Best Practices: Signalized Intersection Investments

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BEST PRACTICES, BETTER OUTCOMES

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Executive Summary

With Florida's population expanding rapidly due to increased migration and economic development, the strain on its transportation infrastructure is intensifying. Traditional traffic management approaches are proving increasingly insufficient, resulting in delays, safety issues, and operational inefficiencies. Furthermore, aging and suboptimal intersection infrastructure significantly contributes to the ever-increasing recurring congestion and delays on arterials in the state.

This study explores current and best practices for signalized intersection investments to address existing challenges and ensure future-proof solutions, aiming to provide stakeholders with guidance that enhances operational efficiency, safety, and overall benefits for all road users.

Overall, we observe that signalized intersection infrastructure and connectivity vary significantly across the United States and Florida, making a one-size-fits-all investment strategy unfeasible. Nevertheless, our review of the literature reveals systematic approaches like life-cycle assessments and national trend analyses that support informed decision-making. Nationwide, emerging technologies powered by artificial intelligence (AI) are advancing safety and mobility at signalized intersections. Although issues such as latency and real-time processing accuracy remain, they are being progressively resolved. Future investment planning should facilitate the integration of these technologies to maximize their benefits and effectiveness.

Based on these findings, we derive the following phased (short-term, medium-term, long-term) policy recommendations towards best investment practices:

- **Digitize existing infrastructure (short-term)**: Invest in digitizing existing signalized intersection infrastructure using a standardized approach to ensure consistent data collection across the state.
- **Foster collaborative partnerships and workforce development (short-term)**: Establish and promote collaborative approaches via inter-agency coordination, public-private partnerships, and workforce development to optimize resources and accelerate technology deployment. This can be achieved through funding public-private pilot programs deploying scalable and innovative technologies across the state.
- **Develop uniform state-wide protocols and guidelines (medium-term)**: Establish and fund uniform state-wide protocols for the systematic deployment, maintenance, and upgrading of signalized intersections.
- **Promote open-data initiatives for intersection management (medium-term)**: Encourage adoption of open-data practices that allow for easy sharing of all non-proprietary datasets, fostering innovation and transparency. This is especially crucial for the rapid development and deployment of advanced AI-powered traffic management solutions.
- **Invest in future proof and scalable design elements (long-term)**: Prioritize investments in modular, connectivity-ready, and interoperable systems/components for all upgrades and new signalized intersections, ensuring adaptability with evolving technologies.
- **Performance-driven investments (long-term)**: Prioritize intersection investments by outlining standardized state-wide performance targets.

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Acronyms

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
AI	Artificial Intelligence
ATCMTD	Advanced Transportation and Congestion Management Technologies Deployment
ATCS	Adaptive Traffic Control Systems
AV	Automated Vehicle
CAV	Connected and Automated Vehicle
CUTR	Center for Urban Transportation Research
CV	Connected Vehicle
CV2X	Cellular Vehicle-to-Everything
EEBL	Electronic Emergency Brake Light
ERDW	End of Ramp Deceleration Warning
FCW	Forward Collision Warning
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
IMA	Intersection Movement Assist
I-SIG	Intelligent Traffic Signal System
ITE	Institute of Transportation Engineers
ITS	Intelligent Transportation Systems
LiDAR	Light Detection and Ranging
LOS	Level of Service
MPO	Metropolitan Planning Organization
MUTCD	Manual on Uniform Traffic Control Devices
OBU	On-Board Unit
OTP	On-time Performance
PCW	Pedestrian Collision Warning
POG	Percent Arrival on Green
RLVW	Red Light Violation Warning
RSU	Roadside Unit
SPaT	Signal Phasing and Timing
TMC	Traffic Management Center
TRB	Transportation Research Board
TSP	Transit Signal Priority
TT	Travel Time
TTI	Travel Time Index
USDOT	U.S. Department of Transportation
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
VMT	Vehicle Miles Traveled
VRU	Vulnerable Road User
WWE/D	Wrong Way Entry/Driver

1. Introduction

The enhancement of safety for all road users holds a paramount significance in the pursuit of the U.S. Department of Transportation (USDOT) National Roadway Safety Strategy (NRSS), envisioning zero roadway fatalities across the nation. This vision is paving way for advanced research and technologies geared towards improving safety at intersections. While safety is the primary concern, given its direct link to preventing injuries and loss of life, addressing mobility challenges is equally crucial. Efficient traffic flows with minimal delays and queuing not only enhance the overall functionality and safety of the transportation networks, but also contribute to sustainability by lowering tailpipe emissions and fuel consumption [1, 2].

As Florida's population continues to grow rapidly at a projected yearly rate of 1.2% to 1.6% due to an uptick in migration and economic progress, the demand on its transportation infrastructure is rising steadily [3, 4]. Traditional traffic management methods are becoming increasingly inadequate, leading to delays, road safety challenges, and operational inefficiencies. Aging and poorly optimized intersection infrastructure is a major factor, accounting for 50 to 65 percent of recurring congestion and delays on arterials in Florida [5].

Intersections are crucial points in our transportation system where vulnerable road users (VRUs) (i.e., pedestrians, cyclists) and motorists converge, creating an environment of increased safety risk. The inherent interaction complexity and need for heightened situational awareness present unique challenges to all users, especially VRUs, often leading to adverse consequences such as property damage, injuries, and even fatalities. All intersections present unique mobility and safety challenges based on the motorized and non-motorized traffic serviced and physical characteristics. However, signalized intersections require significantly more capital for infrastructure investment and are strategically placed in areas servicing higher volumes of VRUs and vehicular traffic [6]. When compared to unsignalized intersections, signalized intersections are more prevalent in urban areas and often feature unique or more complex layouts designed to promote safe speeds, clear line of sight, smooth traffic progression and coordination, and universal access, all within the constraints of the limited right-of-way.

To systematically address existing challenges and ensure future-proof solutions, this study explores current and best practices for investments in signalized intersections. Our goal is to provide a guidance document/briefing to stakeholders that highlights practices that maximize operational efficiency, enhance safety, and deliver the greatest benefits to all road users. We discuss use cases at a local, national, and global level to offer an overview and key lessons learned from emerging technological advancements.

1.1. Objectives

The objectives of this study are as follows:

- Perform a comprehensive search on best practices on signalized intersections infrastructure investments.
- Document best practices, emphasizing the adoption of new technologies that leverage smart and adaptive systems.
- Identify and review three use cases of emerging technologies at signalized intersections, with a focus on state, national, and international deployments and lessons.

- Provide recommendations to inform policy makers on potential strategies and key elements towards achieving standardization in signalized intersection infrastructure investments across Florida.

1.2. Purpose and Intended Audience

The purpose of this report is to outline key strategies for improving investments related to signalized intersections, particularly through the integration of new, intelligent technologies. The report is directed at stakeholders and policymakers, providing a comprehensive overview to guide informed decisions on a standardized approach to investments in signalized intersection infrastructure across Florida, optimizing both near and long-term benefits for all users.

1.3. Document Layout

Following the introduction, this report delves into the safety and operational mobility challenges. This is followed by a comprehensive overview of the current state of infrastructure at signalized intersections, split into design and standards and existing investment and operations planning strategies. We then present a detailed overview of selected emerging technologies across three use cases, i.e., local, national, and global. Based on the findings and general outlook, we provide policy considerations towards best investment practices, followed by concluding remarks.

2. Safety and Mobility Challenges at Signalized Intersections

With over 320,000 signalized intersections in the United States and more than 16,500 in Florida alone, understanding the current challenges in operations and safety is crucial [1, 7]. Given that the average driver encounters nearly five traffic signals per trip, the efficiency and safety of these intersections directly impact daily commutes and overall traffic flow. This section breaks down the existing challenges at signalized intersections, supported by data-driven insights, into categories of safety and operational mobility.

