Modernize Census Infrastructure Technology

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A Research Report from the Pacific Southwest Region University Transportation Center

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Disclosure

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Abstract

This report comprehensively reviews available traffic census technologies, focusing on assessing traditional methods—such as inductive loops, magnetometers, and infrared sensors—and advanced solutions, including video analytics, radar, and LiDAR. The study evaluates each technology's accuracy, cost-effectiveness, ease of implementation, and environmental resilience using a structured evaluation matrix. It also conducts a lifecycle cost analysis to clearly distinguish between traditional systems, known for their affordability and low maintenance needs, and modern technologies, which offer greater data precision and detailed analytics suitable for complex urban and multimodal traffic environments. Based on this thorough analysis, the report provides specific technology recommendations for deployment across various roadway environments, including freeways, arterials, and intersections. Additionally, it outlines best practices for effective training, maintenance protocols, and risk management to ensure sustained performance and reliability of traffic sensing technologies.

Modernize Census Infrastructure Technology

Executive Summary

This report provides a comprehensive review and analysis of current traffic census technologies, exploring both traditional methods—including inductive loops, magnetometers, and infrared sensors—and advanced solutions such as video analytics, radar, and LiDAR. Traditional sensing technologies are recognized for their affordability, simplicity, and resilience in stable traffic conditions; however, they exhibit significant limitations regarding accuracy, adaptability, and the ability to deliver detailed behavioral insights necessary for complex traffic scenarios.

Advanced sensing technologies are thoroughly assessed, highlighting their superior accuracy, richer data collection capabilities, and effectiveness in dynamic, multimodal, and densely trafficked urban areas. Although these technologies require higher initial investments and involve more complex maintenance processes, their enhanced data capabilities significantly contribute to improved traffic management, enhanced safety, and optimized traffic flows.

A structured evaluation matrix is employed to systematically compare critical attributes such as accuracy, cost-effectiveness, ease of implementation, and environmental resilience. Complementing this qualitative assessment, a lifecycle cost analysis quantifies and contrasts the financial implications of traditional versus modern technologies, clearly delineating their cost profiles over extended operational periods.

Based on these comprehensive evaluations, targeted recommendations are provided for different roadway environments, with attention to both functional demands and the potential for future scalability through AI and edge computing integration. California's Freeway Performance Measurement System (PeMS) continues to serve as a foundational data source, supporting these recommendations with a robust, statewide stream of historical and real-time traffic data.

Intersections, especially in urban multimodal areas, benefit from integrated sensing systems that combine LiDAR, video detection, and infrared sensors. This combination enables high-resolution perception of diverse road users, including pedestrians and cyclists, and supports adaptive signal control and V2X communication. As edge computing becomes more prevalent, intersections are also becoming nodes for advanced AI-enabled analytics, allowing cities to manage traffic in real time with greater precision and safety outcomes. For arterial roads, a combination of magnetometers and video detection systems is suggested, offering a balance between detailed data collection, ease of retrofitting, and operational flexibility. These corridors often experience mixed traffic flow and moderate speeds, where mid-resolution sensing provides ample insight without the higher costs associated with full 3D perception.

For freeway corridors, sensor recommendations are differentiated by functional zones. On mainline segments, where traffic generally moves at high speeds with consistent lane-following behavior, radar and inductive loops are recommended due to their proven reliability, cost-effectiveness, and compatibility with existing infrastructure. These low-resolution sensors provide sufficient aggregate data for traffic flow monitoring and are well suited for long stretches of uninterrupted freeway. In contrast, freeway hot spots—such as on-ramps, off-ramps, and merging zones—require more advanced sensing

solutions. These areas are characterized by dynamic vehicle interactions, including frequent lane changes and variable speeds. To address this complexity, a layered sensor strategy is advised. Traditional technologies such as magnetometers and inductive loops can continue supporting ramp metering and queue detection. However, by integrating high-resolution sensors like LiDAR and video detection systems alongside edge computing platforms, these hot spots can also support real-time analytics and complex decision-making. This hybrid model not only enables immediate traffic control improvements but also lays the groundwork for Cooperative Driving Automation (CDA) and AI-enhanced traffic prediction systems.

The report also emphasizes best practices in training, standardized maintenance protocols, and proactive risk management strategies to ensure the long-term reliability and functionality of traffic sensing systems as they scale and evolve across the state. These practices will be especially important in supporting local agencies that manage a mix of legacy and next-generation technologies within increasingly complex traffic environments.

Introduction

Accurate and comprehensive traffic census data plays a critical role in shaping transportation planning, infrastructure investment, and real-time operational strategies. Agencies like Caltrans rely on this data to monitor roadway performance, evaluate safety and efficiency, and support long-term mobility planning efforts (California Department of Transportation, 2020). As traffic volumes rise, transportation systems become more multimodal, and urban environments grow increasingly complex, the demand for richer, real-time data continues to escalate (FHWA, 2022).

Historically, traffic data collection has been driven by traditional sensing technologies such as inductive loops, magnetometers, and infrared sensors. These systems are generally fixed-location and designed to measure core traffic parameters like vehicle count, speed, and occupancy. Their strengths lie in their reliability, simplicity, and cost-efficiency, making them well-suited for long-term monitoring, particularly in freeway and rural settings (FHWA, 2014). However, they provide only aggregate-level insights and are not equipped to detect or analyze individual vehicle characteristics or interactions. As a result, they fall short in meeting the needs of today's urban environments, which demand more dynamic and detailed traffic information.

Modern sensing technologies—such as traffic video analytics, LiDAR, and multi-sensor fusion platforms—address these limitations by capturing high-resolution, behavior-level traffic data. These systems can identify and classify individual road users, track movements across multiple lanes, and detect complex interactions at intersections or in multimodal zones. Crucially, they support the evolving needs of Cooperative Driving Automation (CDA) vehicles, which rely on detailed and real-time environmental data to operate safely and efficiently (NCHRP, 2021). While modern systems offer richer datasets and greater flexibility, they also come with higher costs, more complex maintenance needs, and greater sensitivity to environmental factors. Understanding both the capabilities and limitations of traditional and emerging technologies is essential to designing a robust, scalable, and future-ready traffic census framework.

Summary of Findings from Literature Review

The literature review for Task 1 explores a wide range of technologies employed in traffic census data collection. Both traditional methods, such as Inductive Loop and Magnetometer technologies, as well as more advanced approaches like Video Detection Systems, Infrared Sensors, Traffic Radar, and LiDAR, were evaluated (Guerrero-Ibáñez et al., 2018). This review discusses each technology's strengths, limitations, cost, environmental performance, and potential for future use, providing an in-depth understanding of their applicability to Caltrans's traffic census modernization efforts.

Traditional Traffic Census Technologies

Traditional traffic sensing technologies have long been at the heart of transportation monitoring, forming the foundation for modern traffic data collection. As illustrated in Figure 1, they are primarily used to measure key metrics like vehicle volume, speed, and lane occupancy. Their enduring value comes from their simplicity, reliability, and cost-effectiveness, particularly in areas with consistent traffic patterns. However, their limitations—especially in high-density, multimodal, or rapidly changing urban environments—have become increasingly apparent. This section reviews three of the most commonly used traditional technologies: inductive loops, magnetometers, and infrared sensors.

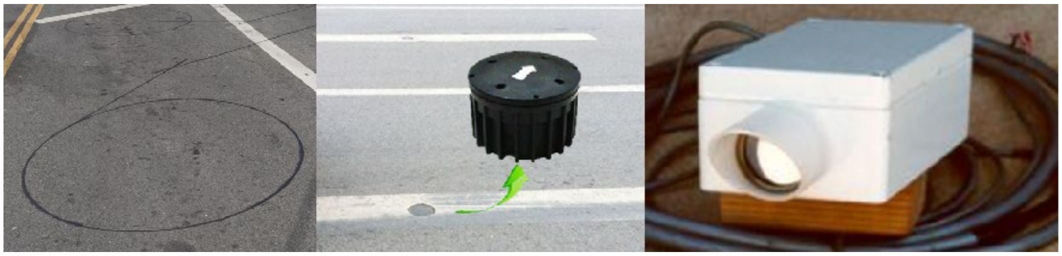

Figure 1. Examples of traditional traffic sensing technologies: from left to right — inductive loop, magnetometer, and infrared sensor.

Inductive Loop technology is one of the most mature and widely deployed vehicle detection methods. These systems consist of loops of wire embedded into the pavement that create electromagnetic fields capable of sensing the presence of vehicles as they pass over. Inductive loops provide accurate detection and counting, making them suitable for long-term, continuous monitoring (Ali et al., 2011). Their primary advantages include strong performance in diverse weather conditions and a long operational lifespan, which contribute to a low total cost of ownership (Marszalek et al., 2015). Because of their high detection accuracy, they are commonly used in highway applications, particularly in locations where traffic patterns are consistent and environmental wear on pavement is minimal.

However, inductive loops face significant drawbacks that limit their applicability in complex traffic environments. Installation requires invasive pavement cuts, often leading to lane closures and traffic disruption. In high-traffic or urban environments, this installation process can become logistically challenging and costly. Maintenance is also a concern, as the embedded loops are susceptible to damage from pavement degradation, resurfacing, or construction activities. Over time, environmental stressors and heavy vehicle loads can reduce sensor accuracy and reliability, necessitating costly and labor-intensive repairs (Marszalek et al., 2015). From a data perspective, inductive loops are limited to binary detection and cannot distinguish between closely spaced vehicles or identify vehicle types. This restricts their ability to provide behavioral insights or support applications like real-time adaptive traffic management or detailed safety analysis (Cherrett et al., 2000).

