Summary Report on Request for Information (RFI): Enhancing the Safety of Vulnerable Road Users at Intersections

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16. Abstract

In response to growing concerns regarding the safety of vulnerable road users at intersections and as part of the recent National Roadway Safety Strategy (NRSS) Call to Action, DOT aims to transform intersection safety through the innovative application of emerging technologies to identify and mitigate unsafe conditions involving vehicles and vulnerable road users. Of particular interest in addressing intersection safety are technologies such as machine sensing and perception, data fusion, artificial intelligence (AI) and machine learning (ML), trajectory and path prediction, vehicle-to-everything (V2X) communications, and real-time decision-making. Technological advancements in these and other areas offer an opportunity to improve intersection safety at scale in new and effective ways. The innovations operating in a real-time context are intended to augment (but not substitute for) a comprehensive suite of intersection safety considerations, including alternative intersection geometric design and changes to local traffic safety policies.

To better understand the feasibility and potential application of technologies that could enhance intersection safety, the DOT published the *Enhancing the Safety of Vulnerable Road Users at Intersections; Request for Information (RFI)* in the Federal Register, which was posted on September 16, 2022, and closed on November 15, 2022. The purpose of this report is to summarize insights from the 221 RFI responses received to inform DOT efforts for intersection safety as well as other departmental safety initiatives.

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Executive Summary

In response to growing concerns regarding the safety of vulnerable road users at intersections and as part of the recent National Roadway Safety Strategy (NRSS) Call to Action, the U.S. Department of Transportation (DOT) aims to transform intersection safety through the innovative application of emerging technologies to identify and mitigate unsafe conditions involving vehicles and vulnerable road users. Of particular interest in addressing intersection safety are technologies such as machine sensing and perception, data fusion, artificial intelligence (AI) and machine learning (ML), trajectory and path prediction, vehicle-to-everything (V2X) communications, and real-time decision-making. Technological advancements in these and other areas offer an opportunity to improve intersection safety at scale in new and effective ways. The innovations operating in a real-time context are intended to augment (but not substitute for) a comprehensive suite of intersection safety considerations, including alternative intersection geometric design and changes to local traffic safety policies.

To better understand the feasibility and potential application of technologies that could enhance intersection safety, the DOT published the Enhancing the Safety of Vulnerable Road Users at Intersections; Request for Information (RFI) in the Federal Register, which was posted on September 16, 2022 and closed on November 15, 2022. The purpose of this report is to summarize insights from the 221 RFI responses received to inform DOT efforts for intersection safety as well as other departmental safety initiatives. The report is organized according to the question areas covered in the RFI.

Key takeaways overall are summarized below:

- **Overall Feasibility:** Respondents generally suggested that it is feasible to develop an intersection safety system for vulnerable road users based on the technologies mentioned in the RFI, specifically including machine vision and sensor fusion. However, a number of crucial and non-trivial technical and non-technical challenges remain before widespread implementation is possible.
- **Challenges:** While the system building blocks or components of the proposed intersection safety system concept mostly exist, important challenges remain. For example, technical challenges include the need for improved position accuracy and latency concerns for real-time safety applications. Other challenges include the need for standards development and adoption, communications/spectrum uncertainty, and sustainability of a public-private partnership model.

- **Broader Safety Context:** Many responses, especially those from private citizens and advocacy organizations, emphasized the criticality of vulnerable road user safety within a holistic context combining technology with policy measures and traffic calming. Additionally, numerous responses noted that warnings alone may not bring sizeable safety benefits. Control actions (e.g., automatic emergency braking, signal changes) should also be considered to better protect vulnerable road users and drivers.
- **Real-Time Operations:** Low latency is critical for real-time safety applications, with tradeoffs between latency, detection accuracy, and cost. Edge computing offers promise to reduce latency, protect privacy, and scale readily.
- **Sensors:** Cameras, radar, and LiDAR were the most frequently mentioned modes of perception in RFI responses. Using existing sensors at intersections can help save on costs but could require additional calibration since existing sensors are generally designed to detect vehicles, not vulnerable road users.
- **Key Technologies:** AI and machine vision, multi-access edge computing (MEC), 5G, and V2X could be important emerging technologies for enhancing safety.
- **Costs:** Costs are highly dependent on the solution proposed and the availability of supporting infrastructure in actual deployments. Reducing costs will be an important factor in driving deployment of these systems at scale.