2.1. Traffic Safety at Intersections

In 2022, the Federal Highway Administration (FHWA) reported a total of 42,514 fatalities (representing an 9.0% increase from 2020 and a slight reduction from 2021), of which 12,036 (i.e., 28.3%) occurred at intersections[1]. Additionally, VRU fatalities have also been on the rise, with bicyclist and pedestrian fatalities at intersections increasing by 11.6% from 2021 to 2022 [8].

Although signalized intersections represent approximately one tenth of the intersections in the United States, they account for one third of all intersection-related fatal crashes. Even more concerning, the data, controlling for travel behavioral changes resulting from the 2019 coronavirus disease (COVID-19) pandemic, reveal a 27.5% rise in fatalities at signalized intersections from 2019 to 2022 [8, 9]. Figure 1 summarizes the fatality statistics, grouped by intersection type, between 2016 and 2022 [10]. Overall, we observe that the total fatalities at signalized intersections are increasing at an alarming average rate of 4.3% every year as compared to 1.7% at unsignalized intersections, suggesting the need for immediate intervention.

[1] https://highways.dot.gov/safety/intersection-safety/about

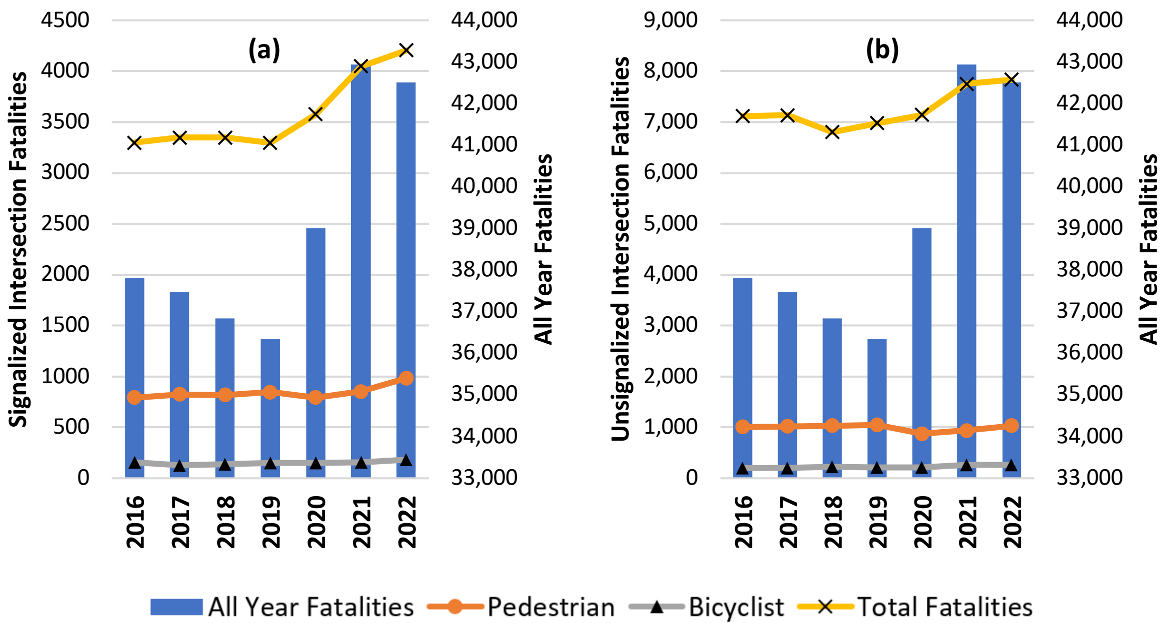

Figure 1 (a) signalized and (b) unsignalized (i.e., stop, yield, or uncontrolled) intersection fatality trend

Similar trends observed in Figure 1 are also observed across intersections in Florida. Table 1 presents the intersection-related crashes by severity over a five-year period in Florida[2].

Table 1 5-year summary of intersection-related crashes in Florida

	All Florida	**Intersection-related**			**Bicyclist at Intersection**			**Pedestrian at Intersection**		
Year	**Crashes**	**No Injury**	**Injury**	**Fatal**	**No Injury**	**Injury**	**Fatal**	**No Injury**	**Injury**	**Fatal**
2019	746,191	130,536	58,253	834	603	2,624	52	328	1,748	139
2020	589,873	103,993	50,258	876	556	2,430	68	246	1,362	132
2021	703,385	124,447	58,868	990	570	2,595	51	285	1,602	159
2022	708,427	128,510	60,542	937	699	2,953	68	345	1,908	150
2023	713,594	130,178	60,757	949	737	3,552	72	394	2,092	181
Total	**3,461,470**	**617,664**	**288,678**	**4,586**	**3,165**	**14,154**	**311**	**1,598**	**8,712**	**761**
Grand Total	**3,461,470**	**910,928**			**17,630**			**11,071**		

A few key statistics derived from Table 1, over the past five years in Florida, stand out:

- 26.3% of crashes in Florida are related to intersections.
- 32.2% of crashes at intersections lead to an injury or death.
- 23.4% of fatal crashes at intersections involve VRUs.
- As compared to 2019, intersection-related fatal crashes were up 13.8% in 2023.
- A 20.1% reduction in crashes was observed in Florida from 2019 to 2020, however, intersection-related fatal crashes increased by 5%.

[2] https://signal4analytics.com/

- There are 2.4 times more pedestrian fatalities at intersections than bicyclists.
- VRU-involved fatal crashes have been increasing at an annual rate of 7.4% between 2019 and 2023.
- 83.4% of crashes at intersections involving VRUs lead to an injury or death.

The above data-driven insights highlight that safety is a major concern, with crashes and VRU fatalities on the rise. This underscores the need for investments in signalized intersections to encompass advanced safety architecture. Emerging technologies such as edge processing, Artificial Intelligence (AI), and connected and automated vehicles (CAVs) present unprecedented opportunities to significantly enhance the safety of all users at intersections.

2.2. Operational and Mobility Challenges at Intersections

Estimating operational efficiency at signalized intersections is essential for effective traffic management, especially considering that, on average, a driver in the U.S. encounters five traffic signals per trip, with control delays accounting for at least 10% of the total trip duration [11]. Traditionally, traffic agencies relied on manual vehicle counts to estimate intersection efficiency. These methods are often limited to a particular period of the day and often cost a substantial amount of capital (around $5,000 per study) to execute, limiting resources to periodically update signal timing with respect to changing traffic patterns [12, 13]. As a result, many traffic signals across the nation still operate as they did 30 or more years ago, using pre-timed/fixed patterns. These fixed signals typically have one pattern for peak times, such as weekday rush hours, and another for off-peak times like late nights or weekends, often prioritizing the flow along the major street (i.e., arterial with greater traffic volumes) [14]. This leads to prolonged delays on the minor legs, affecting user experience and equitable access.

About 25 to 40 percent of signalized intersections in the U.S. consist of some form of actuation/adaptive response, with sensors adjusting signal phases by traffic demand [15]. However, these have their fair share of issues, such as failed detection of motorcyclists, increased control delays, and limited or no pedestrian phases [16]. Even with adaptive traffic control systems (ATCS), not all traffic conditions can be addressed, such as incidents, planned special events, and severe weather.

The advent of newer data sources coupled with cloud processing, such as real-time traffic data, connected vehicle data, and cell phone GPS sensors, has made it easier and more accurate to assess conditions and readily provide/apply mitigation strategies at traffic signals. A demonstration of the capability of such data sources was provided by INRIX, a global transportation mobility and safety data provider. By analyzing anonymous GPS data over a one month period covering 242,757 signalized intersections across 50 states (including Washington, DC) and 2,443 counties in the U.S., INRIX developed a performance scorecard that ranks the top metropolitan areas and individual intersections with the highest delays and associated emissions [11]. Miami, FL was recorded to have the longest average delay per vehicle at traffic signals, with 24.9 seconds, followed by New York, NY at 23.1 seconds per vehicle [1]. Moreover, three intersections in Florida ranked among the top ten for peak hour delays nationwide, as shown in Figure 2, suggesting a need for operational improvements.

