting household trajectory data into estimated traffic counts by roadway segment and comparing those estimates with observed sensor counts. GPS data are essential for this step because they identify where and when sampled vehicles traverse specific facilities.

The most appropriate facility for validation is usually one associated with the HOT or HOV corridor and equipped with reliable sensors. Because GPS data may not always distinguish managed-lane use from general-purpose use, validation is generally more robust when based on total facility counts rather than lane-specific counts.

The validation process begins by expanding household sample data to represent the population using socio-demographic and geographical information obtained from surveyed households. Each household receives an expansion factor based on its population size and achieved sample size, as illustrated in **Table 2**. Households are indexed by h rather than i, so that the household expansion factor is not confused with the link index i used throughout Section 3.2.

Table 2. Example of a Household Sample Size Table

Household	Housing Location	Household Size	…	Income Level	Population Size	Sample Size	Expansion Factor ($w_h = p_h/s_h$)
1	O_1	3	…	Low	p_1	s_1	w_1
2	O_1	4	…	Low	p_2	s_2	w_2
3	O_2	3	…	High	p_3	s_3	w_3
…	…	…	…	…	…	…	…
n	O_m	3	…	High	p_n	s_n	w_n

Next, daily trip trajectories are used to identify which sampled trips traverse the HOT corridor. Those trips are multiplied by the appropriate expansion factors to estimate total daily traffic counts from the sample. This is repeated for each observation day.

These estimated counts are then compared with observed sensor counts. For each day, the ratio of observed to estimated counts defines a validation factor. If the average validation factor differs substantially from 1, this indicates the sample does not accurately (or at least precisely) capture regional travel for the whole population. In this case, adjustments to expansion factors (based on geography) or the sampling approach may be necessary.

Integrate Data with the Emissions Model

To estimate emissions, household-based data must be converted into a format compatible with EMFAC. The model requires VMT by speed bin to produce emissions estimates. Accurate estimation of VMT by speed bin is therefore central to the entire analysis.

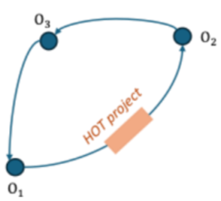
Distribution of household groups

Group number	Housing location	Household size	...	Income level	Population size	Sample size	Expansion Factor ($w_i = p_i/s_i$)	Adjusted Expansion Factor
1	O_1	3	...	low	p_1	s_1	w_1	w'_1
2	O_2	4	...	low	p_2	s_2	w_2	w'_2

Vehicle trajectories

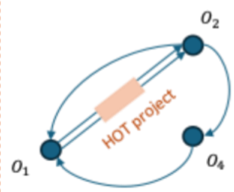
T_k^i: The set of samples in the i-th sample group on the k-th date

$s_1 = 1, T_k^1 = \{T_{1,k}^1\}$



Time interval	Travel Distance (miles)	Average Speed (mph)
1	d_1	v_1
2	d_2	v_2
...	...	...
$T_1 - 1$	d_{T_1-1}	v_{T_1-1}
T_1	d_{T_1}	v_{T_1}

$s_2 = 1, T_k^2 = \{T_{1,k}^2\}$



Time interval	Travel Distance (miles)	Average Speed (mph)
1	d'_1	v'_1
2	d'_2	v'_2
...	...	...
$T_2 - 1$	d'_{T_2-1}	v'_{T_2-1}
T_2	d'_{T_2}	v'_{T_2}

Speed bin distribution

Speed bin (mph)	Travel Distance (miles)	Adjusted Expansion Factor	VMT for Household Type 1
$0 \leq v < 10$	3	w'_1	$3w'_1$
$10 \leq v < 20$	5		$5w'_1$
...	...		...
$90 \leq v < 100$	0		0

Speed bin (mph)	Travel Distance (miles)	Adjusted Expansion Factor	VMT for Household Type 2
$0 \leq v < 10$	2	w'_2	$2w'_2$
$10 \leq v < 20$	10		$10w'_2$
...	...		...
$90 \leq v < 100$	2		$2w'_2$

Speed bin (mph)	Total VMT (veh·miles)
$0 \leq v < 10$	$3w'_1 + 2w'_2$
$10 \leq v < 20$	$5w'_1 + 10w'_2$
...	...
$90 \leq v < 100$	$2w'_2$

Emission Model (e.g., EMFAC model)

Figure 3. Example of VMT Calculation by Speed Bin from Household-Based Surveys

Using the household-type table and the expansion factors, analysts can process the trajectory data from each sampled household. OBD-II devices output distance and speed data, which allow analysts to calculate travel distance and average speed for given time intervals. The time interval length for trajectory processing should be chosen to reduce noise without masking meaningful variation in driving conditions.

Each interval is then assigned to the appropriate speed bin, and the associated travel distance is added to that bin. Summing across intervals produces a speed-bin VMT distribution for each sampled household.