1 Introduction

1.1 Background

Improving the safety of pedestrians, bicyclists, and other vulnerable road users is of critical importance to achieving the objectives of the DOT National Roadway Safety Strategy (NRSS) and DOT's vision of zero fatalities and serious injuries across our transportation system (DOT n.d.). According to data from the National Highway Traffic Safety Administration (NHTSA), in 2020 there were 10,626 traffic fatalities in the United States at roadway intersections, including 1,674 pedestrian and 355 bicyclist fatalities. These fatalities at intersections represent 27% of the total of 38,824 road traffic deaths recorded in 2020. Early estimates in 2021 point to further increases, with pedestrian fatalities up 13% and pedalcyclist fatalities up 5% compared to 2020 (NHTSA, 2022).

In response to these growing concerns and as part of the recent National Roadway Safety Strategy (NRSS) Call to Action, the DOT aims to transform intersection safety through the innovative application of machine vision, sensor fusion, and real-time decision-making to identify and mitigate unsafe conditions involving vehicles and vulnerable road users. Of particular interest in addressing intersection safety include emerging technology areas, e.g., machine sensing and perception, data fusion, artificial intelligence (AI) and machine learning (ML), trajectory and path prediction, vehicle-to-everything (V2X) communications, and real-time decision-making. Technological advancements in these and other areas offer an opportunity to improve intersection safety at scale in new and effective ways.

The DOT seeks to develop new, cost-effective, real-time roadway intersection safety and warning system concepts. Further, to set the stage for nationwide deployment, the potential safety benefits relative to the estimated incremental costs of such concepts must be compelling enough to motivate eventual at-scale deployment across the nation.

1.2 Overview of RFI

To improve safety at a national scale, cost-effective safety solutions are required that can set the stage for broader, nationwide deployment. DOT recognizes that technology development and integration is one of many potentially cost-effective approaches for improving safety at intersections. The innovations operating in a real-time context are intended to augment (but not substitute for) a comprehensive suite of intersection safety considerations, including alternative intersection geometric design and changes to local traffic safety policies. This concept aligns with the NRSS and supplements current and existing DOT safety efforts, such as the FHWA Complete Streets Program and FHWA Proven Safety Countermeasures.

To better understand the technologies that could enhance intersection safety, the DOT published the *Enhancing the Safety of Vulnerable Road Users at Intersections; Request for Information (RFI)* in the Federal Register, which was posted on September 16, 2022 and closed on November 15, 2022 (DOT, 2022). Specifically, the RFI sought information on a conceptual vulnerable road user and vehicle warning system building on existing and emerging vehicle automation technologies—including machine vision, perception, sensor fusion, real-time decision-making, AI, and V2X communications. Responses to the RFI were intended to inform DOT on the status of technologies that can be used to improve or enhance the safety of pedestrians, bicyclists, and other vulnerable road users at or near roadway intersections, including the status of the current technical development or deployment of those technologies.

To prompt feedback, DOT included 27 specific questions, broken into four question categories: (A) General Technical Considerations, (B) System Installation and Deployment, (C) Human Factors and Performance Measurement, and (D) Development Costs and Time to Deployment. However, respondents were not required to follow the questions or suggested format in their responses. There were also no response length minimums or maximums. Some responses were as short as a phrase while others were over 20 pages in length.

The number and depth of the RFI responses pointed to a wide variety of technologies that could be integrated to enhance intersection safety today or in the near-term. RFI responses also included valuable feedback on considering such a proposed system in a broader context that includes warnings within a full range of intersection safety-related decision-making.

1.3 Purpose of the Report

The purpose of this report is to summarize insights from the 221 RFI responses received to help inform DOT efforts for intersection safety as well as other departmental safety initiatives.

The technical support team systematically reviewed all RFI responses (including comments and attachments), recording key pieces of data and key insights along the way. Key pieces of data include the respondent's name, date their response was posted, their estimated organization type (e.g., State DOT), and which questions (if any) they directly responded to in the RFI. Key insights were captured by the four RFI question categories (e.g., General Technical Considerations) and sub-categories teased out from the questions and responses (e.g., Data Considerations) rather than by individual RFI question since only 6 of the 221 RFI responses answered all 27 questions in the RFI. The information provided in each subsection of this report attempts to summarize high-level insights across all responses while also providing specific examples from respondents when possible. Specific respondent names are included in this report, since their responses are posted publicly on the Federal Register. Please see Appendix A for a complete list of the 221 respondents.