Magnetometer sensors offer a less invasive alternative by detecting changes in magnetic fields caused by the movement of metal objects, such as vehicles. These sensors are typically installed in shallow holes in the pavement and require less roadwork, making them faster and easier to deploy than inductive loops (Sun et al., 2013). Magnetometers are often used where pavement preservation is a concern, and their modular design allows for greater flexibility in installation and maintenance. They offer moderate accuracy in vehicle detection and are relatively resilient to harsh weather and pavement wear (Zhou et al., 2015). These strengths make them a practical solution in low-to-moderate volume settings or as temporary detection solutions in construction zones.

Despite these advantages, magnetometers share many of the same functional limitations as inductive loops. They do not have the capacity to classify vehicles by size or type, and they cannot track vehicle trajectories or provide turning movement counts (Bogdanski et al., 2018). The resolution of the data they collect is generally limited to presence detection and basic volume counts. Furthermore, magnetometers typically lack the processing power or integration needed for real-time system-wide coordination or detailed traffic behavior analytics (Coifman et al., 1998). As transportation systems evolve toward dynamic, data-rich management models, magnetometers may struggle to keep pace with requirements for high granularity and interoperability. However, their durability and ease of deployment ensure they will likely retain a role in more limited or constrained applications, particularly in rural or cost-sensitive settings (Barth et al., 2014).

Infrared Sensors represent another class of traditional traffic sensing technologies that detect the thermal energy emitted by vehicles. These systems are particularly valuable in low-visibility conditions such as nighttime, fog, or heavy rain, where vision-based systems may struggle to perform reliably (Guerrero-Ibáñez et al., 2018). Infrared sensors are often used as complementary tools to fill performance gaps in video detection systems. They are relatively inexpensive to install and operate and typically require little ongoing maintenance (Saeed et al., 2020). Their low sensitivity to lighting conditions makes them ideal for environments where visibility fluctuates or cannot be controlled.

However, infrared sensors are constrained in the level of detail they can provide. They are primarily designed for presence detection and struggle to distinguish between different types of vehicles or identify non-motorized road users, such as pedestrians or cyclists (Sheik Mohammed et al., 2011). Additionally, extreme environmental temperatures can impact their performance and calibration, potentially reducing accuracy in regions with harsh climates (Coifman et al., 1998). Because they are unable to deliver rich behavioral data or support advanced applications like multimodal analytics or predictive modeling, their use is best reserved for specialized conditions—such as supplementing other sensor systems in low-visibility areas (Wang et al., 2020). Looking ahead, the greatest value of infrared sensors may lie in integrated sensor suites, where they can contribute redundancy and resiliency in challenging environments (Bogdanski et al., 2018; Ponnusamy et al., 2021).

In summary, inductive loops, magnetometers, and infrared sensors continue to serve as dependable, cost-effective tools in traffic monitoring. Their limitations, however—particularly in data richness, ease of deployment, and adaptability to modern traffic management needs—underscore the necessity of transitioning toward more intelligent, multi-functional sensing systems. As traffic monitoring goals shift toward real-time, multimodal, and behavior-level insights, the traditional technologies reviewed in this section will likely be supplemented or replaced by more advanced solutions in urban and high-density areas while continuing to serve targeted roles in stable, less complex environments.

Transition to Modern Technologies

Modern traffic census technologies represent a transformative shift in how roadway activity is detected, analyzed, and managed. Modern traffic sensing technologies go beyond the basic presence or volume detection of traditional systems, offering deeper insights into vehicle behavior, classification, and interactions across different modes of transport. Figure 2 illustrates common examples of these advanced sensors, including a video detection system, radar, and LiDAR. These advanced tools are not only capable of identifying individual vehicles and tracking their movements, but they also enable predictive analytics, real-time data integration, and support for CDA vehicles. As urban environments grow denser and transportation systems become more interconnected, the demand for intelligent, high-resolution data collection has elevated these modern technologies from experimental to essential components of modern traffic infrastructure.

Figure 2. Examples of modern traffic sensing technologies: from left to right — video detection system, radar, and solid-state LiDAR.

Video Detection Systems leverage camera-based monitoring systems (often enhanced by AI and machine learning algorithms) to detect, classify, and track various road users in real time (Shao et al., 2020). These systems can capture both quantitative data—such as vehicle counts, travel time, and lane occupancy—and qualitative data such as vehicle trajectories, turning patterns, and pedestrian crossings (Chen et al., 2021). With appropriate training data and deep learning algorithms, modern video systems can identify buses, trucks, bicycles, and pedestrians with high precision, even in dynamic environments. Their adaptability allows for installation on existing infrastructure, such as traffic signals, streetlights, or overhead gantries, making them a flexible and cost-efficient option for retrofitting urban corridors (Zhang et al., 2021). Additionally, video detection supports centralized monitoring and remote diagnostics, enabling operators to detect anomalies and adjust signal timing in real time (Zhang et al., 2020). However, performance is contingent upon visibility. Video systems are susceptible to weather-related issues, glare, and occlusions from large vehicles or roadside objects, which can interfere with detection accuracy (Hu et al., 2021; Wang et al., 2020). Regular cleaning and calibration are necessary to maintain performance, and coverage gaps may occur in highly congested or poorly lit areas (He et al., 2023). As AI and edge processing continue to advance, however, video detection systems are becoming more resilient and capable of supporting real-time traffic control, incident detection, and integrated multimodal analysis (Shao et al., 2020; Xie et al., 2021; Channi et al., 2021; Ponnusamy et al., 2024).

Traffic Radar technology uses microwave or millimeter-wave radio signals to detect vehicle movement, enabling continuous speed and trajectory monitoring in real time (Guerrero-Ibáñez et al., 2018). Radar systems are particularly valued for their resilience to environmental interference. Unlike video or infrared sensors, radar remains effective in rain, fog, dust, and darkness, making it ideal for ensuring uninterrupted detection in all-weather conditions (Sheik Mohammed et al., 2011; Marszalek et al., 2015). These systems can monitor multiple targets simultaneously, detect vehicle presence across several lanes, and differentiate between approaching and receding vehicles. Radar has proven valuable in speed enforcement zones, freeway flow monitoring, and ramp metering systems (Barth et al., 2014; Bogdanski et al., 2018). Installation is generally simple, often requiring only a single pole-mounted unit, which reduces the disruption and maintenance typically associated with in-road sensors. However, radar's primary limitations include its inability to provide visual confirmation or detailed classification. It cannot distinguish between a compact car and a delivery truck with the same confidence as a camera or LiDAR, nor can it detect non-metallic objects with precision (Ponnusamy et al., 2021). Despite these constraints, radar plays an essential role in sensor fusion systems, especially as a backbone for detecting movement in low-visibility conditions and enhancing overall system reliability (Zhang et al., 2020).

LiDAR (Light Detection and Ranging) represents the frontier of high-definition traffic sensing. LiDAR works by emitting rapid laser pulses and recording the time it takes for the light to return after hitting an object, generating dense 3D point clouds of the surroundings (Guerrero-Ibáñez et al., 2018). This makes it possible to precisely map road geometries, classify multiple types of road users, and assess traffic dynamics with centimeter-level accuracy (Zhang et al., 2020; Sun et al., 2013). LiDAR excels in environments requiring high spatial resolution and full-scene perception, such as multimodal intersections, roundabouts, or crosswalks. It is particularly beneficial for identifying and protecting vulnerable road users like cyclists and pedestrians, and its capabilities are foundational to CDA operations and autonomous vehicle deployments (Chen et al., 2021). Furthermore, LiDAR does not rely on ambient light, making it suitable for nighttime or shaded area operations. However, high equipment costs and vulnerability to precipitation remain key challenges (Xie et al., 2021). The laser signals can be scattered or blocked by rain, fog, or snow, leading to temporary loss of resolution or false positives. Sensor placement and orientation are also critical, as blind spots or sparsity in point clouds can affect detection accuracy. Nonetheless, LiDAR's continued evolution, supported by declining costs and improved resistance to environmental conditions, positions it as a cornerstone of next-generation traffic infrastructure (Guerrero-Ibáñez et al., 2018).

Together, these modern technologies redefine the capabilities of traffic census data collection. They not only provide richer, multi-dimensional datasets but also enable proactive, adaptive traffic management aligned with the needs of CDA vehicles, real-time urban analytics, and integrated smart city systems. As transportation agencies move toward holistic, system-wide optimization, the combination of video, radar, and LiDAR—each compensating for the others' limitations—will be essential in building a resilient, accurate, and future-ready traffic sensing ecosystem. They offer scalable, adaptive, and high-resolution solutions capable of addressing the demands of modern transportation systems. While no single technology is universally superior, each brings distinct advantages. As traffic environments evolve to accommodate CDA vehicles, smart infrastructure, and multimodal transportation, combining these technologies through integrated systems will be key to creating robust, future-ready traffic monitoring solutions.

Evaluation Matrix and Key Insights

A broad range of traffic sensing technologies are discussed, including both traditional systems such as inductive loops, magnetometers, and infrared sensors, and advanced technologies like video detection systems, traffic radar, and LiDAR. To better understand and compare these technologies, an evaluation matrix has been developed and is presented in Table 1. This matrix provides a structured overview of each technology's strengths and weaknesses across key criteria such as accuracy, cost-effectiveness, implementation difficulty, and resilience to environmental conditions. As shown in Table 1, it plays a critical role in highlighting the trade-offs among technologies and helps match specific tools to operational contexts.