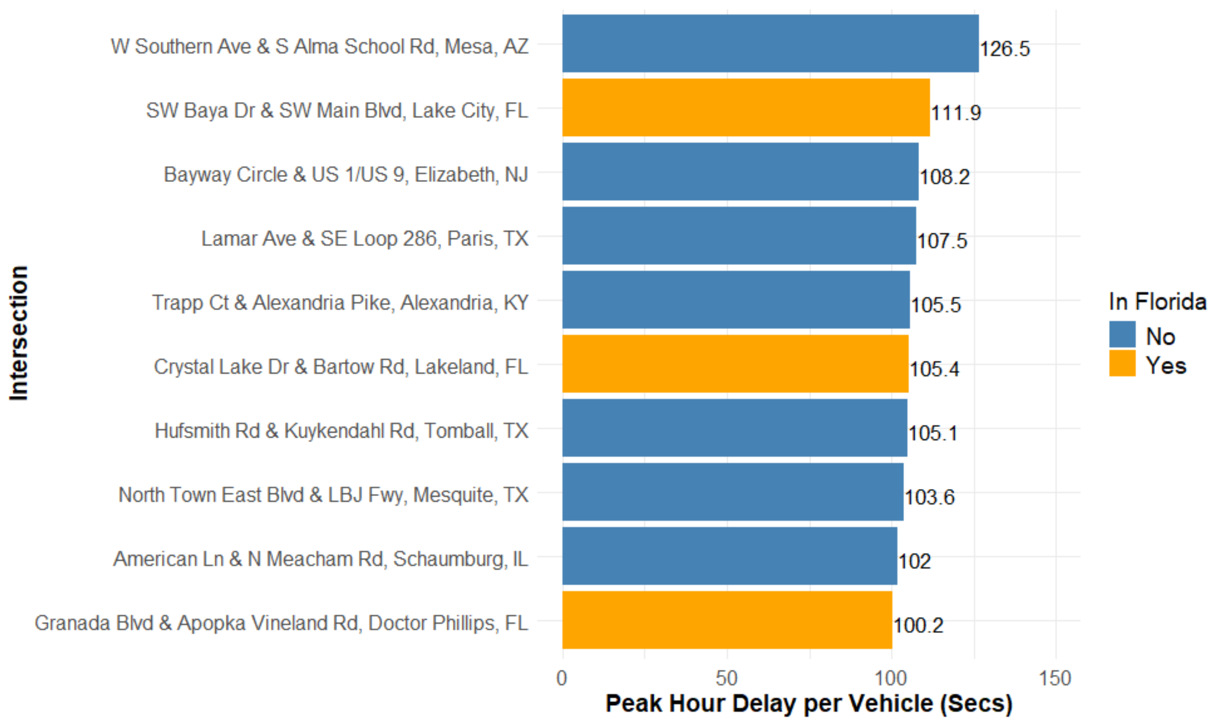

Figure 2 INRIX estimated top ten signalized intersections in 2022 by peak hour delay [1, 11]

From the 16,694 signalized intersections analyzed in Florida, the following metrics are derived:

- The average delay per vehicle was 20.4 seconds as compared to the national average of 18.1 seconds.
- The average percentage of vehicles arriving on green without stopping at the intersection was 64.7% as compared to the national average of 63.5%.
- The total daily delay per signal was 178.3 hours (national average 117.4 hours), resulting in approximately 1328 pounds of CO_2 emissions per day.
- Most of the signalized intersections are primarily designed to prioritize motor vehicle throughput efficiency, often with limited consideration for VRUs, thus resulting in the observed fatality trends.

Overall, signalized intersections in Florida perform on par with the national average in terms of arrival on green. However, due to higher traffic volumes, the total daily delay at Florida's intersections exceeds the national average by over 1.5 times, contributing to significantly greater emissions. This difference underscores the need for targeted interventions to optimize traffic signal flow in order to address the growing demands of the population and facilitate sustainable trips.

3. Current State of Signalized Intersection Infrastructure

3.1. Design and Standards

Signalized intersections in the United States are typically designed according to guidelines established by the Manual on Uniform Traffic Control Devices (MUTCD) [6]. However, individual states also incorporate state-specific guidelines to address localized environmental conditions and traffic challenges. The MUTCD recommends engineering judgement and provides nine condition-specific warrants to determine if a signalized intersection is required at a location and they include:

- Warrant 1, Eight-Hour Vehicular Volume: Traffic volumes meet minimum thresholds for eight hours.
- Warrant 2, Four-Hour Vehicular Volume: High traffic volumes during any four hours.
- Warrant 3, Peak Hour: Consistently high traffic during specific peak hours.
- Warrant 4, Pedestrian Volume: High pedestrian activity needing safe crossing time.
- Warrant 5, School Crossing: Proximity to schools to enable safe crossing for children.
- Warrant 6, Coordinated Signal System: Maintain flow in areas with closely spaced signals.
- Warrant 7, Crash Experience: History of high crash frequency at intersection.
- Warrant 8, Roadway Network: Facilitate movement in complex road networks.
- Warrant 9, Intersection Near a Grade Crossing: Prevent vehicles from being trapped near or on railroad crossings.

Chapter 5 in the MUTCD briefly touches on the considerations for Connected and Automated Vehicles (CAVs) [6]. A systematic approach on traffic control device selection, application, and maintenance, is suggested while accommodating both human and automated driving. A summary of the recommendations are as follows:

- Apply consistent traffic control devices across similar roadways and intersections.
- Eliminate unnecessary devices that no longer benefit vehicle operation or navigation, enhancing clarity for both human drivers and CAVs.
- Improved and consistent pavement markings at intersections to better support automation systems that rely on sensors and algorithms for accurate path detection.

At the state-level, the Florida Department of Transportation (FDOT) design manual closely follows the guidelines provided in the MUTCD and the American Association of State Highway and Transportation Officials (AASHTO) Standard Specifications for Structural Supports for Highway Signs, Luminaires and Traffic Signals [17].

3.2. Investment and Operation Planning Strategies

Effective traffic signal operation relies on a series of interconnected factors. As illustrated in Figure 3, communication and detection are the foundation of signalized intersection infrastructure. Without these, signals cannot adapt to changing traffic demands, and operators cannot effectively monitor or manage operations [18]. After establishing these foundational elements, signal timings can be fine-tuned to align with operational objectives. Efficiency gains from investing in advanced systems are possible, but only when the current infrastructure is fully optimized and leveraged. Figure 3 also emphasizes the critical role of collaboration between maintenance and operations teams in maximizing signal performance.

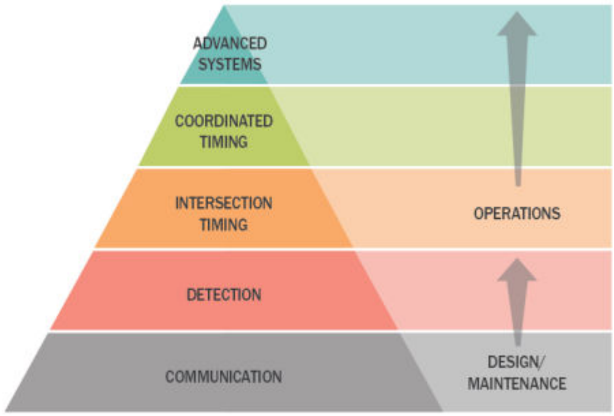

Figure 3 Achieving efficiency in traffic signal operations [18]

3.2.1. Nationwide

This subsection presents an overview of nationwide guidelines and strategic plans aimed towards signalized infrastructure management.

a) Traffic Signal Management Plans – An Objectives- and Performance-based Approach for Improving the Design, Operations, and Maintenance of Traffic Signal Systems [19]

Overview
This document, published in 2015 by the FHWA, provides a framework for developing Traffic Signal Management Plans (TSMP) by leveraging insights from various model traffic signal programs [19]. A TSMP is designed to outline and align an agency's goals, objectives, strategies, and performance measures, ensuring that the most critical outcomes are achieved within limited investment resources. This also helps practitioners strategically link their activities in traffic signal design, operations, maintenance, and management with their agency's overarching mobility and safety goals.