1.4 Organization of the Report

In addition to the introductory and concluding sections, the information in this report is organized by the four broad question areas in the RFI: General Technical Considerations (Section 3), System Installation and Deployment (Section 4), Human Factors and Performance Measurement (Section 5), and Development Costs and Time to Deployment (Section 6). Specifically, this report is organized into the following sections:

- **Section 2 Summary Data on RFI Responses** – provides a high-level summary on the number and nature of RFI responses.
- **Section 3 General Technical Considerations** – summarizes general technical considerations mentioned in RFI responses, organized by AI, machine vision, and sensor fusion technologies; sensor types for detection and perception; data considerations; considerations for real-time applications; and other technical considerations.
- **Section 4 System Installation and Deployment** – summarizes insights with respect to system installation and deployment mentioned in RFI responses, organized by suggested use cases/scenarios; considerations for alerts/warnings; modes of connectivity; and standards and considerations for interoperability.
- **Section 5 Human Factors and Performance Measurement** – summarizes insights with respect to human factors and performance measurement mentioned in RFI responses, organized by human factors; evaluation, testing, and validation considerations; and potential performance measures.
- **Section 6 Development Costs and Time to Deployment** – summarizes key insights on development costs and time to deployment mentioned in RFI responses, organized by timeline; partners; and costs.
- **Section 7 Key Takeaways** – summarizes key takeaways overall and by RFI question category.
- **Section 8 References** – lists the references mentioned in this report.
- **Appendix A**. – discusses details on the total number of responses (221) and includes a list of all respondents.
- **Appendix B**. – lists both DOT and Noblis staff who reviewed and supported this report.

2 Summary Data on RFI Responses

This chapter provides high-level summary data on the RFI responses received, broken down by respondent organization category (Section 2.1) and the nature of the responses (Section 2.2).

2.1 Breakdown of RFI Responses

A total of 221 RFI responses were received, as assessed by the reviewers. For details on the counting of responses, assumptions made by the reviewers, and complete tables of all responses by category, please see Appendix A. **Figure 1** shows the number of RFI responses by respondent organization type.