Table 1. Evaluation matrix of discussed sensing technologies

Technology	Inductive Loop	Magnetometer	Video Detection Systems (RGB cameras)	LiDAR	Traffic Radar	Infrared Sensors
Accuracy	Moderate	Moderate	High	Very High	Moderate to High	High
Cost-effectiveness	High	Moderate	Moderate	Low	Low to Moderate	Moderate
Ease of Implementation	Low	Moderate	Moderate	Low	High	High
Resilience to Illumination	High	High	Low	High	High	High
Resilience to Rain	High	High	Low	Moderate	Moderate	High
Resilience to Snow	Moderate	High	Low	Moderate	Moderate	High
Resilience to Temperature	High	High	Moderate	High	High	Moderate
Resilience to Dirt and Debris	Moderate	High	Moderate	Moderate	High	Moderate
Resilience to Vibration	High	High	Low	High	High	High
Resilience to Maintenance Requirements	Moderate	High	Low	Low	High	Moderate
Resilience to Signal Interference	High	High	Moderate	Moderate	High	High
Potential for Future Use	Low	Moderate	High	Very High	High	High

Traditional technologies reviewed include inductive loops, magnetometers, and infrared sensors. According to the evaluation matrix (Table 1), these systems score well in cost-effectiveness, durability, and resistance to maintenance demands. Their simplicity and robustness make them particularly effective in rural and suburban environments where traffic volumes are lower and road conditions are more stable. In such settings, the demand for high-resolution or behavior-level data is minimal, so the performance gain from deploying high-end sensors may not justify their cost. Meanwhile, traditional technologies benefit from a sturdy structure that keeps maintenance requirements low, reducing the need for frequent servicing or technician visits. However, they fall short in data richness and adaptability, making them less suitable for high-density or multimodal traffic contexts where detailed, real-time behavioral insights are necessary.

Modern sensing technologies evaluated in this review include video detection systems, radar, and LiDAR. As shown in Table 1, these systems excel in accuracy, data granularity, and potential for future integration with CDA vehicle systems and smart infrastructure. The matrix shows that while these technologies offer superior performance in dynamic and complex traffic scenarios, they also come with higher costs, environmental sensitivities, and more complex maintenance requirements. Their strengths make them well-suited for urban areas, intersections, and multimodal corridors where traffic volumes are high and vehicle interactions are complex. In these environments, the performance gain from using more advanced, intelligent sensors is significant, providing actionable insights for congestion mitigation, safety enhancements, and support for CDA vehicle systems.

Together, the insights from the literature and the evaluation matrix offer a foundation for informed decision-making. They highlight the complementary nature of different technologies and support a strategy focused on multi-sensor integration. The following sections of this report will build on these findings through a detailed lifecycle cost analysis, specific technology recommendations, and a deployment roadmap to help Caltrans modernize its traffic census infrastructure effectively across various operational settings.

Lifecycle Cost Analysis

Building on the previous section's review of traditional and modern traffic sensing technologies, this section shifts focus to their long-term financial implications. While performance and technical capabilities are essential, the sustainability of each technology also depends on its total cost of ownership over time. Lifecycle cost analysis accounts for the full spectrum of expenditures—from initial installation to recurring maintenance, software or hardware upgrades, and eventual replacement. These considerations are crucial for determining the practicality and scalability of a technology in specific deployment contexts.

Understanding these costs is especially important for transportation agencies like Caltrans, which must manage infrastructure investments across a range of settings—from rural highways to complex urban intersections (**California Department of Transportation, 2020)**. The long-term affordability of technology can significantly influence its suitability for widespread deployment. For example, a system with high initial costs but low operational expenses may be justified in urban areas where its advanced capabilities offer clear benefits (**Federal Highway Administration, 2019**). Conversely, low-cost traditional systems may remain appropriate in low-density corridors with limited data needs. The following analysis aims to clarify these trade-offs by comparing the estimated 10-year lifecycle costs of both traditional and modern sensing technologies using quantitative modeling and visual summaries.

Traditional Technologies: Cost-Efficient and Durable

Traditional sensing systems—including inductive loops, magnetometers, and infrared sensors—are characterized by relatively low initial costs and long-term durability. According to data from various transportation and ITS research sources, the initial cost for inductive loop installations ranges from $400 to $600 per lane, with maintenance typically required every 2–5 years due to pavement degradation (FHWA, 2017; FHWA, 2014). Magnetometers, which are non-invasive and easier to install, typically cost between $600 and $1,000 per unit and have a longer operational life with minimal calibration needs (FHWA, 2014). Infrared sensors, commonly used in low-visibility areas, range from $1,000 to $2,000 and require relatively low maintenance, except for occasional sensor alignment and diagnostics (Caltrans DRISI, 2019). These estimated cost benchmarks are summarized in Table 2.

Table 2. Summary of Estimated Initial, Maintenance, Replacement, and Total Lifecycle Costs for Traditional Traffic Sensing Technologies Over a 10-Year Period

Technology	Initial Cost (USD)	Maintenance Frequency	Maintenance Cost (USD, 10 years)	Replacement Cycle	Replacement Cost (USD)	Total Lifecycle Cost (USD)
Inductive Loop	500	3 years	450	10 years	500	1950
Magnetometer	800	4 years	500	10 years	800	2100
Infrared Sensor	1500	Annually	1000	10 years	1500	4000

To ensure a fair and consistent comparison, the lifecycle cost of each traditional sensor is assessed over a 10-year operational period (FHWA, 2019; Caltrans, 2020). This timeframe reflects the typical planning horizon used by transportation agencies for capital investments and infrastructure upgrades. Each sensor's cost profile incorporates three main components: initial installation costs, cumulative maintenance expenses based on reported service intervals, and the cost of a full replacement should the technology's useful life fall within the evaluation period (FHWA, 2014).

Maintenance costs are derived by multiplying the average number of service events over ten years by the typical cost per service (ITS America, 2020). For example:

Inductive Loop: With a maintenance interval of every 3 years and a cost of $150 per service, this results in three cycles and a total maintenance cost of $450 (FHWA, 2017).

Magnetometer: Serviced approximately every 4 years at $200 per visit, this equates to 2.5 maintenance events, totaling $500 (ITS America, 2020).

Infrared Sensor: Maintained annually at $100 per service, resulting in ten service events over a decade for a total of $1,000 (Caltrans DRISI, 2019).

The total lifecycle cost for each technology is calculated by summing its initial installation cost, cumulative maintenance cost over a 10-year period, and the cost of a single replacement during that period. The results are as follows:

Inductive Loop: The initial installation cost is estimated at $500. Over ten years, three scheduled maintenance visits at $150 each bring the total maintenance cost to $450. A full replacement near the end of the cycle adds another $500, yielding a total lifecycle cost of $1,950.

Magnetometer: With an installation cost of approximately $800, and an average of 2.5 maintenance events at $200 each totaling $500, plus a full replacement of $800, the estimated lifecycle cost sums to $2,100.

Infrared Sensor: The sensor's initial cost is $1,500. With annual maintenance at $100 over ten years, the maintenance total is $1,000. Including a replacement cost of $1,500, the complete lifecycle cost amounts to $4,000.

The analysis of lifecycle costs confirms that traditional sensing technologies incur modest expenditures over a standard 10-year planning horizon, making them financially appealing for long-term infrastructure planning. These systems benefit from low upfront procurement costs—ranging from $500 to $1,500—as well as predictable maintenance schedules that help control operational expenses. For instance, magnetometers typically require two to three servicing visits over a decade, while infrared sensors require more frequent, though relatively inexpensive, annual maintenance.

This consistency in cost simplifies financial forecasting and allows transportation agencies to plan capital and operational budgets with a high degree of certainty. It also aligns well with routine infrastructure maintenance cycles, reducing the complexity of integrating these systems into long-term asset management programs. The inclusion of a one-time replacement cost further ensures that the lifecycle estimate reflects real-world use conditions and expected technology turnover.

The analysis establishes a common basis for comparing technologies with different lifespans and service requirements by breaking down each cost element- initial investment, maintenance, and replacement. This methodology avoids biases in favor of either low-maintenance or long-lasting systems and presents a realistic picture of each sensor's economic footprint. As a result, the lifecycle profiles produced in this evaluation offer transportation agencies a reliable benchmark for budgeting, procurement planning, and performance-based decision-making.

Modern Technologies: High Investment, High Return

Modern sensing technologies—including video detection systems, radar, and LiDAR—are engineered to capture detailed, real-time traffic data with a high degree of spatial and temporal resolution (FHWA, 2014). These technologies are increasingly used in smart transportation applications, including adaptive signal control, multimodal analytics, and CDA support. However, these advanced capabilities come at a considerably higher cost, both in initial investment and long-term upkeep, compared to traditional sensing solutions. These cost benchmarks are summarized in Table 3.

Table 3. Consolidated Lifecycle Characteristics and Costs of Modern Traffic Sensing Technologies

Technology	Initial Cost (USD)	Maintenance Frequency	Maintenance Cost (USD, 10 years)	Replacement Cycle	Replacement Cost (USD)	Total Lifecycle Cost (USD)
Video Detection	7,500	Monthly	9,600	10 years	7,500	24,600
Radar	4,000	2 years	2,500	10 years	4,000	10,500

LiDAR	30,000	Annually	15,000	10 years	30,000	75,000

The lifecycle cost analysis for these technologies follows the same structure as for traditional systems, assessing each sensor over a 10-year operational window (FHWA, 2019). This timeframe captures common service life estimates and aligns with public agency planning horizons for infrastructure investment. Each sensor's cost profile includes an average installation cost, cumulative maintenance over a decade, and a one-time replacement to reflect typical end-of-life reinvestment. Installation costs vary substantially depending on the technology. Video detection systems typically cost between $5,000 and $10,000 per unit, driven by the need for camera hardware, software integration, and configuration. Radar systems are generally more affordable, with installation costs ranging from $2,500 to $5,000 per unit. LiDAR represents the most expensive option, with unit costs ranging between $10,000 and $50,000 depending on range, resolution, and integration complexity.