That distribution is scaled to the household type using the expansion factor, yielding VMT by speed bin for each household group. **Figure 3** illustrates the process for two household types.

Finally, VMT is summed across household groups within each speed bin to produce the population-level VMT distribution used by EMFAC to estimate total GHG emissions.

Cost

Cost is an important consideration in general, and particularly when comparing the household-based approach with the infrastructure-based approach. This subsection provides information obtained on the price of household-based surveys.

Naturally, the overall cost depends primarily on the coverage and sample size. Larger samples improve statistical precision but increase recruitment, incentive, and data-processing costs. Longer data-collection windows improve the representativeness of VMT and speed-bin estimates but increase respondent burden and device-management needs. Similarly, OBD-II or GPS-enabled devices generally provide more accurate vehicle-specific VMT and speed profiles than self-reported travel diaries, but they add costs for hardware, cellular service or data transfer, technical support, deployment, and participant assistance. Smartphone-app approaches may reduce hardware costs but can introduce compatibility, battery, compliance, and privacy-management challenges. These trade-offs should be evaluated in relation to the core purpose of the household-based approach: producing defensible regional estimates of VMT by speed bin and, where feasible, vehicle type as well as understanding the travel behavior changes underlying the changes in VMT by speed bin.

The largest cost driver in moving from an online questionnaire to an instrumented design is recruitment: persuading households to install and maintain a device or an application is substantially more difficult than obtaining questionnaire responses, which raises the incentive levels and the screening effort required per completed household.

The next several subsections provide information on the cost of conducting household travel surveys.

National Household Travel Survey (NHTS) Add-On Program Cost

The 2022 National Household Travel Survey (NHTS), sponsored by the Federal Highway Administration (FHWA), was conducted by Ipsos, a global research company specializing in survey design and data collection. Ipsos has extensive experience managing large-scale transportation and public opinion surveys for government agencies and other organizations.

The NHTS Add-On program, through which Ipsos collects data, allows states, local jurisdictions, and government agencies to purchase additional samples at a cost of approximately $260 to $275 per household. The core survey Add-On program also enables the purchasing jurisdiction to add up to six additional questions to the survey within their geographic area (BERK Consulting, 2024).

Puget Sound Regional Travel Survey Cost

Resource Systems Group (RSG) was selected as the prime consultant for the 2023 Puget Sound Regional Travel Survey, with WestGroup Research as a subconsultant (RSG, 2024). RSG conducts household travel surveys using its proprietary smartphone application, rMove®, that uses smartphone sensors such as GPS, accelerometers, Wi-Fi, and compasses to record travel behavior (RSG, 2026). The 2023 Puget Sound Regional Travel Survey had a budget of $970,000 for Wave 1, targeting a minimum of 3,080 completed households, implying approximately $315 per completed household (Office of Minority and Women's Business Enterprises, 2022).

Household Travel Survey Cost using GPS Tracking Device

OBD-II devices have been used alongside GPS units in major household travel surveys to capture detailed vehicle engine data. The California Household Travel Survey (CHTS) used a combination of computer-assisted telephone interviewing (CATI), online surveys, and three types of GPS devices: wearable, in-vehicle, and in-vehicle plus an OBD unit. Households that participated in the GPS-assisted portion used the in-vehicle or in-vehicle plus OBD devices for a total of seven days (Caltrans, 2013).

Plug-and-play OBD-II GPS tracking devices are often priced from around $39.95, connecting to a vehicle's OBD-II port. Hardwired units designed for long-term durability range from $100 to $299+. Activation fees typically run between $0 and $50 per device (GPS Insight, 2026). For research-grade OBD-II devices used in travel surveys (which must record multi-parameter engine data at high frequency), costs are higher. Factors that influence device design and cost in travel surveys include costs per unit, ease of acquisition and operation by transportation professionals, and ease of operation by survey respondents.

Summary

Table 3 summarizes order-of-magnitude cost ranges that are useful for early planning. These ranges should be interpreted as planning benchmarks rather than project-specific estimates. Actual costs will depend on the target sample size identified in Section 3.1.4, the duration and timing of data collection described in Section 3.1.5, and whether the same households are retained across survey waves or replaced with independent cross-sectional samples.