Key Takeaways
While the document is relatively old, it captures the essence of traffic signal operations and planning. The following are the key takeaways that can be applied to future signalized infrastructure investments:

- Achieving good basic service (prioritizing the most important tasks within operations, maintenance, and design, and with a limited set of resources) is key.
- Setting meaningful and performance measures for traffic signal operations (e.g., maximum allowable delay, critical queue length, level of service) provides a basis for assessing effectiveness of policies and investment decisions.
- Encouraging collaborative approaches across stakeholders to combine, review, and distill the rationale for investments and implementation.
- A phased implementation approach is recommended, that allows time to uncover lessons learned, especially with new technologies, before full scale installation.

b) Saving Lives with Connectivity: A Plan to Accelerate V2X Deployment [20]

Overview
The National vehicle to everything (V2X) Deployment Plan captures the vision of USDOT in strategically deploying wireless connectivity over the next 13 years (2024 to 2036) to enhance transportation safety, security, and efficiency, with a strong emphasis on privacy and consumer protection. Specific targets towards signalized intersection infrastructure are identified.

Key Takeaways

- Require states, local governments, tribes, and public agencies to update investment and transportation plans to include V2X technology.
- Envisioned long-term goal of 85% of signalized intersections in the top 75 metropolitan areas to have V2X capabilities.
- Funding of 50 regional deployments with interoperable V2X technologies.
- Adoption of standardized interoperability and cybersecurity practices across V2X infrastructure.
- Expectation from transit and freight operators to enable the use of on-board V2X applications for enhancing safety and efficiency.

c) Applying Transportation Asset Management to Traffic Signals: A Primer [21]

Overview

This primer, funded by the FHWA, outlines how to apply Transportation Asset Management (TAM) principles to traffic signal assets. It serves as a resource for transportation agencies managing and maintaining traffic signals, improving asset management practices, and planning new traffic signal assets with an understanding of long-term responsibilities and costs [21]. Of specific interest to this project are chapters 6 and 7, focusing on lifecycle planning and investment allocation towards traffic signals.

Key Takeaways

Technology assets like traffic signals can become obsolete even if they are physically in good condition, due to rapidly changing technology and public expectations [21]. Agencies can adopt risk-based strategies to manage obsolescence:

- Signal lifecycle: Consider major mid-life upgrades or replacements when systems cannot support new concepts (e.g., emergency vehicle and transit priorities, connected vehicles).
- Identify vulnerable components: Focus on the component level where most obsolescence issues occur, hindering integration with newer systems. Evaluate the probability and impact of obsolescence for each component.
- Mitigation strategies: Implement modular design considerations, firmware upgrades, and supplier maintenance support.

Figure 4 shows a simple lifecycle planning model developed by California Department of Transportation (Caltrans) to determine deteriorating rates and expected future conditions of a traffic signal asset.

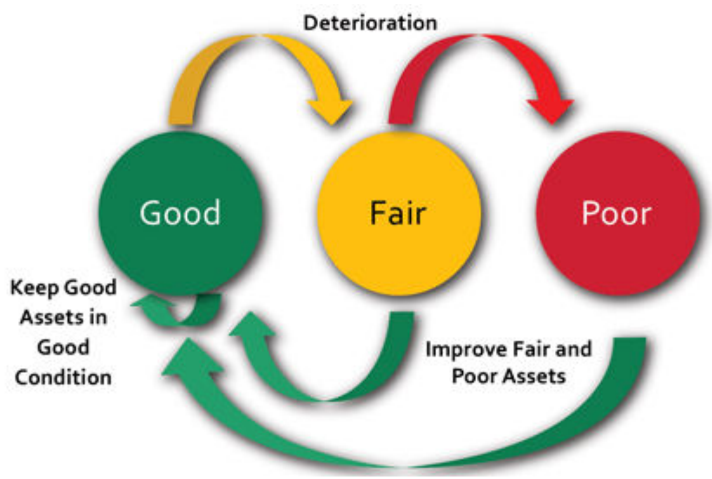

Figure 4 Lifecycle assessment model by Caltrans [22]

The document also highlights the three stages of resource allocation for a successful investment outcome i.e., stage 1: financial plan, life cycle plan, risk assessment; stage 2: resource allocation decision making; and stage 3: investment strategy [21].

d) USDOT Intersection Safety Challenge[3]

Overview

In early 2024, the USDOT announced 15 winners (one from Florida) of the first stage of the intersection safety challenge, aimed at transforming intersection safety via innovative systems that identify, predict, and mitigate unsafe conditions for all users. The core concept involved designing an intersection safety system that economically accomplishes the following:

- Analyzes real-time sensor data using machine learning.
- Classifies and tracks vehicles and vulnerable road users.
- Predicts movements and future trajectories within and around the intersection.

Key Takeaways

Figure 5 presents a comprehensive overview of USDOT's intersection systems integration vision. The envisioned minimum infrastructure required for all signalized intersections is clearly identified (i.e., mounting locations, sensors, signal controller, lighting, roadside unit (RSU), and power). The system is required to integrate real-time sensor data using machine learning to classify and track vehicles and VRUs, predicting their movements and future trajectories within and around intersections. Adaptable intersection control configurations with advanced warnings capabilities are a necessity. The system should also be able to alert both connected and non-connected users through innovative methods to ensure timely and effective responses to unsafe conditions.

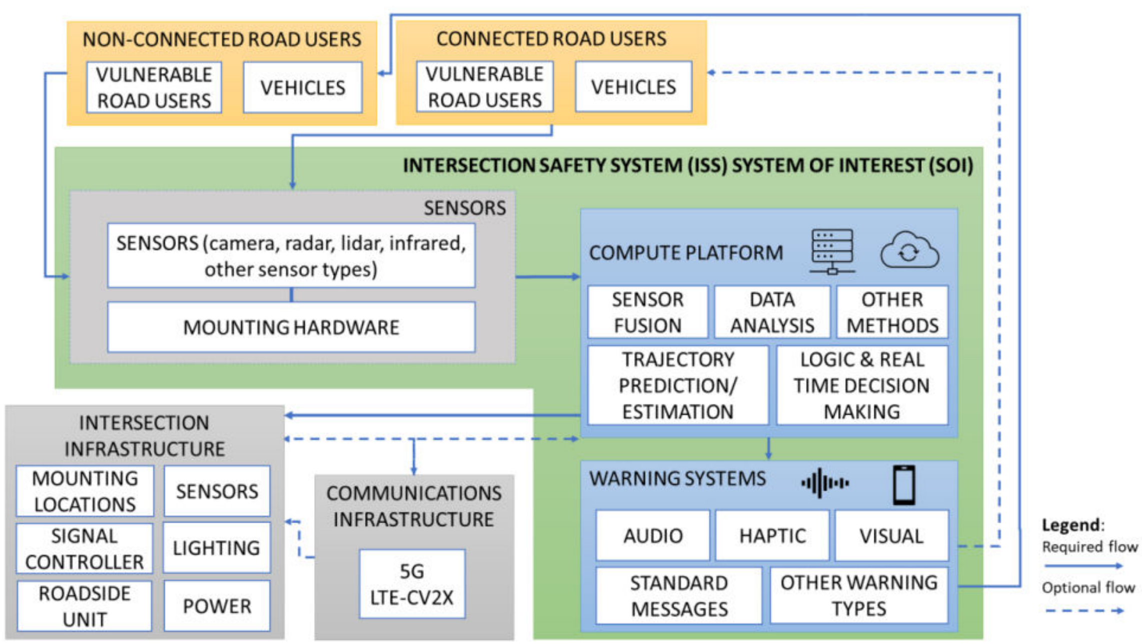

Figure 5 Conceptual framework of required and optional systems integration[3]

[3] https://www.challenge.gov/?challenge=us-dot-intersection-safety-challenge&tab=overview

Overall, the design and implementation plan for the intersection safety challenge offers valuable insights into the future of system integration and safety enhancements at traffic signals, offering actionable direction for making informed investment decisions.