Maintenance requirements also differ significantly. Video systems require monthly servicing, including lens cleaning and software updates. Radar systems, by contrast, are more resilient and typically only require servicing every two years. LiDAR, due to its sensitivity and precision demands, must be calibrated and cleaned annually. The estimated 10-year maintenance costs, based on current pricing and field practice, are as follows:

Video Detection: With monthly maintenance visits estimated at $80 each, the total over 120 months reaches approximately $9,600 (FHWA, 2014).

Radar: Serviced five times over 10 years at $500 per event, resulting in a total maintenance cost of $2,500 (FHWA, 2017).

LiDAR: Annual service at $1,500 per visit costs $15,000 over the 10-year period (FHWA, 2019).

Lifecycle costs, inclusive of initial installation, maintenance, and replacement, are summarized below:

Video Detection: An average installation cost of $7,500, combined with $9,600 in maintenance and $7,500 for replacement, yields a total lifecycle cost of $24,600.

Radar: Estimated at $4,000 for installation, $2,500 for maintenance, and $4,000 for replacement, totaling $10,500.

LiDAR: The total lifecycle cost is $75,000, including $30,000 for installation, $15,000 for maintenance, and $30,000 for replacement.

These results illustrate the financial complexity associated with modern sensing technologies. Although the total costs are significantly higher—especially in the case of LiDAR—they reflect the integration of advanced detection capabilities essential for next-generation transportation infrastructure. Technologies like video detection and radar systems offer a more balanced profile, providing actionable traffic intelligence at a more moderate cost.

Moreover, modern sensors often function as integrated data hubs, enabling various analytics applications such as pedestrian detection, queue length monitoring, and speed profiling. This multifunctional utility supports broader ITS goals by consolidating sensing functions into fewer devices, thereby enhancing efficiency and reducing redundancy. Their compatibility with connected vehicle systems and smart traffic control platforms also strengthens their long-term value.

For transportation agencies, the decision to invest in modern technologies should not rely on lifecycle cost alone. These figures must be considered in conjunction with modern systems' broader strategic value, such as real-time responsiveness, expanded multimodal data collection, and alignment with statewide mobility initiatives. While upfront and operational costs are high, the potential long-term benefits in terms of safety, efficiency, and system adaptability may ultimately outweigh those initial investments. Their ability to integrate with CDA vehicles and support predictive analytics offers significant operational advantages in high-density or multimodal corridors, where real-time precision can drive meaningful outcomes.

Lifecycle Cost Summary

The lifecycle cost analysis presented in this section highlights the financial distinctions between traditional and modern traffic sensing technologies over a standardized 10-year period. Traditional systems, such as inductive loops, magnetometers, and infrared sensors, show relatively low total costs due to minimal installation and maintenance demands, making them fiscally practical in environments where simplicity and durability are priorities. In contrast, modern technologies—including video detection, radar, and LiDAR—require higher upfront and maintenance investments but offer greater data precision and operational intelligence that can support advanced transportation management systems. While modern systems involve higher lifecycle expenditures, they also deliver strategic value in terms of real-time analytics, integration with smart infrastructure, and adaptability to multimodal, high-density conditions. This analysis equips transportation agencies with a grounded, cost-based framework to guide technology selection decisions based on both financial sustainability and long-term system performance.

Technology Recommendations

This section provides specific recommendations for selecting traffic sensing technologies across a variety of roadway environments. The recommendations are informed by the evaluation matrix and lifecycle cost analysis presented earlier in the report and are organized around three primary roadway types: freeways (including mainline segments and ramps), arterials, and intersections. Each of these settings presents distinct operational characteristics, including differences in traffic speed, volume, environmental exposure, and multimodal activity. Table 4 summarizes these key conditions to help contextualize the technology guidance that follows.

The recommended technologies are grouped into two categories: traditional low-resolution systems and modern high-resolution systems. Low-resolution systems offer basic yet reliable performance and are often favored for their durability and lower cost. In contrast, high-resolution systems provide richer, real-time data that supports advanced traffic management and automation but typically involve higher costs and more complex maintenance. The recommendations that follow are designed to match the functional requirements of each roadway type while balancing performance needs with cost-effectiveness and long-term sustainability.

Table 4. Summary of Operational Characteristics by Roadway Type

Roadway Type	Key Characteristics	Operational Priorities
Freeways (mainline and ramp)	High-speed segments, merging behavior, weather sensitivity	Speed detection, queue monitoring, environmental resilience, and advanced traffic control (ramp segment)
Arterials	Moderate speed and volume, mixed access, moderate complexity	Flexible installation, flow efficiency
Intersections	High complexity, multimodal conflicts, diverse road users	High-resolution detection, safety analytics

Sensor Recommendation for Freeways

As shown in Table 4, freeways are defined by their high-speed traffic flow, merging activity, and exposure to diverse environmental conditions. These characteristics are tied to their role in long-distance, uninterrupted travel with high vehicular throughput. In general, freeway sensing technologies should prioritize accuracy across a wide range of speeds, resilience to environmental conditions, and minimal disruption during installation. High-resolution systems are well-suited for complex, high-interaction areas like ramps, offering the added benefit of supporting future integration with CDA technologies. Lower-resolution, durable sensors are more appropriate for mainline segments where the focus is on broad traffic monitoring and flow analysis and where cost control remains a priority (FHWA, 2014; FHWA, 2017).

Within freeway environments, two distinct zones require differentiated sensing strategies. First, there are hot spot areas such as on-ramps and off-ramps, where lane changes, merging, and queuing behaviors are frequent and more dynamic. These areas tend to experience higher traffic volumes and more unpredictable interactions, making them strong candidates for high-resolution sensing technologies that can capture detailed vehicle behavior and support fine-grained control measures. Second, there are mainline segments, which are typically characterized by steady, high-speed, lane-following behavior over longer distances. In these segments, lower-resolution technologies are often sufficient, as the primary need is to monitor overall traffic conditions, such as volume, speed, and occupancy at an aggregate level.

Freeway **hot spots**, such as **on-ramps** and **off-ramps**, experience frequent acceleration, deceleration, lane changing, and **merging** behaviors, particularly in high-volume corridors. These areas benefit significantly from high-resolution sensing technologies that can deliver granular, real-time data. Tools like LiDAR and video analytics enable precise tracking of individual vehicle movements, classification, and detection of complex interactions, which are critical for enhancing safety and efficiency. Their deployment is especially justifiable in locations where congestion and traffic volume are consistently high, and where the data supports advanced traffic control strategies and prepares infrastructure for CDA. However, these technologies involve higher capital and maintenance costs. To balance performance and affordability, a hybrid sensor approach is recommended. In particular, traditional traffic control methods based on low-resolution technologies—such as inductive loops based ramp metering—remain effective for monitoring queue length and vehicle presence. Magnetometers, in particular, are cost-effective, compact, and resilient to weather, and their range-based detection allows for flexible installation. This combination of new and legacy systems provides scalability, supports existing infrastructure, and helps manage costs while improving performance. On the other hand, communication infrastructure, such as V2X devices, is also essential for CDA, though it falls outside the scope of this traffic census-focused discussion.

Freeway **mainline** segments, by contrast, are characterized by more stable travel patterns—predominantly high-speed, lane-following behavior across longer distances. The primary sensing goal in these areas is to monitor flow, speed, and occupancy at an aggregate level. For these purposes, low-resolution technologies such as magnetometers, inductive loops, and radar are sufficient and more economically feasible. Magnetometers stand out for their robustness in harsh environmental conditions, including rain and fog, and their ability to detect vehicles within a certain range, offering flexibility and low installation disruption. Inductive loops, while requiring pavement cuts, have long lifespans and do not need batteries—making them particularly cost-effective, especially for extended freeway segments. Radar sensors complement these technologies by performing reliably in low-visibility conditions and providing accurate speed detection across a wide range of vehicle speeds. These technologies are also compatible with California's Freeway Performance Measurement System (California Department of Transportation, PeMS, n.d.), which aggregates sensor data statewide for traffic planning and operations. Given the broad geographic coverage required for freeway mainlines, deploying durable, low-cost sensors ensures financial sustainability while delivering the essential traffic data needed for effective network management.

Sensor Recommendation for Arterials

Arterial roads are primary urban and suburban corridors designed to move traffic between local streets and freeways. Unlike freeways, which emphasize uninterrupted high-speed movement, and unlike intersections, which focus on localized traffic control, arterials are characterized by moderate-speed, continuous flow across long stretches of roadway. These roads typically operate at speeds between 30 and 50 mph and feature multiple intersections, turning lanes, access points, and driveways. Their operational complexity stems from the need to balance through-traffic efficiency with frequent signalized interruptions and cross-traffic movements.

To address these challenges, sensing technologies along with arterials must provide wide-area monitoring, be easily installed in constrained environments, and integrate seamlessly with corridor-level traffic control systems. The recommended technologies are **Video Detection Systems** and **Magnetometers**, which together support reliable detection of vehicle presence, speed, volume, and lane utilization.

Magnetometers are embedded in or mounted on the road surface, offering lane-level accuracy with minimal surface disruption. Their compact and wireless design is well-suited to busy corridors with limited construction access or underground infrastructure. While high-resolution technologies like LiDAR offer precise 3D sensing, they are not preferred in this context due to their high cost and limited added value. Arterials are typically fast-moving and dominated by vehicles, with minimal presence of vulnerable road users (VRUs). As a result, the demand for detailed object-level sensing—essential for detecting and tracking small or non-motorized road users—is significantly reduced (Meng et al., 2024).