Table 3. Order-of-Magnitude Cost Ranges for Household-Based Travel Survey Data Collection Methods

Cost Component	Estimated Range
OBD-II Plug-and-Play Device (Hardware)	\$40–\$300+ per Vehicle
Cellular/Data Subscription (If Applicable)	\$15–\$50 per Vehicle/Month
Cost per Completed Household (Computer-Assisted Telephone Interview) Survey	\$150–\$200 per Household
Cost per Completed Household (Face-to-Face)	\$350+ per Household
Cost per Completed Household (GPS/OBD-Enhanced)	~\$300+ per Household
Cost per Completed Household (Smart-Phone App-Based Surveys)	~\$315 per Household
Participant Incentive (Typical)	\$20 - \$100 per Household
Device Return Incentive (GPS/OBD Surveys)	\$20 - \$60 per Device

For HOT lane evaluations, these cost ranges imply that analysts should treat budget development as part of the sampling and evaluation design. A lower-cost survey may be adequate for collecting contextual information, but it may not provide the trajectory detail needed to estimate VMT by speed bin. Conversely, a fully instrumented household survey can better support the emissions-model integration described in Section 3.1.7, but the added precision must justify the higher cost. A practical budget should therefore specify the expected number of completed households, the number of vehicles instrumented per household, the length of collection waves, device and data-management costs, incentives, validation activities, and post-processing required to produce the final EMFAC inputs.

Because the required sample size in Section 3.1.4 varies with the inverse square of the margin of error, total survey cost varies in the same way. Using \$300 per completed household, which approximates the cost of trajectory-grade instrumentation, together with the values in Section 3.1.4 (S = 24 miles and Z = 1.645), a margin of error of 0.5 miles requires approximately 6,235 households, or roughly \$1.9 million per wave. Relaxing the margin of error to 1.0 mile lowers the requirement to approximately 1,559 households, or roughly \$0.5 million. Tightening it to 0.25 miles raises the requirement to approximately 24,939 households, or roughly \$7.5 million. Because a before-and-after evaluation requires at least two waves, these per-wave figures roughly double for a minimal two-wave design, and increase further if the medium- and long-term follow-up waves described in Section 3.1.5 are also funded.

Two qualifications apply to these figures. First, they cover data collection only. They exclude agency or consultant staff time for travel shed delineation, sample expansion, data validation, and emissions modeling, as well as the cost of any commercial origin-destination data used to define the travel shed in Section 3.1.2.

Second, the household-based figures above and the infrastructure-based figures in Appendix B are not derived over an identical study area: the infrastructure-based estimate rests on an Orange County network inventory, whereas the household-based estimate applies national household daily VMT moments from the 2022 NHTS. The two sets of figures are therefore best read as indicating relative magnitude rather than a precise cost difference.

The central recommendation is to align budget allocation decisions with the data-quality requirements established as described in Section 3.1: the survey should be large enough, geographically representative enough, temporally comparable enough, and instrumented well enough to support before-and-after estimates of regional VMT and GHG emissions.

Infrastructure-Based Survey Data: Sampling Roadway Segments Using Traffic Sensor Data and On-Site Samples

Traffic sensors such as loop detectors, magnetometers, and radar systems are already deployed on Caltrans freeways throughout the state. These fixed-point sensors measure traffic volume, occupancy, and speed, making them a valuable source of data for estimating VMT by speed bin.

Their main limitation is uneven coverage. In California, systems such as PeMS provide extensive freeway monitoring but much less coverage on arterials, local roads, and intersections. Because these roads make up most of the state's roadway network, this gap limits any attempt to estimate regionwide VMT and emissions using the existing PeMS sensor network alone.

To address that limitation, we propose a hybrid approach that combines existing continuous freeway sensor data with sampled observations at typically unmonitored locations obtained via manual counts, video, or portable detectors. Together, these two sources can support a complete estimate of VMT changes and the resulting changes in GHG emissions.

The infrastructure-based methodology follows the same three phases introduced in Section 2: data collection, data validation, and integration with the emissions model. **Figure 4** summarizes the workflow. The data-collection phase includes specifying the required variables, selecting collection tools, and determining where and when to sample.

Appendix B provides an example of a segment count and cost estimate for an infrastructure-based sampling program in Orange County. Sampling 3 to 5 percent of arterial and major-collector segments is estimated to cost approximately $0.67 to $1.11 million for a complete before-and-after program. At a comparable geographic scope, this is several times less than a household-based travel survey, although the two estimates are not derived over an identical study area, as noted in Section 3.1.8.

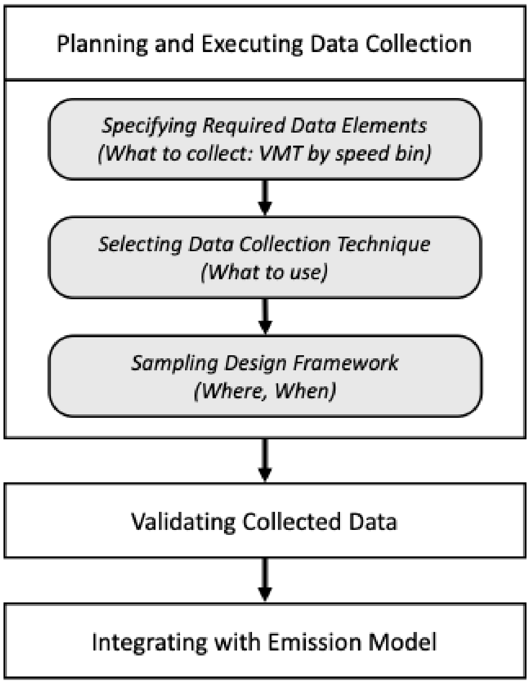


Figure 4. The Methodology for Sampling Roadway Segments using Traffic Sensor Data and On-Site Samples