3.2.2. State-specific

Table 2 presents a non-exhaustive compilation of key elements within investment- and planning-related documents for signalized intersections by state.

Table 2 Compilation of signalized Intersection-related investment and planning documents by State

State	Document Title	Investment/Planning Elements Discussed
Alabama	Statewide TSMO Master Plan: Traffic Signal Management [23]	• Identified critical elements to ensure regional coordination and maintenance of traffic signals. They include resource Integration, allocation, and management, information documentation and exchange, equipment sharing, pooled funding, personnel training and development, systems integration, and institutional integration.
Florida	Statewide Arterial Management Program (STAMP)-Action Plan [24]	• Implement central system upgrades for all districts. • Define data analytics requirements for performance assessments. • Set goals for standardized performance dashboards. • Deploy advanced detection technologies and share insights. • Create a STAMP funding and program tutorial. • Plan for additional staffing to support the defined strategies.
New York	Transportation Systems Management and Operations Strategic Plan [25]	• Incorporate considerations for connected vehicles (CVs) into planning and project development, focusing on traffic signal controller upgrades for signal phase and timing. • Support the use of high occupancy modes by implementing priority strategies at signalized intersections. • Enhance traffic signal coordination to reduce unnecessary delays. • Implement workforce training for the design, simulation, performance measurement, and maintenance of traffic signals. • Use strategies like freight signal priority and queue jumpers to enhance local access to freight hubs.
Oregon	Oregon Department of Transportation: Traffic Signal Management Plan [18]	• Specific goals for traffic signal management plan i.e., optimize mobility and accessibility, maximize operational efficiency, safe right-of-way for all modes, support economic vitality, and preserve traffic signal infrastructure. • Identified specific tactics to achieve the goals i.e., ensure accommodation of all users, proactively monitor signal operations, inter-agency and private-sector coordination, user-centric performance metrics.

State	Document Title	Investment/Planning Elements Discussed
South Carolina	Strategic 10-Year Asset Management Plan [26]	• Reduction in idling and emissions through retimed signals, intelligent transportation systems, intersection improvements, and other strategies. • Creating a comprehensive inventory of transportation infrastructure assets.
Texas	Texas Strategic Highway Safety Plan: Intersection Safety Emphasis Area [27]	• Systematic evaluation and digitization of signalized intersection inventory and controls. • Best practices and use of innovative intersection designs. • Innovative data-driven techniques to curb traffic violations at high-volume locations. • Investing in data to identify traffic flow problems and apply strategies (i.e., signal timing optimization and coordination)
Utah	Utah Transportation Asset Management Plan [28]	• Life-cycle planning for the signal system is under development. • Currently, traffic signal electronics and infrastructure are replaced on a priority basis as follows: prioritize system-critical elements that would shut down the system if they failed, address electronics nearing the end of their 10-year lifespan, and consider technology upgrades that offer benefits in capacity, preservation, or safety that outweigh the costs.

3.3. Section Summary

Overall, signalized intersection infrastructure and connectivity vary significantly across Florida and, more broadly, throughout the United States, making the "one solution for all" investment approach challenging in terms of feasibility and scalability. The following is a summary of the observed key findings:

- The most common signalized intersection layout consists of four legs with 32 vehicle-to-vehicle and 24 vehicle-to-pedestrian conflict points.
- Most of the signalized intersections are primarily designed to prioritize motor vehicle throughput efficiency, often with limited consideration for VRUs, thus resulting in the observed fatality trends.
- Signalized intersections typically consist of a central processing unit (CPU), traffic signal cabinet, backup signal plan, controller cards, phase timing hardware, signal heads, IP communications, conflict monitor, time clock, power supply, local user interface, and pre-emption hardware.
- A majority of existing signalized systems lack upgradeability and modularity, as well as interoperability due to limited data transfer/sharing capabilities, resulting in higher costs for complete overhauls.
- Approximately 25% to 40% of signalized intersections in the U.S. currently support adaptive traffic control systems (ATCS), indicating the presence of sensors and newer communication infrastructure [15]. This figure is expected to exceed 70% by the year 2030.
- There is very limited guidance in the MUTCD regarding the design and implementation of traffic signals and other control devices in a mixed traffic environment (i.e., human drivers and CAVs).

- Studies have shown critical vulnerabilities within legacy signal controllers and connected infrastructure especially related to malicious control, outdated firmware, encryption, privacy, and data security [29, 30].
- Short- and medium-term plans across most states of traffic signal investment involve asset management and personnel training/development.
- Long-term plans of traffic signal investment across most states involve provisions for the integration of advanced technologies and equitable access.
- There is a lack of dedicated protocols or standards towards over-the-air updates for intelligent intersection infrastructure, to ensure operational efficiency, longevity, and network security.

4. Emerging Technologies

The transportation industry and technology are rapidly evolving to embrace artificial intelligence (AI) and its ever-growing data needs. This evolution is paving way for novel solutions at signalized intersections to mitigate mobility and safety challenges. In this section, we highlight and examine three distinct deployments of emerging technologies at the local, national, and global levels, demonstrating their varied approaches and capturing their implications for the future of signalized infrastructure investments. It should be noted that the goal of this section is to objectively showcase the distinct solutions available, serving as an informative overview rather than a recommendation of any given entity or approach.

4.1. Use Case 1-Local: Connected Infrastructure

4.1.1. Overview

As part of the USDOT Intelligent Transportation Systems Joint Program Office (ITS JPO), three connected vehicle (CV) projects were awarded across the United States. The Tampa Hillsborough Expressway Authority (THEA) CV Pilot Deployment was one of the three CV projects funded in 2015, focusing on vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) applications to improve traffic safety and mobility within the strategically selected study area in and near downtown Tampa, Florida. The THEA CV Pilot deployed in four phases (1-Concept development, 2-Design/build/test, 3-Maintain and operate, and 4-Real-world test site) to systematically execute system and performance evaluation and document lessons learned for future deployments. Phase 4 of the pilot also tackled other USDOT goals for the deployment, such as the continued maintenance and operation of the CV system, performance evaluation, and engaging original equipment manufacturers (OEMs) (i.e., Honda, Hyundai, and Toyota) to facilitate interoperability of CV applications [31]. Additionally, novel to this deployment, onboard unit (OBU) firmware and configuration parameters could be updated over the air while participants travel within the study area, without the need to visit the installation facility.

The project installed 49 roadside units (RSUs) and enrolled more than 1,000 commuters providing a robust participant panel to meet the USDOT evaluation requirements [32]. Participants' vehicles were equipped with aftermarket or OEM OBUs capable of delivering warnings via a Human Machine Interface (HMI) installed in the vehicle's rearview mirror, as shown in Figure 6.