Video Detection Systems complement magnetometers by enhancing spatial awareness and providing richer datasets that include vehicle classification, queuing dynamics, and turning movement counts. Their deployment on existing poles or mast arms allows for minimal infrastructure upgrades. Cities such as Sacramento and Portland have successfully leveraged video detection on key arterials to improve traffic signal coordination and reduce corridor delays during peak travel periods (City of Sacramento, 2021; FHWA, 2017). When used together, these technologies provide both the breadth and depth of traffic data necessary to support adaptive signal timing and performance-based arterial management strategies. Deployed on poles or signal arms, video systems offer flexible installation and retrofitting opportunities. In cities like Sacramento and Portland, arterial deployment of video detection has demonstrated success in improving traffic signal coordination and reducing arterial delay during peak travel hours (City of Sacramento, 2021; FHWA, 2017).

It is important to recognize that while radar sensors offer depth perception and remain effective in adverse weather, their low resolution and long detection range produce point clouds that are sparse and widely dispersed (Bilik, 2022). This sparsity makes it more difficult to extract meaningful features for identifying and differentiating objects—particularly in arterial environments where vehicles often travel closely in parallel lanes. As a result, radar may not provide the precision needed for accurate vehicle detection, tracking, or traffic prediction. For arterial applications, video detection systems and magnetometers are generally more reliable and already offer sufficient data for effective traffic monitoring, limiting the performance gains that radar can provide. Intersections with heavy traffic and frequent VRU activity are discussed separately, where high-resolution technologies such as LiDAR, cameras, and edge computing are better suited.

Overall, the combination of these two sensor types ensures continuous data collection across varied segments of an arterial, enabling smarter signal operations and better integration with corridor-wide traffic management strategies. Their synergy provides both spatial coverage and functional depth, making them well-suited to the operational demands of urban and suburban arterials.

Sensor Recommendation for Intersections

Intersections are dynamic and highly interactive components of the roadway network, where various travel modes—such as motor vehicles, bicycles, and pedestrians—must navigate shared space in close proximity. These locations serve as transition points between different roadway types and accommodate frequent stops, starts, and turning movements. Their compact design and mixed-use nature make them especially prone to conflicts and delays, requiring precise monitoring and rapid data processing to manage operations effectively.

These environments are also key deployment zones for emerging Vehicle-to-Everything (V2X) applications. As shown in Figure 3, recent research has demonstrated (Xiang et al., 2023) how infrastructure-based sensing at intersections using a combination of LiDAR and camera systems (i.e., video detection systems) can extend the detection performance of edge-side (i.e., infrastructure computing devices) and the perception performance of CDA vehicles. By detecting and tracking objects beyond a vehicle's direct line of sight, such systems facilitate cooperative perception, enabling the exchange of situational data about vulnerable road users (VRUs), vehicle paths, and potential conflicts. In turn, this cooperative awareness supports advanced use cases such as automated intersection crossing, near-miss analysis, and behavior prediction for safety-critical applications.

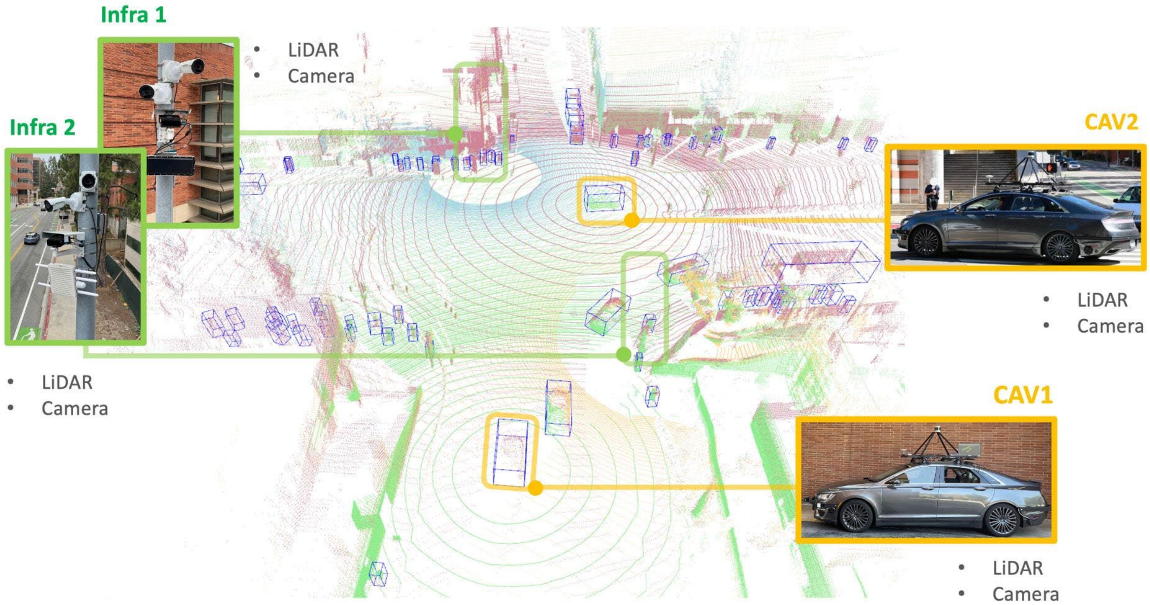

Figure 3. Sensor system setup diagram at the UCLA Smart Intersection (Xiang et al., 2023).

To meet the demands of such complex operations, the recommended sensing technologies for intersections include **LiDAR** and **Video Detection Systems**. LiDAR provides high-resolution 3D point clouds capable of accurately identifying the position, speed, and trajectory of various road users. Its independence from ambient lighting conditions makes it especially valuable during night or poor weather. For example, cities such as San Francisco have deployed LiDAR at major intersections to support multimodal flow monitoring, signal phasing optimization, and proactive safety interventions (City of San Francisco, 2020).

Video Detection Systems enhance intersection sensing by enabling object classification, real-time visual verification, and integration with adaptive signal control platforms. These systems are typically mounted on existing infrastructure, such as signal poles or mast arms, making them well-suited for both new installations and retrofits. When combined with LiDAR, they enable detailed multimodal perception, supporting applications like real-time pedestrian crossing detection, dynamic lane assignment, and emergency vehicle prioritization. Moreover, **infrared sensors** add another layer of robustness by providing reliable detection of vulnerable road users (VRUs)—such as pedestrians and cyclists—even in poor weather or low-light conditions.

While these sensing technologies provide a strong foundation for intersection monitoring, their effectiveness is significantly enhanced when paired with **advanced data processing** (i.e., edge computing devices) and **communication** (i.e., V2X technologies) capabilities. To unlock the full potential of this multimodal sensor ecosystem, the deployment of communication devices and edge computing units is essential. These technologies enable localized processing, reduce latency, and support real-time decision-making at the intersection level. In doing so, they lay the technological foundation for Cooperative Driving Automation (CDA), transforming intersections into intelligent, responsive nodes capable of supporting next-generation traffic management and safety systems. Together, this layered architecture of sensing, computing, and communication forms the backbone of a true CDA-ready infrastructure cluster.

Together, LiDAR and video detection provide a layered sensing ecosystem that is well suited to the intricacies of intersection environments. These technologies enable both traditional traffic signal optimization and emerging cooperative automation strategies. In addition, the multi-model solution paves the foundation for potential AI-enabled multi-model systems, which is the key to further enhancing the sensing and decision-making capability at intersections (Xiang et al., 2023). Their integration at intersections aligns with long-term goals in transportation safety, efficiency, and connected mobility. The increased situational awareness these systems offer is instrumental to broader smart city initiatives and supports national strategies targeting Vision Zero and the widespread adoption of connected vehicle infrastructure.

Deployment Roadmap

This section presents a strategic, phased roadmap for deploying recommended traffic sensing technologies across the state of California, with initial pilot deployments conducted in diverse urban and regional locations such as Los Angeles, San Francisco, San Jose, and Sacramento. The roadmap is designed to ensure that deployment is both scalable and cost-effective while maximizing system performance across diverse traffic environments. It is structured into three key phases—Pilot Deployment, Evaluation and Expansion, and Full-scale Deployment—each with specific objectives, implementation strategies, and supporting actions. The roadmap also includes provisions for training, maintenance, and risk management to support long-term operational sustainability.

Phase 1: Pilot Deployment

The first phase of the statewide technology deployment roadmap focuses on pilot implementation to assess the feasibility, performance, and integration challenges of the recommended traffic-sensing technologies. The objective of this phase is to evaluate high-potential systems across a range of traffic environments in California, starting with selected pilot sites in metropolitan areas such as Los Angeles, San Francisco, San Jose, and Sacramento. These locations were chosen to represent the diversity of California's roadway types, environmental conditions, and operational contexts.

Pilot deployments will target four primary roadway settings: urban intersections, arterial corridors, freeway mainline segments, and freeway on-ramps. These locations and technologies are summarized in Table 5. At **urban intersections**, including sites in Downtown Los Angeles, Koreatown, the San Francisco Financial District, and the San Diego Gaslamp Quarter, LiDAR, video detection systems, and infrared sensors will be installed. These technologies are expected to provide high-resolution detection of vehicles, bicycles, and pedestrians in multimodal conflict zones. Along **arterial roads** such as Wilshire Boulevard and Sunset Boulevard in Los Angeles, El Camino Real in San Jose, and Broadway in Sacramento, magnetometers and video systems will be deployed to assess ease of installation, data granularity, and performance under moderate-speed, mid-volume traffic conditions.