What to Collect: Specify Required Data

As in Section 3.1, the goal is to estimate VMT by speed bin for use in the emissions model. Because roadway-segment sampling observes traffic only at selected locations, the key inputs are link-level traffic counts, average speeds, and the roadway length represented by each observation.

Formally, let each roadway link be indexed by i, each day indexed by d, and each time interval indexed by t. For the observed link i and interval t, the relevant traffic-state variables are average speed, traffic count, and coverage length, defined as the roadway segment represented by the observation.

Let $c_{i,d,t}$ denote the recorded traffic count on link i on day d during time interval t, and let L_i denote the length of link i. Then, link-level VMT for link i on day d during time interval t, is calculated as:

$$VMT_{i,d,t} = c_{i,d,t} \cdot L_i \tag{3}$$

To allocate VMT into speed bins for emission modeling, let K represent a set of predefined speed bins, indexed by $k \in K$. A bin defines a range of speeds, e.g., $[\acute{v}_{k-1,}\acute{v}_k)$. We define an indicator function that equals one when the average speed, $v_{i,d,t}$, on link i during time interval t on day d falls within the bin, and zero otherwise:

$$1_k(v_{i,d,t}) = \begin{cases} 1, & \acute{v}_{k-1} \leq v_{i,d,t} < \acute{v}_k \\ 0, & otherwise \end{cases} \tag{4}$$

Finally, the total VMT corresponding to the speed bin k across all links, days, and time intervals is expressed as:

$$VMT_k = \sum_{i \in I} \sum_{d \in D} \sum_{t \in T} VMT_{i,d,t} \cdot 1_k(v_{i,d,t}), \quad k \in K \tag{5}$$

What to Use: Selecting a Data Collection Technique

PeMS provides extensive freeway monitoring through thousands of detector stations. It records traffic volume, occupancy, speed, and related measures at high temporal resolution, making it the backbone of the infrastructure-based approach on freeways.

As noted above, however, PeMS provides limited coverage on arterials and local streets. Those gaps must be supplemented with on-site data collection methods such as manual counts, video-based analysis, portable automatic counters, or radar or lidar (Federal Highway Administration, 2022). The available tools for obtaining traffic information on roads without fixed sensors can be grouped into manual and automated methods.

Manual Measurements

- **Manual Traffic Counting:** This method offers high accuracy in vehicle classification and occupancy and allows for immediate data availability. However, it poses safety risks in high-traffic areas at night, and measurement quality is prone to observer fatigue. Moreover, it can only measure traffic counts, so it must be paired with an additional method for speed detection.
- **Manual Speed Detection:** These devices, such as those used by police, provide precise spot-speed data using directed beams of radio or laser light. However, because they are manually operated and rely on a narrow line of sight, their use is limited by field-of-view constraints and adverse weather conditions, making continuous monitoring impractical.

Both manual measurements are labor-intensive and, therefore, quite expensive to scale across a regional network of arterial and local roads.

Automatic Devices

- **Portable Automatic Counter Devices:** These allow for continuous, weather-resistant monitoring over several days or weeks. Automated, non-intrusive sensors—such as radar, lidar, or magnetic detectors—apply the same physical principles as manual devices but are designed for semi-permanent installation, with protective housings and wide detection ranges that minimize weather and sight limitations. They typically include integrated speed detection, eliminating the need for additional equipment.
- **Video Image Processing:** This method enables 24-hour monitoring with permanent visual records, which are valuable for quality assurance. Video can also be used to calculate link space mean speed using Edie's generalized traffic flow definitions (Cassidy and Coifman, 1997; Edie, 1963).

Among the on-site options, portable automatic devices are the most practical for regional emissions evaluation. Manual methods can be accurate but are labor-intensive, costly, and difficult to sustain, especially at night. Video provides continuous records but requires substantial storage and processing. Portable automated sensors offer a better balance of cost, durability, and ability to capture both counts and speeds.

Where/When to Collect Data: Sampling Design Framework

As in the household-based approach, the first step is to define the spatial and temporal scope of the data collection. The spatial scope is the HOT lane travel shed, and the temporal scope is the evaluation period over which before-and-after comparisons will be made.

Because it is infeasible to monitor every roadway segment continuously, the sampling design must identify a representative subset of links and time periods for observation.