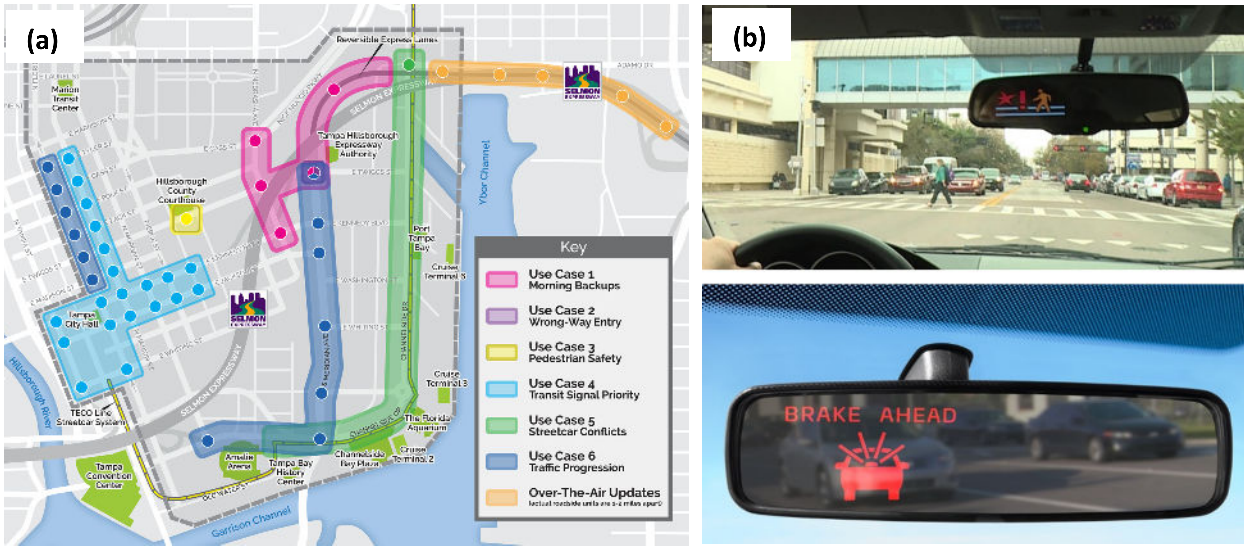

Figure 6 (a) Tampa downtown study area and application deployment map (b) HMI in the vehicle's rearview mirror [32]

4.1.2. Technologies Implemented and Findings

Table 3 outlines the CV applications implemented and their functionality (Figure 6) across one or more of the 38 RSU-equipped signalized intersections in the Tampa downtown area.

Table 3 Applications deployed or tested during the pilot study

Application	Function	At Signalized Intersection
Electronic Emergency Brake Light (EEBL)	Enables broadcast of severe braking events to nearby CVs.	Yes
End of Ramp Deceleration Warning (ERDW)	Alerts driver approaching curve with speed safety warning.	No
Forward Collision Warning (FCW)	Warns driver of impending collision ahead in same lane.	Yes
Intersection Movement Assist (IMA)	Indicates unsafe (i.e., wrong way) entry into an intersection.	Yes
*Intelligent Traffic Signal System (I-SIG)	Adjusts signal timing for optimal flow.	Yes
Pedestrian Collision Warning (PCW)	Warns driver of impending conflict with pedestrian.	Yes
Red Light Violation Warning (RLVW)	Warns drivers of high likelihood to cross stop line in red signal phase.	Yes
Transit Signal Priority (TSP)	Allows transit vehicle to request and receive priority at a signal.	Yes
Vehicle Turning Right in Front of Transit Vehicle (VTRFTV)	Alerts transit vehicle driver, as well as the driver of the car, that the car is attempting to turn right in front of the transit vehicle.	No
Wrong Way Entry/Driver (WWE/D)	Warns driver/nearby CVs of potential and actual wrong direction of travel.	Yes

*Application developed, but was not deployed/tested

The RSUs transmitted and collected over 33 billion counts of the following data: BSMs from vehicles operating in range of an RSU (up to 10 Hz); Signal Phase and Timing Message (SPaT) from RSUs (10 Hz); Map Data Message (MAP) from RSUs containing intersection geometry (1 Hz); Traveler Information Message (TIM) from RSUs at 1 Hz; Signal Request Message (SRM) transmitted by OBUs within range of the Dedicated Short-Range Communication radio of an RSU; Signal Status Message (SSM) broadcast by RSUs for conveying status of SRM back to OBUs; Pedestrian Safety Message (PSM) that triggered the collision alert as J2735 Message Frame [33]

The generalized findings suggest that the deployment of the EEBL, FCW, and IMA applications contributed to preventing 17 potential crashes in the study area. The PCW deployment contributed to avoiding 24 pedestrian crashes. The RLVW was deployed at connected signalized intersections in the study area, with RSUs broadcasting SPaT and MAP messages to the OBUs. The results revealed that out of 51 issued RLVWs, 15 warnings were true positives, and 36 were classified as false positives, indicating the need for additional parameter refinement.

4.1.3. Lessons Learned

While the THEA CV pilot provided several broad insights, the following lessons specifically pertain to the technologies and applications deployed at signalized intersections:

EEBL, FCW, and IMA: These three applications require precise parameter tuning, aligned with roadway geometry, to more accurately reference the spatial interactions between the CVs triggering the warnings.

PCW: The PCW application was effective in detecting pedestrians at intersections but struggled to consistently track the direction of their movement. In some instances, pedestrians were walking along the sidewalk rather than crossing the roadway, when warnings were sent. Similarly, there were cases where the CV and pedestrian were not on a collision path, as the pedestrian had already crossed the crosswalk by the time the warning was issued. Fine-tuning the PCW application parameters to localized environments could improve the accuracy and reliability of the warnings dispatched.

I-SIG: The I-SIG was developed but not deployed across the signalized intersections due to technological constraints in accurately estimating queue length (i.e., the distance from the stop line to the last vehicle in a lane during the red-light interval of a given signal cycle) from CV infrastructure, a critical measure for real-time signal timing adjustments.

RLVW: Successful and effective deployment of the RLVW application largely depends on accurate, comprehensive, and up-to-date SPaT and MAP messages. Also, the GPS positional accuracy substantially influences the issuance of true and false warnings.

WWE/D: This warning generated several false positive alerts that can be attributed to GPS signal drift and vehicle path estimation algorithms, suggesting room for additional refinement.

As with any large deployment, the THEA CV Pilot faced several challenges in deploying systems that are relatively new with technology suppliers characterized by a high degree of variability in terms of research and development capabilities. This heterogeneity impacted the development, refinement, coordination, and level of maturity of some of the THEA CV Pilot applications (i.e., I-SIG, TSP, PCW). In Phase 4, the participation of OEMS resulted in the deployment of commercial grade OBUs, equipped with software solutions that increased the accuracy of some of the applications. Overall, 62.5 percent of the participants were satisfied with the CV technologies deployed and realized benefits [31]. Further, CV-enabled warning applications are advancing rapidly, with cellphone-based OBU emulators being used as surrogates for physical HMIs, enhancing equitable access for all users.

4.2. Use Case 2-National: Retrofit Solutions

4.2.1. Overview

NoTraffic[4] is an upcoming AI-powered traffic signal platform, comprising of end-to-end hardware and software, that connects road users to the existing city grid with the main goal of addressing current traffic challenges and unlocking smart mobility benefits for cities. NoTraffic's solution is targeted towards:

- Improving adaptability of localized traffic detection and mobility at legacy signal controllers.
- Adapting to inclement weather conditions.
- Accommodating all users at intersections, not just vehicles.
- Lowering delay and costs associated with regular manual maintenance/calibration of signals.

The platform and associated hardware enable digitizing of existing signalized infrastructure and allows traffic management centers (TMCs) to remotely define operation policies/rules at each traffic signal. The platform is currently being piloted or deployed in 30 states, including Florida, and parts of Canada[4].

4.2.2. Technologies Implemented and Findings

The platform relies on a locally installed AI detection sensor at each intersection approach, fusing data elements from self-calibrating sensors, V2X infrastructure, and machine vision. The output is then processed using proprietary microsimulation algorithms to calculate and dispatch optimum signal timing and phase progression for all users including VRUs, in real-time (shown in Figure 7Figure 9) [34]. The operating system also allows for smart signal optimization for emergency vehicle preemption, transit vehicle priority, and planned special events, reducing delays and crashes.