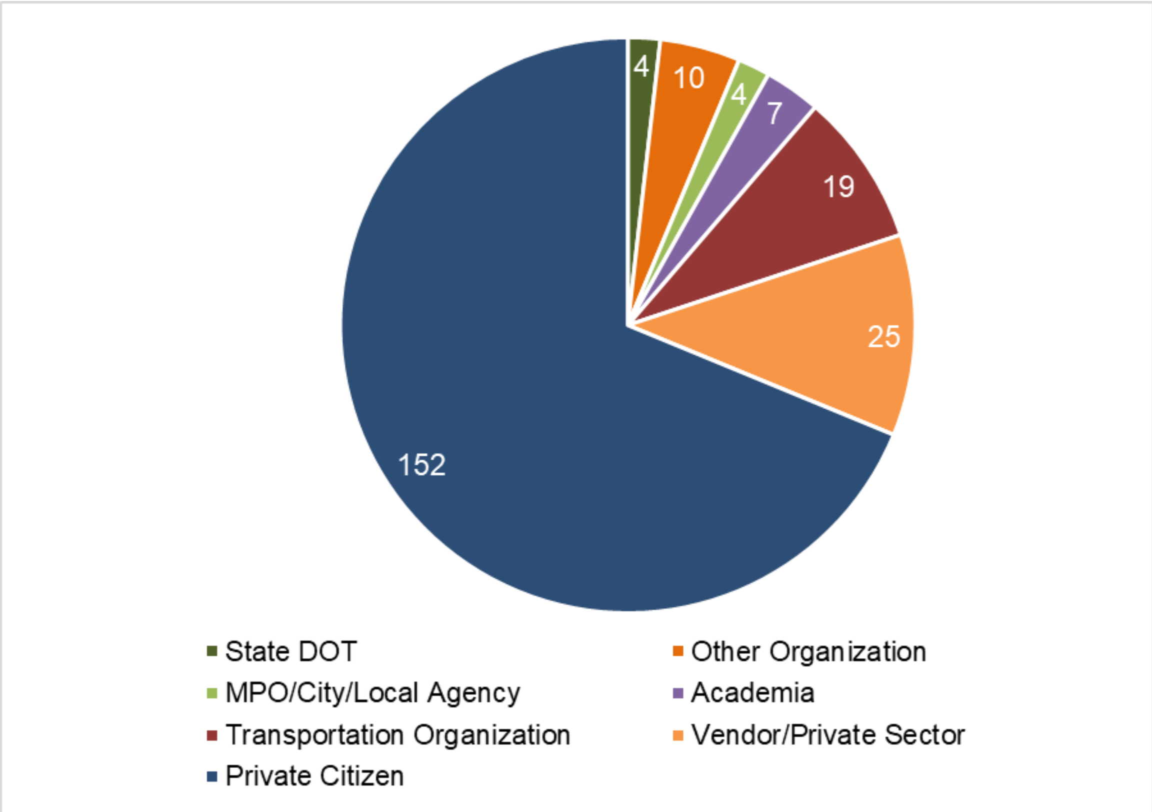

Figure 1. Number of RFI Responses by Organization Type

As shown in **Figure 1**, roughly one-third of the responses came from vendors or private sector companies, transportation organizations, academia, state DOTs, local agencies or cities, and other organizations such as policy organizations, advocacy organizations, and large organizations engaged in a variety of domain areas (e.g., SAE International). Over two-thirds of the responses were from private citizens. Most of the responses from private citizens were brief, non-technical comments that did not directly address the RFI questions.

Therefore, **Figure 2** shows the percent of responses received by organization type, excluding non-technical inputs from private citizens. Over a third of the technical responses came from vendors or others from the private sector and over a quarter from transportation organizations.

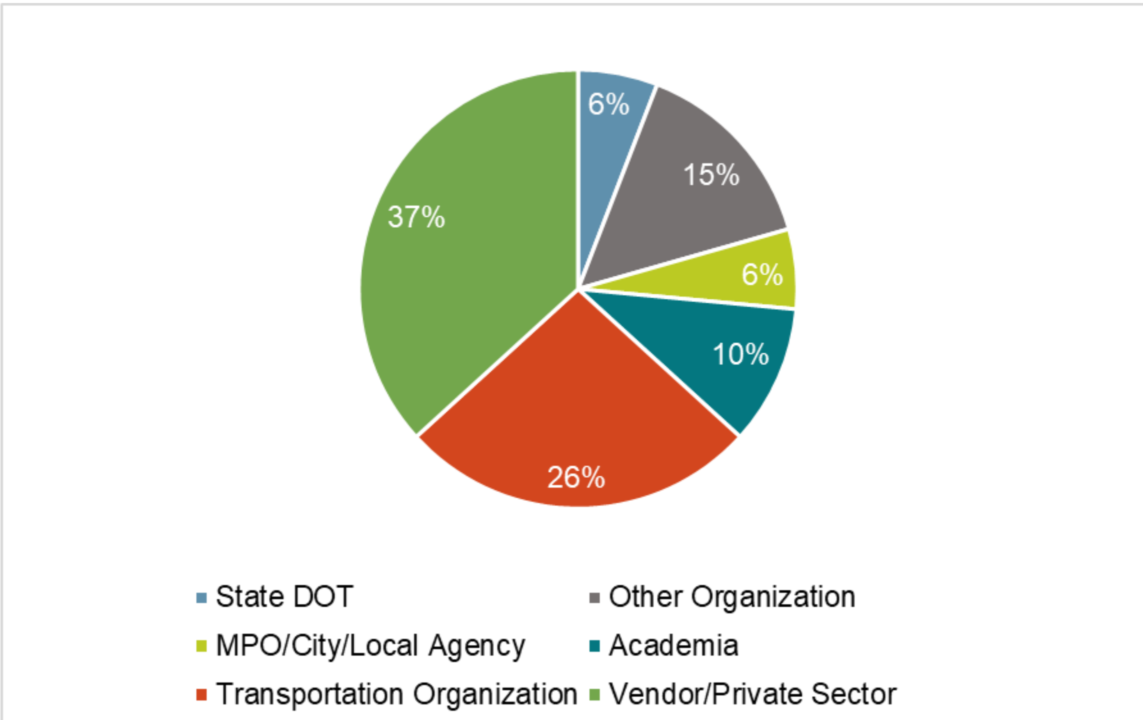

Figure 2. Percent of RFI Responses by Organization Type (excluding non-technical inputs)