Table 5. Pilot Deployment Locations and Technologies

Pilot Environment	Example Locations	Deployed Technologies
Intersections	Downtown LA, Koreatown; SF Financial District; San Diego Gaslamp Quarter	LiDAR, Video Systems, and Infrared Sensor
Arterials	Wilshire Blvd (LA), Sunset Blvd (LA); El Camino Real (San Jose); Broadway (Sacramento)	Magnetometers and Video Systems
Freeway Mainline	I-405, I-10 (LA); I-80 (Bay Area); SR-99 (Central Valley)	Magnetometers, Inductive Loops, and Radar
Freeway On-Ramps	US-101 ramps (Hollywood); SR-87 (San Jose); I-5 (Sacramento)	LiDAR, Video Systems, and Existing Census Technologies

Freeway test sites include high-speed segments of I-405 and I-10 in Los Angeles, I-80 in the Bay Area, and SR-99 in the Central Valley. These corridors will be divided into two distinct categories for sensor deployment: **mainline segments** and **hot spot areas**, such as ramps and merging zones. For mainline segments, magnetometers, inductive loops, and radar sensors will be deployed to evaluate real-time speed, volume, and occupancy under steady, high-speed traffic conditions. These sensors offer cost-effective and reliable monitoring for general traffic flow analysis. In contrast, hot spots, including on-ramps and interchange merging areas at locations such as US-101 in Hollywood, SR-87 in San Jose, and I-5 in Sacramento, will be equipped with high-resolution sensors such as LiDAR and video detection systems. These will be deployed alongside existing census technologies like inductive loops and magnetometers to assess their ability to capture complex vehicle interactions and operate effectively under challenging visibility conditions, including fog, low light, and peak-hour congestion.

During this pilot phase, Caltrans district offices and regional traffic agencies will coordinate access, permitting, and right-of-way approvals. System integration will focus on ensuring data compatibility with existing local traffic management systems, such as LADOT's ATSAC (Los Angeles Department of Transportation, 2018) infrastructure. A structured data collection effort will document system performance across several dimensions, including detection accuracy, reliability, environmental sensitivity, installation feasibility, and integration with existing infrastructure. This foundational dataset will inform the evaluation metrics and deployment criteria used in subsequent phases of the roadmap.

Phase 2: Evaluation and Expansion

The second phase of the statewide deployment roadmap focuses on systematically evaluating the technologies piloted in Phase 1 and expanding deployments based on measured performance and operational feedback. The objective is to transition from localized, proof-of-concept installations to broader functional implementation across California's key corridors and intersections. To guide this transition, a set of evaluation criteria has been established to ensure that decisions are not only evidence-based but also aligned with long-term operational and strategic needs. As summarized in Table 6, these criteria include detection accuracy, false positive rate, environmental robustness, and staff/user satisfaction—each selected for its direct impact on system reliability, safety outcomes, and overall return on investment. These evaluation criteria are developed to ensure that expansion decisions are grounded in both empirical evidence and stakeholder priorities.

Table 6. Evaluation Criteria for Pilot Technology Performance

Evaluation Metric	Description
Detection Accuracy	Precision in identifying vehicles, volumes, and movement classifications
False Positive Rate	Frequency of incorrect detections across different environmental contexts
Environmental Robustness	Sensor performance in low light, rain, fog, and heat
Staff/User Satisfaction	Ease of use, operational reliability, and integration feedback

Detection accuracy measures how precisely a sensing system identifies vehicles, their volumes, and movement classifications. This metric is foundational to any traffic monitoring or control system because it underpins all downstream processes such as signal optimization, congestion management, and safety analysis. For example, at an intersection, the ability to differentiate between left-turning vehicles, through traffic, and bicycles ensures appropriate signal phasing. On arterials, accurate detection allows for better coordination of green waves and improved traffic flow. Inaccurate data can lead to mistimed signals, inefficient operations, and even increased crash risk. Without high accuracy, no advanced analytics or AI can reliably improve performance, making this a core requirement for scaling any sensor system.

False positive rate assesses how frequently a system generates incorrect detections, such as falsely identifying movement where none exists. This criterion is important because frequent false alarms can degrade system performance, lead to wasted green time, and cause unnecessary interventions. For example, on a foggy freeway ramp, a high false positive rate could lead to excessive ramp metering activations, disrupting throughput and reducing public trust. In busy arterial environments, false positives can result in incorrect pedestrian phase triggers or emergency preemption activations. Minimizing false positives ensures clean, actionable data and reduces the operational noise that can burden traffic management teams and degrade decision quality.

Environmental robustness evaluates a sensor's ability to function consistently in real-world weather and lighting conditions. This is critical because outdoor traffic environments are highly variable—featuring fog on the coast, extreme heat in inland deserts, and rain or low light in mountainous regions. Sensors that cannot maintain consistent performance across these conditions will suffer from data gaps, reduced reliability, and increased maintenance costs. For example, a camera may struggle during early morning glare or nighttime rain, while a magnetometer or radar may continue functioning without interruption.

Staff/user satisfaction reflects the day-to-day usability of the system from the perspective of those managing it. Even the most advanced technology can fail in the field if it is too difficult to install, operate, or integrate into existing workflows. Traffic technicians need intuitive interfaces for calibration and maintenance, while central operators must be able to interpret and act on data easily. Systems that are easy to use not only reduce training time and errors but also improve long-term adoption and cost efficiency—key for successful statewide scaling.

Once evaluated, the expansion planning will be informed by the pilot outcomes in locations such as Los Angeles, San Francisco, San Jose, and Sacramento, and extended to additional regions including San Bernardino, Fresno, Bakersfield, and Redding. These cities represent a range of traffic profiles, geographic terrains, and environmental conditions, making them well-suited to validate scalability across California.

For high-volume **freeway** corridors, including stretches of I-5 in the Central Valley, I-80 near Sacramento, and US-101 in the Bay Area, sensor deployment will be divided into mainline segments and hot spot areas, such as ramps and merging zones. For **mainline segments**, magnetometers, inductive loops, and radar sensors will be deployed to monitor speed, volume, and occupancy under high-speed, steady-flow conditions. These sensors have demonstrated strong performance and cost-effectiveness for broad traffic monitoring. For **hot spots**, including the I-710/I-105 interchange and SR-99 access points in Bakersfield, a combination of high-resolution sensors—such as LiDAR, video detection systems, and edge computing devices—will be used. These systems will capture complex vehicle interactions and support advanced traffic management in areas of frequent congestion and lane merging.

Magnetometers and video detection systems will be installed on **arterials** such as Santa Clara Street in San Jose, Figueroa Street in Los Angeles, and Blackstone Avenue in Fresno to enhance corridor signal coordination and data analytics. **Intersections** with high multimodal demand—including areas in Berkeley, Downtown Long Beach, and Santa Rosa—will be prioritized for LiDAR, video detection systems, and infrared sensors to support adaptive signal control, improve visibility under poor lighting conditions, and enhance pedestrian safety strategies.

This phase bridges experimental evaluation and full deployment by using real-world data to guide investment decisions. Sites that exhibit strong pilot outcomes will form the backbone of expanded deployments, while insights from lower-performing sites will inform system refinements, configuration adjustments, and operator training enhancements.

Phase 3: Full-scale Deployment

The third and final phase of the deployment processes focus on the large-scale integration of validated sensing technologies across California's transportation infrastructure. At this stage, the technologies and configurations tested and evaluated in the earlier phases are considered ready for broad implementation. This phase prioritizes deployment based on roadway type and functional context, ensuring that each sensor package aligns with the operational needs and environmental constraints of its specific setting.

For **urban intersections**, such as those located at Hollywood Boulevard and Highland Avenue in Los Angeles, video detection systems will be deployed in combination with LiDAR and infrared sensors. These environments involve complex interactions among vehicles, transit, bicycles, and pedestrians, necessitating high-resolution sensing and cooperative automation capabilities. The layered data produced by LiDAR and camera fusion supports adaptive signal control, V2X applications, and safety interventions, while infrared sensors enhance detection reliability under poor lighting or adverse weather conditions.

In **suburban arterials**, including corridors such as Fairfax Avenue and Crenshaw Boulevard, a combination of magnetometers and video detection systems will be deployed. This pairing allows for flexible installation and provides robust data on traffic flow and intersection approach behavior without the need for extensive civil works. The hybrid system balances performance with cost-efficiency and is especially well-suited for signalized arterial corridors that experience varying traffic loads throughout the day.

On **rural freeway corridors**, where the roadway is predominately composed of long stretches of straightaways—such as the northern segments of I-5 or portions of SR-58, inductive loops are the preferred technology. Their low cost, proven durability, and ability to provide consistent lane-level data make them an effective solution for monitoring traffic volumes and detecting incidents in areas with stable pavement and limited access for frequent maintenance.

On **freeway ramps and merging areas**, where short-range, high-frequency detection is essential, a combination of radar, video, and LiDAR sensors will be installed, complemented by existing census technologies such as inductive loops and magnetometers. Locations like the I-10/I-405 interchange or the SR-99 access ramps will benefit from this integrated setup, which supports detailed vehicle interaction analysis and maintains reliable detection in both high-speed and low-visibility conditions.

To support real-time monitoring and decision-making, a centralized data platform will be developed. This platform will integrate data feeds from all deployed sensors and provide Caltrans and regional agencies with visualizations, alerts, and analytics capabilities. It will support system-wide performance monitoring, enable cross-jurisdictional data sharing, and facilitate long-term planning through historical trend analysis.