Framework for Spatial Sampling Design

Site selection should use a two-tiered framework that captures both regional and corridor-level effects, as illustrated in **Figure 5**. The regional tier covers the broader network, including major freeways and arterials that may experience route substitution or demand shifts. The corridor tier focuses on the HOT facility and nearby access ramps, frontage roads, and local streets, where more localized diversions and access effects may occur.

At the regional level, site selection can be informed by engineering judgment, navigation tools, or travel-demand modeling. The process should begin by identifying which major facilities are covered and where targeted on-site sampling is still needed.

At the corridor level, candidate sites should include roadway segments within roughly 1 to 3 miles of the HOT conversion, such as access ramps, frontage roads, cross streets, and connecting local roads. These facilities often lack permanent sensors and are therefore the main targets for on-site sampling.

Comprehensive coverage of all potentially affected local roads is neither practical nor necessary. Instead, the design should rely on strategic sampling at representative locations.

A practical rule-based procedure is to group candidate links by function, such as HOT access facilities, parallel routes, and connecting streets, and then classify them by proximity to HOT access points. Sampling locations can then be allocated across these categories at roughly similar rates.

Importantly, the same sites should be sampled before and after implementation of the HOT lane.

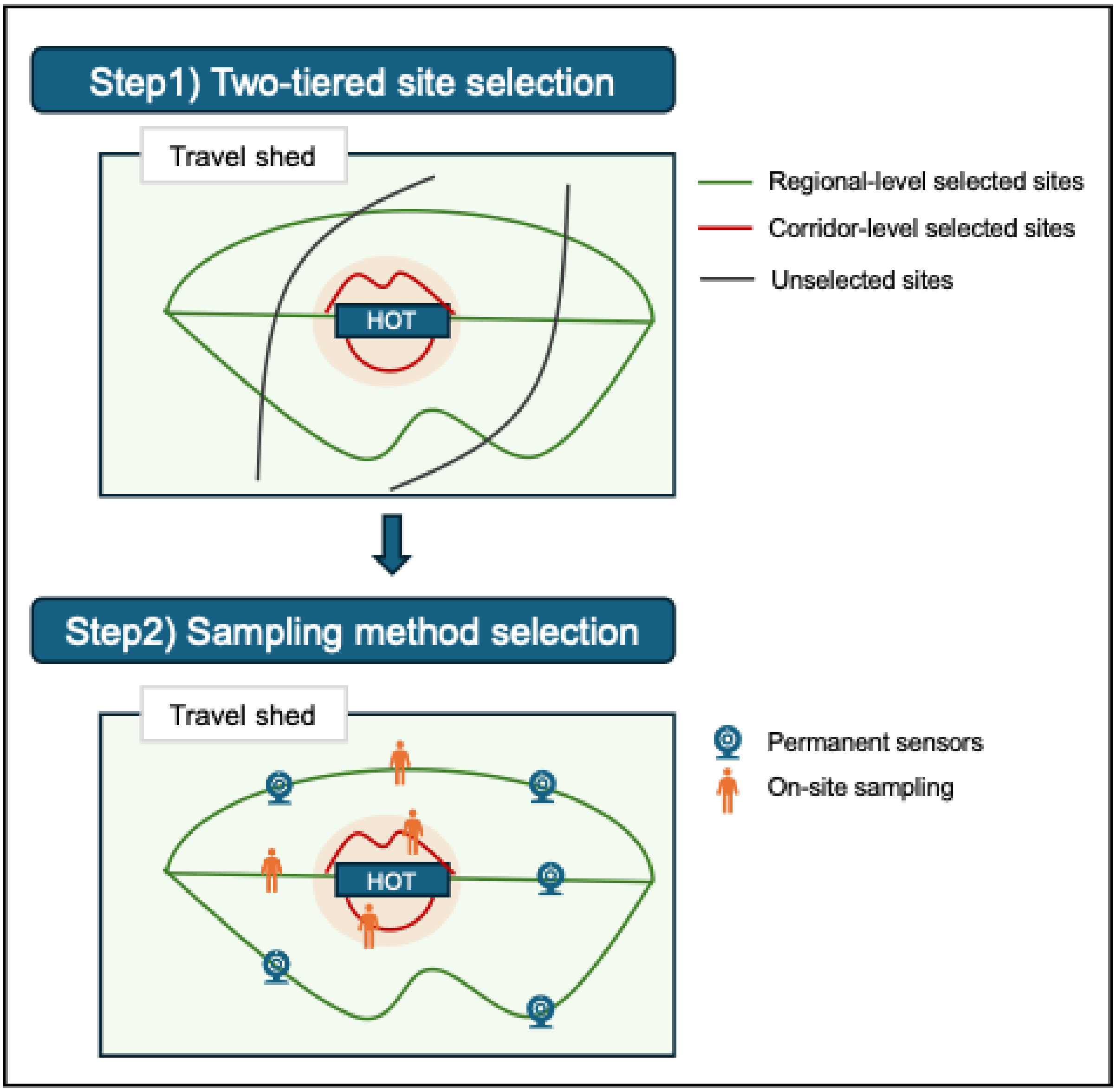


Figure 5. Two-Site Site Selection and Sampling Method Allocation

Framework for Temporal Sampling Design

After sites are selected, the temporal sampling plan specifies when field observations occur. Because weekday (commute-driven) and weekend (discretionary) traffic patterns differ systematically, we stratify monitoring by day type to ensure both are represented and to reduce within-stratum variance.