Figure 3 shows the cumulative number of responses received over time by organization type. While the RFI was posted on Friday, September 16, 2022, the first responses did not appear until Monday, September 19. Responses were posted to the docket gradually over the course of the first 6-7 weeks of the RFI being open. However, during the last few days before the RFI closed, there was a significant influx in postings, from 93 total on November 13 to 165 total on November 14, 197 total on November 15, 220 total by November 18, and 221 by December 21.

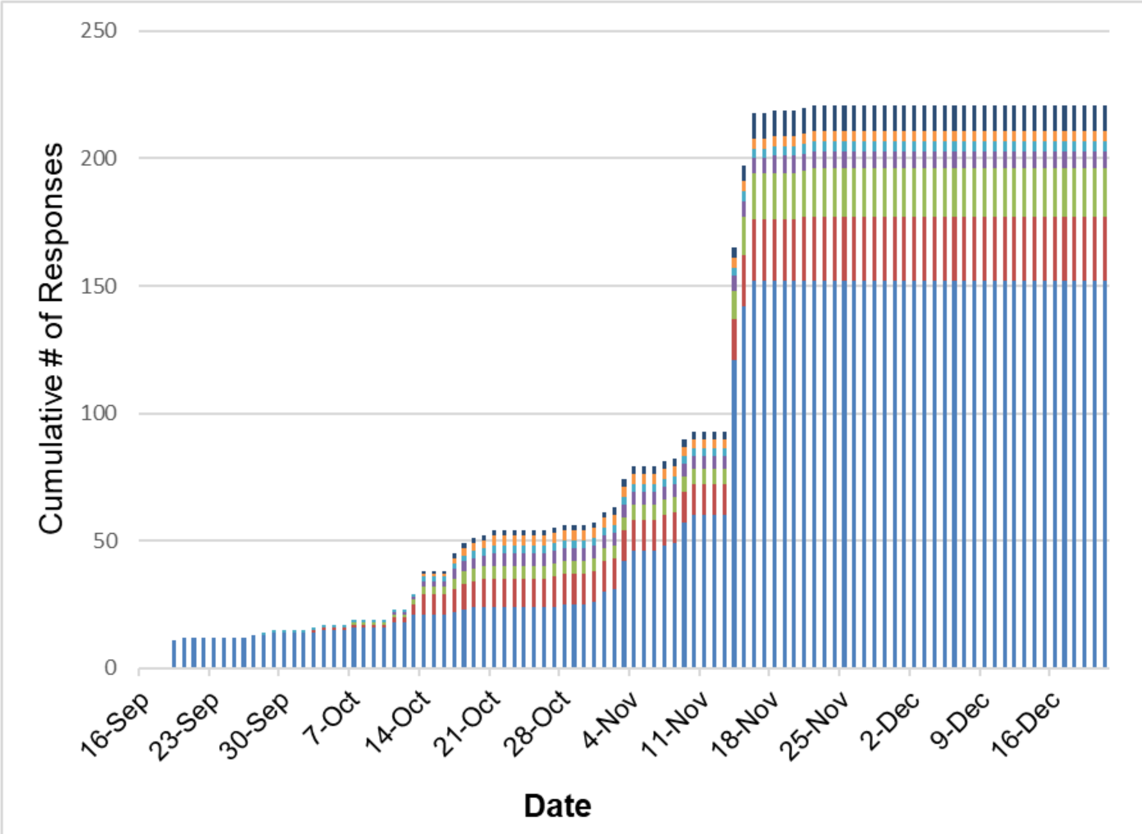

Figure 3. Cumulative Number of Responses Received by Date, Broken Down by Organization Type

2.2 Data on RFI Responses

The RFI responses offered many valuable insights that will help inform next steps for DOT's vision of improving vulnerable road user safety at intersections. 70 out of 221 responses were considered technical responses, where the respondents either directly answer the RFI questions or provided technical input. Among the 70 technical responses, roughly half answered at least some of the RFI questions directly. **Figure 4** shows the breakdown of number of responses that answered none, some, many, most, or all of the RFI questions directly, based on the total number of 27 specific RFI questions:

- None = answered 0 of the specific RFI questions.
- Some = answered 1 to 5 of the specific RFI questions.
- Many = answered 6 to 13 of the specific RFI questions.
- Most = answered 14 to 26 of the specific RFI questions.
- All = answered all 27 of the 27 total RFI questions.