Table 7. Full-Scale Deployment Plan by Roadway Environment

Roadway Type	Example Locations	Technologies
Intersections	Hollywood Blvd & Highland Ave (Los Angeles); Downtown Long Beach; Berkeley	LiDAR, Video Systems, and Infrared Sensors
Arterials	Crenshaw Blvd (LA); Santa Clara St (San Jose); Blackstone Ave (Fresno); H St (Redding)	Magnetometers and Video Detection
Freeway Mainline	Northern stretches of I-5; SR-99 (Bakersfield); I-80 (Sacramento); US-101 (Bay Area)	Magnetometers, Inductive Loops, and Radar
Freeway Ramps	I-10/I-405 Interchange (LA); SR-87 (San Jose); SR-99 access ramps (Central Valley)	LiDAR, Video Systems, and Existing Census Technologies

Table 7 outlines the full-scale deployment plan organized by roadway type. The technologies listed are chosen based on their demonstrated effectiveness, environmental suitability, and ability to meet operational goals identified in earlier phases. Each sensor package is optimized for the specific traffic conditions, infrastructure characteristics, and data requirements of its deployment context. The full-scale deployment plan is organized by roadway type. The technologies listed are chosen based on their demonstrated effectiveness, environmental suitability, and ability to meet operational goals identified in earlier phases. Each sensor package is optimized for the specific traffic conditions, infrastructure characteristics, and data requirements of its deployment context. Integrated data platforms will be developed to visualize real-time system status and support multi-jurisdictional coordination. These platforms will consolidate inputs from all sensor types and enable analytics to evaluate performance metrics across the entire state.

Phase 4: Training and Maintenance

To promote long-term functionality and ensure operator readiness across California's sensor network, it is recommended that a structured training and maintenance program be implemented in parallel with full-scale deployment. This proactive approach would equip agency staff with the knowledge and tools needed to maximize sensor performance, reduce system downtime, and streamline ongoing technical support.

It is advised that Caltrans coordinate a statewide training initiative in partnership with district offices and local agencies. The program should include regional workshops, on-site demonstrations, and easily accessible digital modules tailored to the specific technologies deployed. For example, personnel working with LiDAR and radar systems would benefit from advanced calibration training, while operators of video and magnetometer systems should be oriented on image-based analytics and embedded signal processing workflows. Supplemental materials—such as user guides, troubleshooting checklists, and training videos—should be developed to reinforce workshop content and support long-term knowledge retention. Additionally, training materials such as user manuals and video tutorials will be developed to ensure that staff can refer to system-specific best practices as needed.

Maintenance protocols should be clearly defined and standardized to reflect the specific needs of each sensing technology. For instance, it is recommended that video detection systems be cleaned and recalibrated quarterly, while LiDAR systems undergo full calibration on an annual basis. Radar and infrared sensors, which require less frequent servicing, may be inspected semi-annually to verify alignment and signal quality. Pavement-based sensors such as inductive loops and magnetometers should be remotely monitored and physically inspected biannually in coordination with scheduled pavement maintenance activities.

To streamline ongoing support, Caltrans should consider establishing regional maintenance teams with dedicated service zones and designated points of contact. These teams would oversee preventative maintenance, respond to service disruptions, and conduct routine performance evaluations. It is further recommended that a centralized asset management system be implemented to track the health, service history, and geographic distribution of all deployed sensors. This system would enable data-driven planning for replacements, upgrades, and performance optimization over the lifecycle of the deployment.

Phase 5: Risk Management

A comprehensive risk management strategy is essential to ensure the long-term resilience and effectiveness of California's statewide traffic sensing network. This strategy should address four primary risk categories, each of which presents unique threats to system performance and imposes potential costs if not proactively mitigated:

Technology Failure: Sensor malfunction or hardware degradation can result in inaccurate or missing traffic data, leading to signal timing errors, delayed incident detection, and reduced system reliability. In high-volume corridors, the financial impact of failed sensors can exceed $10,000 per day due to subsequent traffic congestion and mismanaged flows (FHWA, 2017). To mitigate this risk, Caltrans is recommended to adopt redundancy protocols—such as dual-sensor configurations at critical nodes—and implement real-time health monitoring to trigger alerts for preventive maintenance or immediate replacement.

Environmental Sensitivity: Weather conditions such as fog, heavy rain, and low-light environments can significantly impair sensor performance, especially for camera-based systems. Studies have shown that unplanned delays caused by poor sensor performance in such conditions can cost $500 to $2,000 per hour per affected corridor (NCHRP Report 775, 2014). It is advised that Caltrans prioritizes the deployment of hybrid sensor systems (e.g., radar combined with video or infrared sensors) to ensure reliable detection in varying environmental conditions.

Cybersecurity and Data Integrity: As infrastructure becomes increasingly connected, the risk of cyberattacks and data breaches grows. Compromised traffic management systems could lead to public safety concerns and legal liability. The cost of a major cyberattack on a metropolitan traffic system could exceed $100,000 in response, recovery, and reputational damage (FHWA, 2021). To reduce this vulnerability, Caltrans should implement encrypted data transmission protocols, access-controlled APIs, and system-wide cybersecurity audits aligned with state IT standards.

Interoperability Challenges: Lack of compatibility between devices from different vendors or non-compliance with data standards can result in costly reconfiguration or system isolation. Reworking integration efforts across corridors may cost between $50,000 and $200,000 per instance (NIST, 2018). To prevent this, Caltrans should enforce NTCIP compliance and adopt open, standards-based platforms that support long-term vendor flexibility and system scalability.

Figure 4 summarizes the estimated cost of failures for all four categories. The two highest-impact risk categories, cybersecurity and interoperability, pose significant single-event and systemic risks, respectively. Cybersecurity breaches, for instance, can result in losses exceeding $100,000 due to operational disruption, emergency response, and reputational harm (FHWA, 2021). Interoperability challenges can cost $50,000 to $200,000 per corridor if devices cannot communicate effectively or adhere to data standards (USDOT, 2016). These risks demand immediate attention and mitigation through encrypted communication, compliance with open standards like NTCIP, and regular system-wide audits.

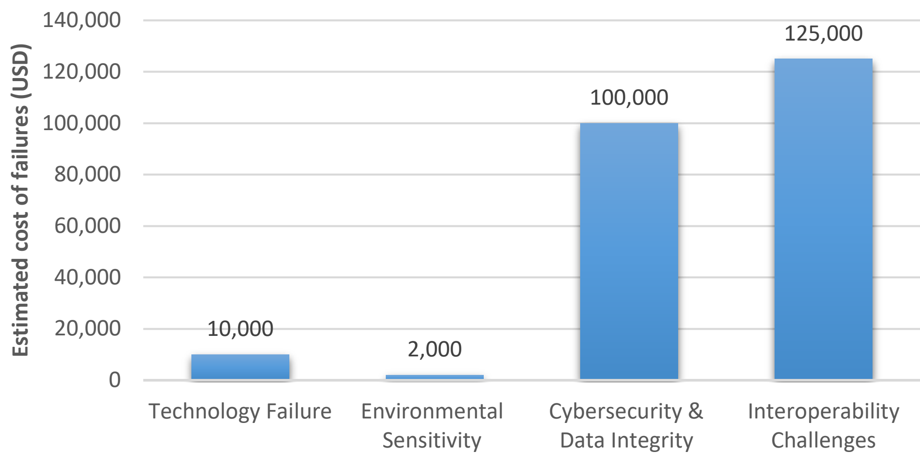

Figure 4. Estimated cost of failures for four potential risk categories

In contrast, environmental sensitivity and technology failure represent more localized, recurring risks. Though lower in cost per event—typically $500 to $2,000 per hour for weather-related disruptions (NCHRP, 2014) and $10,000 per day for sensor malfunctions (FHWA, 2017)—they still contribute significantly to operational inefficiencies when aggregated across corridors. Addressing these risks through hybrid sensor configurations and real-time health monitoring systems can ensure stable performance and consistent data delivery. By proactively planning for these risks and incorporating mitigation strategies during deployment, Caltrans can support a traffic sensing network that is not only robust and responsive but also financially sustainable over the long term. Figure 2 presents a comparative overview of the estimated financial impact associated with each major risk category and reinforces the need for an integrated, resilient approach to risk management.

Conclusion

This report provides a comprehensive strategy for modernizing traffic census data collection throughout the state of California. It begins with a detailed literature review and technology evaluation, offering a comparative analysis between traditional and modern sensing technologies. The report identifies the limitations of legacy systems—such as inductive loops and magnetometers—while highlighting the enhanced capabilities of modern solutions like video detection systems, radar, infrared sensors, and LiDAR. The findings are synthesized into an evaluation matrix that outlines key performance criteria, including accuracy, cost-effectiveness, and environmental robustness.

Building on this foundation, a lifecycle cost analysis compares traditional and modern technologies over a 10-year horizon. The analysis reveals significant differences in upfront investment, maintenance demands, and long-term cost efficiency, helping to inform technology choices tailored to various roadway environments.

The report offers specific sensor recommendations based on roadway type—freeways (including mainline and ramps), arterials, and intersections. Each recommendation is aligned with functional needs and contextual challenges, such as traffic speed, multimodal complexity, and environmental exposure. Notably, intersections were identified as high-priority locations for deploying integrated LiDAR and video systems, supporting both real-time traffic control and advanced applications like V2X-enabled cooperative perception.