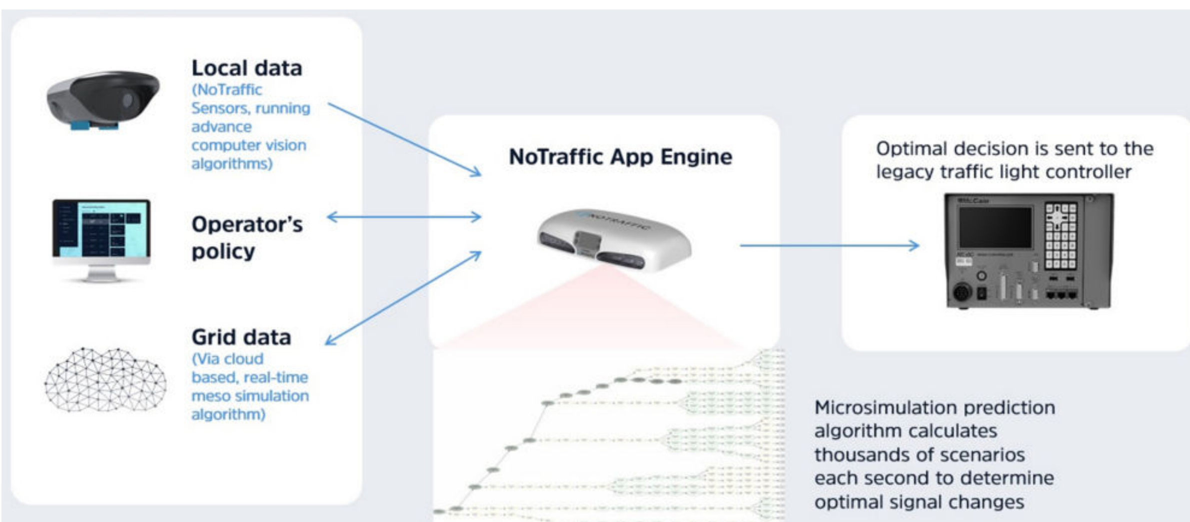

Figure 7 NoTraffic signalized intersection grid digitization [34]

Based on the test corridor in Chandler, Arizona, comprising of ten signalized intersections, the following findings were reported:

[4] https://notraffic.tech/

- Reduction in non-coordinated signal delay by 20%.
- Negligible change to percentage arrival on green during peak periods.
- 3.6% improvement in system-wide delay.
- Improved pedestrian and bicyclist wait times.

4.2.3. Lessons Learned

The following lessons can be derived from the completed case studies and deployments:

- Retrofitting signalized infrastructure in under two hours is a significant achievement, enabling quick modernization and immediate data collection with minimal disruption [35].
- AI-powered hubs provide valuable real-time data, helping agencies monitor infrastructure and implement targeted solutions. However, ensuring effective use of this data is crucial and has not been fully explored.
- More deployment case studies are needed to fully understand the impact of signal timing and phasing optimization algorithms and to evaluate its long-term effectiveness. The current portfolio of case studies shows negligible changes to control delay and little information on the effectiveness of transit and emergency vehicle priorities.
- Establishing partnerships between public agencies is a key challenge for system vendors.

4.3. Use Case 3-Global: Safety and Mitigation Systems

4.3.1. Overview

The Advanced Mobility Analytics Group (AMAG), based in Australia, provides a cloud-based enterprise solution in eight countries for road safety, transportation planning, and network management[5]. The platform is made of three main modules: survey, operations, and safety. The survey module captures and analyzes traffic flows and speeds. The operations module uses live feeds to detect incidents, generate heat maps, and classify/monitor road users at the intersection. The safety module also leverages live feeds and user trajectories to forecast potential crashes, alert users and TMC operators, and recommend countermeasures to prevent future incidents.

4.3.2. Technologies Implemented and Findings

In this use case we only discuss the safety and operations components of this system. The system employs video and LiDAR sensors to generate data for AI-enabled predictive analytics at signalized intersections, as shown in the operational architecture in Figure 8. The system also includes a Countermeasures Dashboard, offering a list of potential solutions for additional evaluation. TMC operators can refine recommendations through an iterative interview tool, providing a comprehensive safety assessment to support public investment in proactive site improvements.

[5] https://amagroup.io/smart-safety/

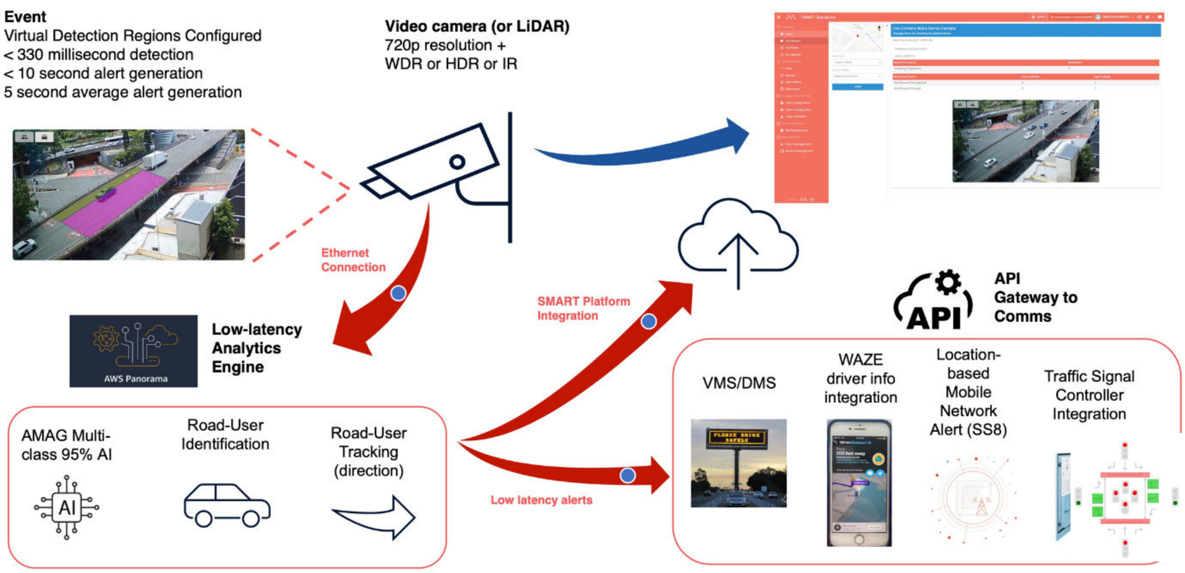

Figure 8 AMAG operational architecture [5]

4.3.3. Lessons Learned

Due to limited information on the system's real-world deployment, the following summarizes the generalized lessons learned:

- The system offers flexibility with options for a short-term subscription model or full installation, catering to varying needs (e.g., overhaul timeline, short-term data insights) and budget constraints.
- The ability to track trajectories and warn users using physical interfaces such as dynamic message signs, cell phones, and traffic signal messages, improves situational awareness.
- AI-based crash prediction not only tallies crashes but also identifies near-misses, enhancing the data's dimensionality for decision making.
- The auto-identification of safety hazards allows for proactive investment in site improvements, ensuring action is taken before the occurrence of adverse events (i.e., crashes, injuries).

4.4. Section Summary

As observed from the select use cases, emerging technologies and AI are bringing unprecedented improvements to safety and mobility at signalized intersections, with a focus on enhancing the utility of existing infrastructure and incorporating modular components as needed. While V2X communication is advancing to address safety concerns, challenges like latency and the accuracy of real-time processing algorithms still need to be resolved [36]. A well-rounded investment strategy in signalized intersections should prioritize streamlined infrastructure digitization, data generation, and data-driven analytics, along with connected infrastructure-based mitigation strategies.