The objective is to estimate the mean daily traffic volume (or VMT) at each site with a specified margin of error. The required monitoring duration depends on: (1) the variability of traffic across days of the week; (2) the desired precision, i.e., how close the estimate must be to the true mean, expressed as a margin of error; and (3) the confidence level, i.e., how certain we require that estimate to be, typically set at 90% for traffic monitoring studies.

Monitoring duration should be determined by the standard sample-size formula within each stratum:

$$n_g = \left(\frac{S_g \times Z_\alpha}{ME_g}\right)^2, \tag{6}$$

where g indexes the day-type strata, so that g is either the weekday or the weekend stratum, S_g is the within-stratum standard deviation of daily traffic volume, Z_α is the z-statistic for the chosen confidence level, and ME_g is the allowable margin of error. S_g can be estimated from PeMS data or prior counts at the site or similar sites.

Example Calculation. Suppose prior counts indicate that weekday daily traffic has a mean of 10,000 vehicles, and a standard deviation, $S_{weekday,}$ of 1,200 vehicles (estimated from prior counts at similar sites), and we seek ME = 5% of the mean (500 vehicles) at 90% confidence (Z_α = 1.645):

$$n_{\text{weekday}} = (1{,}200 \times 1.645/500)^2 = (3.95)^2 \approx 16 \text{ weekdays} \tag{7}$$

For weekend traffic with a mean of 7,000 vehicles, standard deviation, $S_{weekend}$, of 1,050 (estimated from prior counts), and ME = 10% of the mean (700 vehicles):

$$n_{\text{weekend}} = (1{,}050 \times 1.645/700)^2 = (2.47)^2 \approx 7 \text{ weekend days} \tag{8}$$

This yields approximately 23 monitoring days (16 weekdays + 7 weekend days), or roughly 3–4 weeks.

Minimum Recommendations. When site-specific variability data are unavailable, we recommend the following defaults based on FHWA (2022):

- Minimum (48 hours): FHWA (2022) suggests a minimum of a 24-hour monitoring period for roads with traffic volumes of greater than 5,000 AADT and a 48-hour monitoring period for lower-volume roads. Because this is the minimum floor, estimates derived from 48-hour counts may carry large adjustment errors.
- Preferred (7 days): Covers all days of the week, enabling direct estimation of weekly average daily traffic without day-of-week adjustment factors.

Validating Data from Malfunctioning Sensors

Traffic-sensor data are only useful if the sensors are functioning properly. Loop detectors, video image processors, and other systems are vulnerable to hardware failure, communication problems, occlusion, weather effects, and other sources of error (Coifman, 2006; Klein et al., 2006; Minge et al., 2011).

Sensor health should therefore be assessed before the data are used in analysis. Removing invalid observations improves the reliability of estimated traffic conditions and downstream emissions estimates.

Several studies have proposed diagnostic methods for traffic-sensor errors. Early approaches relied on thresholds for volume, occupancy, speed, or density (Payne, 1976), while later work defined acceptable regions in the occupancy–volume space and used daily patterns to identify persistent malfunctions (Chen et al., 2003; Jacobson et al., 1990).

Chen et al. (2003) extended this approach by analyzing data over an entire day rather than single samples. They categorized potential errors into four types: persistent zeros, non-zero occupancy with zero flow, very high occupancy, and constant values. A detector is flagged as malfunctioning if the number of erroneous samples in a day exceeds a predefined threshold.

Because our proposed framework relies on continuous data from permanent sensors and at least 48 hours of on-site sampling, daily validation is necessary. We therefore recommend a daily screening approach similar to that of Chen et al. (2003), in which only days with acceptable error rates are retained for analysis.

Integrating Data with the Emission Model

After validation, the final step is to convert raw traffic data into VMT by speed bin. Permanent sensors and on-site observations both provide traffic counts and average speeds at regular intervals, which are used to calculate link-level temporal VMT as defined in Section 3.2.1.

$$VMT_{i,d,t} = c_{i,d,t} \cdot L_i \tag{9}$$

On-site sampling data must first be scaled to the full evaluation period using a temporal expansion factor, while permanent-sensor data require no such adjustment.