A five-phase implementation roadmap guides the modernization effort through clear and complementary stages. Phase 1 launches pilot deployments in varied traffic environments to test feasibility and collect baseline data. Phase 2 focuses on evaluation and expansion, applying pilot insights to refine and scale deployments. Phase 3 transitions to full-scale implementation tailored to roadway types and regional needs. Phase 4 establishes training and maintenance protocols to ensure operational continuity. Phase 5 introduces a risk management framework addressing technical, environmental, cybersecurity, and interoperability concerns. Together, these phases offer a practical and sustainable path to statewide traffic sensing modernization.

Key accomplishments of this report include:

- Development of a decision framework for sensor selection based on performance, cost, and roadway function.
- A literature review that systematically compares traditional sensing technologies and modern systems, identifying strengths, limitations, and suitability across different operational contexts.
- A scalable roadmap for statewide deployment of traffic sensing technologies.
- Lifecycle cost models for comparative evaluation of traditional and modern systems.
- Practical risk mitigation strategies addressing environmental, technological, and cybersecurity concerns.

By integrating research, evaluation, planning, and implementation guidance, this report positions Caltrans and its partners to deploy a future-ready, data-rich traffic census system that supports safety, efficiency, and innovation in transportation management statewide.

References

Ali, S. Sheik Mohammed, Boby George, Lelitha Vanajakshi, and Jayashankar Venkatraman. "A multiple inductive loop vehicle detection system for heterogeneous and lane-less traffic." IEEE Transactions on Instrumentation and Measurement 61, no. 5 (2011): 1353-1360.

Barth, M., & Boriboonsomsin, K. (2014). Real-world carbon dioxide impacts of traffic congestion. Transportation Research Record: Journal of the Transportation Research Board, (2021), 163-171.

Bogdanski, L., & Posen, J. (2018). Evaluating magnetometer performance for vehicle detection in high-traffic urban environments. Journal of Transportation Technologies, 8(3), 91-103.

Bilik, I. (2022). Comparative analysis of radar and lidar technologies for automotive applications. IEEE Intelligent Transportation Systems Magazine, 15(1), 244-269.

Caltrans Division of Research, Innovation and System Information (DRISI). (2019). *Infrared sensor performance report for low-visibility conditions*. California Department of Transportation. https://dot.ca.gov/programs/research-innovation-system-information

California Department of Transportation. (2020). Transportation Asset Management Plan 2020. https://dot.ca.gov/programs/asset-management

California Department of Transportation. (n.d.). *PeMS: Freeway Performance Measurement System*. https://pems.dot.ca.gov

Channi, Shreya Basavaraj, Shreya S. Reddy, A. S. Shriya, Poornima A. Totad, and Abdul Haq. "AI Powered YOLO based traffic management system through application advancement." NEW ARCH-INTERNATIONAL JOURNAL OF CONTEMPORARY ARCHITECTURE 8, no. 1s (2021): 166-173.

Cherrett, Tom, Hugh Bell, and Mike McDonald. "Traffic management parameters from single inductive loop detectors." Transportation Research Record 1719, no. 1 (2000): 112-120.

Chen, L., Pan, Z., & Li, Y. (2021). Video-based traffic flow estimation using deep learning. IEEE Access, 9, 105321-105332.

City of Sacramento. (2021). Traffic operations center – Advanced traffic management systems (ATMS) deployment. https://www.cityofsacramento.org/Public-Works/Engineering-Services/Traffic-Operations

Coifman, B., Beymer, D., McLauchlan, P., & Malik, J. (1998). A real-time computer vision system for vehicle tracking and traffic surveillance. Transportation Research Part C: Emerging Technologies, 6(4), 271-288.

Federal Highway Administration. (2014). *Traffic monitoring guide*. U.S. Department of Transportation. https://www.fhwa.dot.gov/policyinformation/tmguide/

Federal Highway Administration. (2017). *Traffic detector handbook: Third edition – Volume I*. U.S. Department of Transportation. https://www.fhwa.dot.gov/publications/research/operations/its/06108/06108.pdf

Federal Highway Administration. (2017). Traffic Signal Timing Manual (2nd ed.). U.S. Department of Transportation. https://ops.fhwa.dot.gov/publications/fhwahop18024/index.htm

Federal Highway Administration. (2019). Emerging technologies in transportation: Connected and automated vehicle research. U.S. Department of Transportation. https://highways.dot.gov/research/operations/emerging-technologies

Federal Highway Administration. (2019). *Lifecycle cost analysis primer*. U.S. Department of Transportation. https://www.fhwa.dot.gov/infrastructure/asstmgmt/lccaprim.cfm

Federal Highway Administration. (2021). Cybersecurity Framework Implementation for Intelligent Transportation Systems (ITS). U.S. Department of Transportation. https://www.fhwa.dot.gov/publications/research/operations/21019/21019.pdf

Federal Highway Administration. (2022). Traffic Monitoring Guide (6th ed.). U.S. Department of Transportation. https://www.fhwa.dot.gov/policyinformation/tmguide/

Guerrero-Ibáñez, Juan, Sherali Zeadally, and Juan Contreras-Castillo. "Sensor technologies for intelligent transportation systems." Sensors 18, no. 4 (2018): 1212.

Hu, C., Fang, Y., Wang, H., & Wang, H. (2021). Adaptive multi-view vehicle detection in traffic video using deep learning. Sensors, 21(6), 1925.

He, Zhitao, Yongyi Chen, Dan Zhang, and Mohammed Abdulaal. "Vehicle Anomaly Detection by Attention-Enhanced Temporal Convolutional Network." In 2023 IEEE 6th International Conference on Industrial Cyber-Physical Systems (ICPS), pp. 1-6. IEEE, 2023.

Los Angeles Department of Transportation. (n.d.). Advanced Transportation System and Coordination (ATSAC). https://ladot.lacity.gov/projects/transportation-technology/atsac

Marszalek, Zbigniew, Ryszard Sroka, and Tadeusz Zeglen. "Inductive loop for vehicle axle detection from first concepts to the system based on changes in the sensor impedance components." In 2015 20th International Conference on Methods and Models in Automation and Robotics (MMAR), pp. 765-769. IEEE, 2015.

Meng, Z., Xia, X., & Ma, J. (2024). Toward foundation models for inclusive object detection: Geometry- and category-aware feature extraction across road user categories. IEEE Transactions on Systems, Man, and Cybernetics: Systems.

National Cooperative Highway Research Program. (2014). NCHRP Report 775: Performance-Based Management of Traffic Signal Systems. Transportation Research Board. https://www.trb.org/Main/Blurbs/170352.aspx

National Institute of Standards and Technology. (2018). Framework for Improving Critical Infrastructure Cybersecurity (Version 1.1). U.S. Department of Commerce. https://nvlpubs.nist.gov/nistpubs/CSWP/NIST.CSWP.04162018.pdf

National Cooperative Highway Research Program. (2021). NCHRP Report 953: Roadway Infrastructure to Support Connected Vehicle and Automated Vehicle Operations. Transportation Research Board. https://doi.org/10.17226/25978

Ponnusamy, Sivaram, Harshita Chourasia, Seema Babusing Rathod, and Darshan Patil. "AI-Driven Traffic Management Systems: Reducing Congestion and Improving Safety in Smart Cities." In Smart Cities, pp. 96-121. CRC Press.

Saeed, M., El-Shafie, A., Nasir, Q., & Soliman, M. (2020). "Infrared sensors in smart traffic systems." *International Journal of Transportation Science and Technology*, 9(3), 310-324.

Shao, Y., Hou, Y., Li, X., Zhang, Z., & Wu, Y. (2020). Deep learning-based vehicle detection methods for traffic surveillance applications: A review. IEEE Transactions on Intelligent Transportation Systems, 22(4), 2086-2100.

Shao, Y., Hou, Y., & Li, X. (2020). Environmental conditions and video detection performance: A review of deep learning-based approaches. IEEE Access, 8, 202783-202795.

Sheik Mohammed, A. S., George, B., Vanajakshi, L., & Venkatraman, J. (2011). "A multiple inductive loop vehicle detection system for heterogeneous and lane-less traffic." *IEEE Transactions on Instrumentation and Measurement*, 61(5), 1353-1360.

Sun, Z., Wang, X., & Koch, W. (2013). A novel magnetometer-based vehicle detection system. IEEE Transactions on Intelligent Transportation Systems, 14(4), 1773-1781.

Wang, J., Xu, H., Yu, C., Zhang, S., & Yang, Y. (2020). Traffic video anomaly detection based on deep learning algorithms. IEEE Access, 8, 181916-181925.

Xiang, H., Zhao, Y., Liu, X., & Bai, Y. (2023). V2X-REAL: Real-time cooperative perception and tracking in connected vehicle-infrastructure systems. Proceedings of the IEEE Intelligent Transportation Systems Conference (ITSC). https://arxiv.org/abs/2303.15106

Xie, Jiyang, Yixiao Zheng, Ruoyi Du, Weiyu Xiong, Yufei Cao, Zhanyu Ma, Dongpu Cao, and Jun Guo. "Deep learning-based computer vision for surveillance in its: Evaluation of state-of-the-art methods." IEEE Transactions on Vehicular Technology 70, no. 4 (2021): 3027-3042.

Zhang, H., Li, H., Liu, Y., & Li, Z. (2020). A robust video-based system for real-time traffic monitoring. Journal of Transportation Engineering, Part A: Systems, 146(10), 04020103.

Zhang, F., Zheng, Y., Ma, X., & Yuan, X. (2021). Real-time multi-class traffic monitoring using advanced video detection systems. Transportation Research Part C: Emerging Technologies, 126, 103032.

Zhou, X., Gao, H., & Yu, Z. (2015). Vehicle detection and classification in outdoor environments using magnetometer sensors. Sensors, 15(12), 31247-31266.