5. Policy Considerations towards Best Investment Practices

To address the current state of the infrastructure, the challenges identified in this study, and integrate emerging technologies, we propose the following short (0-3 years), medium (3-5 years), and long-term (5+ years) policy considerations with the aim of optimizing and standardizing intersection infrastructure investments across Florida.

a) Digitize existing infrastructure (short-term)

As with any investment, it is critical to have a complete picture of the existing infrastructure. We propose an accelerated short-term goal of investing in digitizing existing signalized intersection infrastructure using a standardized approach to ensure consistent/secure data collection with respect to functionality and performance across the state. This will ensure the following:

- **Data consistency:** Implement uniform data collection standards across to ensure comparability and compatibility, which is crucial for informed investment planning.
- **Real-time monitoring:** Where unavailable, invest in technologies that allow for continuous data collection and real-time monitoring of intersections.
- **Prioritized decision-making:** Utilize the collected data for efficient allocation of resources based on user-centric return on investment (i.e., safety and mobility)

b) Foster collaborative partnerships and workforce development (short-term)

To ensure resource optimization and accelerated technology deployment, we recommend a collaborative approach fostering inter-agency coordination, public-private partnerships, and workforce development. This can be achieved through funding public-private pilot programs deploying scalable and innovative technologies across the state.

Inter-agency coordination not only includes state and federal agencies, but also metropolitan planning organizations (MPOs) and various local entities that are directly affected by signalized infrastructure investments such as public transit providers, local tolling agencies, freight operators, law enforcement, and educational institutions. Coordination will improve decision-making efficiency, promote the sharing of best practices, and ensure a comprehensive understanding of system operations and limitations. Similarly, public-private partnerships can be crucial in rapidly deploying well-tested and cost-effective solutions. As new technologies are explored and deployed, it is also essential to invest in training programs for transportation engineers, planners, and technicians to ensure that they are equipped with the necessary skills to effectively use the generated datasets and support integration into existing systems.

c) Develop uniform state-wide protocols and guidelines (medium-term)

Establish and fund uniform state-wide protocols for the systematic deployment, maintenance, and upgrading of signalized intersections, in line with USDOT's long-term "Saving Lives with Connectivity: A Plan to Accelerate V2X Deployment" goals [20]. These protocols and guidelines should prioritize component interoperability and security, ensuring consistency in infrastructure functionality and data generation.

d) Promote open-data initiatives for intersection management (medium-term)

Encourage adoption of open-data practices that allow for easy sharing of all non-proprietary datasets. These practices, discussed in detail below, can foster innovation and transparency.

- **Data sharing:** Combined with established collaborative partnerships, standardized data sharing can boost coordination between all stakeholders and interoperability within the individual systems/system vendors.
- **Innovation:** By providing open access to the generated datasets, research institutions and private entities can drive advancements in traffic modeling, AI-powered traffic and signal optimization, and smart intersection technologies, further benefiting end users.
- **Transparency:** Publicly accessible traffic data enhances transparency of the deployed solutions, enabling communities to comprehend the effects of infrastructure investments and actively engage in the planning processes.

e) Invest in future-proof and scalable design elements (long-term)

Prioritize investments in modular, connectivity-ready, and interoperable systems/components for all upgrades and new signalized intersections. This ensures the infrastructure remains adaptable to evolving technologies without complete overhaul.

As connected and autonomous infrastructure is being rapidly deployed in the U.S. (with 70 operational sites and 101 planned CV projects[6]), it is essential that new investments towards signalized intersection infrastructure account for, at a minimum, the following elements: high-speed connectivity (i.e., fiber and/or 5G), an intelligent signal controller or processor with remote debugging, RSU, plug and play architecture, signal heads with provision for autonomous driving, accessible warnings/alert broadcast (e.g., audio messages, LED alerts, haptic feedback), and vehicle detection sensors (i.e., radar, ultrasound, light detection and ranging (LiDAR), and cameras). Integration and interoperability within these components are crucial for supporting the next generation of connected and autonomous vehicles, and artificial intelligence (AI) powered traffic optimization protocols.

Based on the reviewed documents and national outlook, we propose three functional objectives for future design of signalized intersections: anticipation, mitigation, and planning. Investments should focus on systems that deploy preventive measures in real-time, such as automatically adjusting crosswalk times or signal phasing and timing, catering to the needs of all road users. These actions should incorporate warning systems (e.g., visual alerts, audio messages, in-vehicle warnings) to enhance situation awareness and mitigate safety concerns at intersections. The systems should also maintain historical logs with a feedback-loop allowing for the use of these datasets in planning and system improvement. A basic framework highlighting the minimum design objectives is shown in Figure 9.

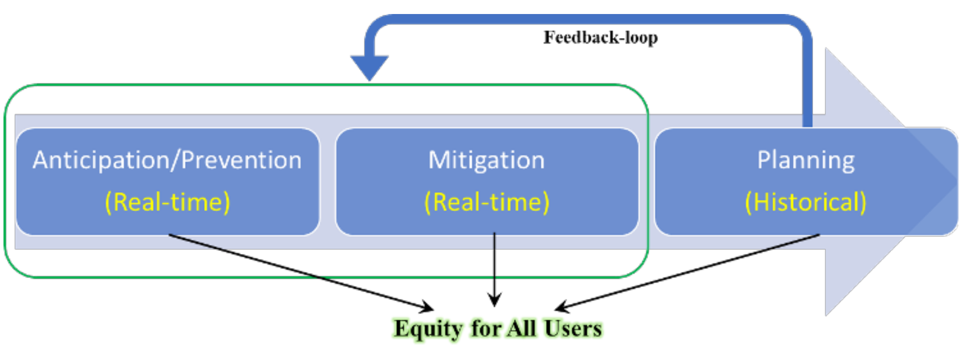

Figure 9 Minimum design objectives

[6] https://www.transportation.gov/research-and-technology/operational-connected-vehicle-deployments-us

f) Performance-driven investments (long-term)

Prioritize intersection investments by outlining standardized performance targets for all signalized intersections in the state:

- **Energy efficiency:** Reduce energy consumption and emissions by 20% through the adoption of efficient technologies like LED traffic signals, solar-powered signage, and adaptive-connected signal control systems.
- **Safety for all:** Achieve a 15% reduction in crashes by investing in intersection infrastructure that meets the safety needs of all road users, including vulnerable populations.

Figure 10 summarizes the policy considerations for optimal investment practices in signalized intersections, categorized by the suggested implementation timelines.

Figure 10 Best investment practices summarized

6. Conclusions

This study delves into the most effective practices for investing in signalized intersections by exploring the existing challenges, current state of practice, and emerging technological solutions. Through an examination of use cases at the local, national, and international levels, we extract key lessons from the latest technological advancements.

Overall, we find that signalized intersection infrastructure and connectivity differ widely across the United States and Florida, making a universal investment approach impractical and difficult to scale. However, through the literature, we identify systematic solutions that aid decision making such as life cycle assessment and outlook on nationwide trends. From a nationwide perspective, emerging technologies and AI are making significant strides in enhancing safety and mobility at signalized intersections. While challenges such as latency and real-time processing accuracy persist with these technologies, they are being actively addressed and improved. Investment planning for future traffic signals should support their integration to fully realize the benefits and functionality.

Based on these findings, we recommend a comprehensive investment strategy for signalized intersections that prioritizes digitization, data analytics, and connected infrastructure to enhance safety and efficiency. To achieve these goals, we propose a series of phased (short-term, medium-term, long-term) policy recommendations, including the digitization of existing infrastructure, fostering collaborative partnerships and workforce development, establishing uniform statewide protocols and guidelines, promoting open-data initiatives for intersection management, investing in future-proof design elements, and ensuring sustainability of investments. Adopting these strategic recommendations will not only address current challenges but also position Florida's transportation infrastructure to meet future demands, ensuring safer, smarter, and more equitable intersections for all road users.

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