The next step is to aggregate VMT across all sampled links within each speed bin. For on-site links, the temporal expansion factor must be applied so that the observations represent the full evaluation period.

As described in Section 3.2.1, the VMT corresponding to speed bin k is then expressed as:

$$VMT_k = \sum_{i\in I}\sum_{d\in D}\sum_{t\in T} VMT_{i,d,t} \cdot 1_k\left(v_{i,d,t}\right) + \tau \cdot \sum_{i\in J}\sum_{d\in D}\sum_{t\in T} c_{i,d,t} \cdot L_i \cdot 1_k\left(v_{i,d,t}\right) \;\; k \in K \tag{10}$$

In this expression, $i \in I$ denotes the set of continuously monitored links, and $j \in J$ denotes the set of sampled links that are not continuously monitored. The temporal expansion factor τ scales the observation days at each sampled site to the full evaluation period, and is computed separately within the weekday and weekend strata defined in Section 3.2.3. A symbol distinct from α is used because α denotes the confidence level in the sample-size expressions above.

The resulting VMT distribution by speed bin is then used as input to EMFAC, together with contextual inputs such as fleet composition and meteorological conditions, to estimate total GHG emissions across the study area.

Conclusion

This report recommends a regional, before-and-after data collection framework for evaluating how HOT lane projects affect VMT, operating speeds, and ultimately GHG emissions. The core analytical requirement is to generate reliable estimates of VMT by speed bin, and where feasible by vehicle type, so that those estimates can be translated into GHG emissions using EMFAC. Because HOT lane projects may affect route choice, departure time, trip length, vehicle occupancy, and activity participation beyond the managed lane facility itself, the evaluation should focus on the broader travel shed, rather than only the HOT lane corridor.

The report identifies two defensible approaches for collecting the data needed for this evaluation. The recommended approach is a household survey-based design that uses OBD-II, GPS-enabled devices, smartphone traces, or similar technologies to measure observed vehicle travel for a representative sample of households in the HOT lane travel shed. This approach is preferred because it can capture detailed travel trajectories, support estimates of VMT by speed bin and vehicle type, and connect observed travel changes to household, traveler, and vehicle characteristics. As a result, it provides the strongest basis for estimating regional GHG impacts and for understanding how those impacts vary across the population.

The infrastructure-based approach is also a credible and worthwhile option. By combining continuous freeway sensor data with strategically sampled counts and speeds on arterials, local roads, ramps, and other unmonitored facilities, this approach can support estimates of regional VMT by speed bin for use in emissions modeling. It is generally less expensive and may be easier to implement than a large household survey, especially when existing monitoring systems can be leveraged. However, it provides less information about the travelers and households behind observed traffic changes and therefore offers less insight into behavioral mechanisms, equity implications, and heterogeneous impacts.

As with most empirical evaluation designs, the choice between these approaches involves a tradeoff between cost and data quality, and the same tradeoff exists within each approach. Larger samples, longer observation periods, more precise measurement technologies, broader geographic coverage, and stronger validation procedures increase the credibility of the results but also increase cost. For this reason, the preferred path is to fund a household survey-based evaluation at a scale sufficient to support defensible regional before-and-after estimates. If that budget is not available, however, the infrastructure-based approach is a good substitute. When carefully designed around a clearly defined travel shed, consistent pre- and post-implementation sampling locations, validated sensor data, and appropriate expansion procedures, it remains a viable and useful method for evaluating HOT lane impacts on GHG emissions.

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Appendix A: HOT Lane Impacts on the Marginal Traveler

This appendix uses a simplified marginal-traveler perspective to illustrate how the addition of HOT lanes may impact various components of traveler behavior.

For lane choice, the marginal single-occupant vehicle (SOV) traveler may pay the toll to access better and more reliable service in the HOT lane than in adjacent general-purpose lanes, especially when their travel is time-sensitive or they place a high value on time savings.

The marginal traveler in a higher-occupancy vehicle (HOV) may receive free or discounted access to the HOT lane, depending on facility rules. Moreover, this HOV traveler can share toll costs with other riders in the vehicle while saving time by traveling in the HOV lane. As such, the marginal HOV traveler is especially likely to use the HOT lane.

In the case of the decision whether to carpool, if HOVs receive free or discounted access, the marginal traveler is more likely to form or join a carpool to take advantage of the HOT lane's service quality and reliability, without bearing the full cost of an SOV using the HOT lane.

HOT lanes may also affect the marginal traveler's departure time and activity scheduling. Because congestion levels and therefore tolls typically vary by time of day, the marginal traveler may adjust their departure times and activity schedules to balance time savings, toll costs, and schedule preferences.

The presence of HOT lanes may also affect the marginal traveler’s route choice, mode choice, and activity location. If a HOT lane meaningfully improves travel time and its reliability at an acceptable price, the marginal traveler may switch routes, shift from transit to driving, or choose different destinations for shopping, recreation, entertainment, or even air travel.[1] Lower expected travel times and greater reliability may also increase the marginal traveler’s overall participation in activities.

In general, we expect the implementation of HOT lanes to induce the following behaviors, which are likely to reduce GHG emissions: an increased likelihood of carpooling and of using transit, assuming transit vehicles have access to HOT lanes. On the other hand, HOT lanes are likely to induce the following behaviors that increase GHG emissions: traveling to farther-away activity locations and engaging in more activities.

[1] Anecdotally, the presence of HOT lanes on the I-405 in Orange County makes air travel from Long Beach Airport considerably more attractive for residents of Irvine, particularly residents who typically fly with multiple family members, and therefore can use the HOT lanes for free.

Appendix B: Orange County Travel Shed Example: Segment Count and Cost Estimate

Part I: Segment Count

To estimate the number of arterial and major-collector road segments in Orange County, we use OpenStreetMap (OSM) data via the OSMnx Python library (Boeing, 2017).

Step 1) Use OSMnx to download the Orange County, CA road network from OpenStreetMap, filtered by the OSM highway tag.

Step 2) From the downloaded network, retain only arterial and major collector edges and count the total number of segments.

Step 1: Each OSM highway tag maps to an FHWA functional class. We download each road type separately using OSMnx and count directed edges directly.

OSM Tag	FHWA Equivalent	Mileage (mi)	Directed Segments	Avg Length (mi)
motorway	Interstate / Freeway	271.1	63	4.30
trunk	Other Freeway / Expressway	46.6	30	1.55
primary	Other Principal Arterial	1,046.8	2,051	0.51
secondary	Minor Arterial	789.6	1,856	0.43
tertiary	Major Collector	308.7	801	0.39

Source: OpenStreetMap (osm.org), queried May 28, 2026, via OSMnx v2.1.0 (Boeing, 2017).

Step 2: We aggregate the OSM classes that correspond to arterials and major collectors:

Scope	Mileage (mi)	Directed Segments	Avg Seg Length
Arterials only (primary + secondary)	1,836 (= 1,046 + 790)	3,907 (=2,051 + 1,856)	0.47 mi
Arterials + Collectors (primary + secondary + tertiary)	2,145 (=1,836 + 309)	4,708 (=3,907 + 801)	0.46 mi

If we adopt the Arterials + Major Collectors scope, this yields 4,708 directed segments covering 2,145 miles.

Part II: Cost Estimate

Step 3 — Equipment: Portable tube classifier (FHWA Scheme F)

All prices from TrafficCounterStore.com (International Road Dynamics), verified May 2026.

Component	Price (USD)	Purpose	Data Collected
Traffic ACE+ Classifier (2-tube)	$876 /unit	Records data, has no built-in sensors	Volume (2-dir) + speed + FHWA Scheme F classification (1-lane sample)
Road tube accessory kit (2-tube)	$204 / unit	Physical sensors	Physical sensors (tubes, clamps, nails) laid across road
Road Reporter II Software	$1,257 / one-time	Configure unit, download data, generate reports	Configure unit, download data, generate reports

Source: *https://trafficcounterstore.com*

For this study, the ACE+ unit cost ($876 + $204 = $1,080/unit) serves as the low-end equipment estimate.

Each classifier records a single lane. Because arterial and major-collector segments in Orange County generally carry more than one lane in each direction, the number of units required scales with lane count rather than with the number of sampled locations. We assume an average of four lanes per segment, so each sampled location requires four units, at $1,080 × 4 = $4,320 per location.

Step 4 — Labor cost per location

Labor installation costs are not publicly listed; we estimate $200 per location. Labor is incurred once per location in each data collection wave.

Step 5 — Total cost

Formula: Total (before and after) = (Equipment per unit × Lanes per segment × Number of locations) + (Software, one-time) + (Labor per location × Number of locations × 2 waves)

Scenario	Penetration	Locations	Equipment	Software	Labor (per wave)	Total (before + after)
A	3%	141	$1,080 × 4 × 141 = $609,120	$1,257	$200 × 141 = $28,200	$609,120 + $1,257 + ($28,200 × 2) = $666,777
B	5%	235	$1,080 × 4 × 235 = $1,015,200	$1,257	$200 × 235 = $47,000	$1,015,200 + $1,257 + ($47,000 × 2) = $1,110,457

Notes: Equipment is purchased rather than rented and is reusable across deployments, so the after-implementation wave adds only installation labor, not equipment or software. Equipment quantities assume an average of four lanes per segment.

Under these assumptions, a complete before-and-after infrastructure-based sampling program in Orange County is estimated to cost approximately $0.67 million at a 3 percent sampling rate and $1.11 million at a 5 percent sampling rate.