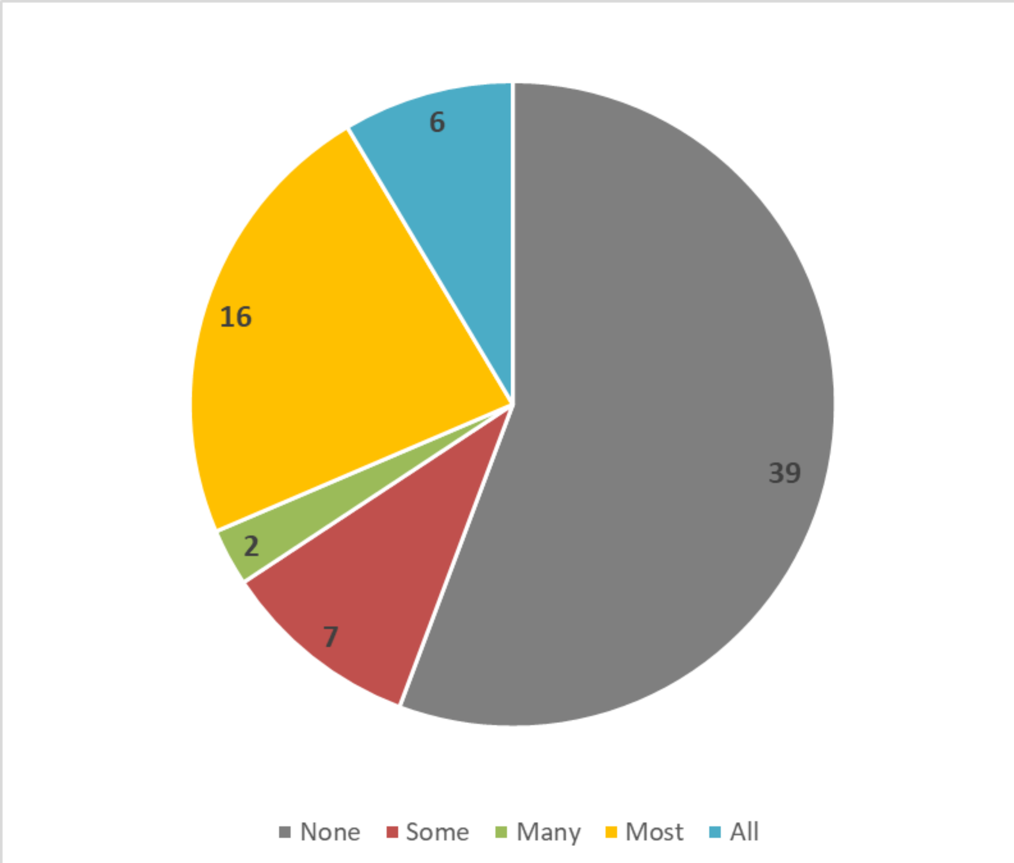

Figure 4. Number of RFI Responses by RFI Questions Answered Directly

Although 39 of the 70 total technical responses did not directly respond to specific questions posed in the RFI, many still provided valuable information about their organization, their technical capabilities and/or solutions, and other insights about technologies that could enhance the safety of vulnerable road users at intersections, as well as their thoughts, concerns, and suggestions. A few of these 39 responses, while they did not respond directly to specific RFI questions, provided insights under one or more of the broader question categories or sections (e.g., General Technical Considerations). The RFI broke down the questions into 4 main sections, with a fifth section for other comments:

- (A) General Technical Considerations – 7 questions.
- (B) System Installation and Deployment – 8 questions.
- (C) Human Factors and Performance Measurement – 7 questions.
- (D) Development Costs and Time to Deployment – 5 questions.
- (E) Other Comments – open ended.

Table 1 shows how many direct responses were received for each of the 27 RFI questions, meaning the respondent clearly indicated which question (or group of questions taken together) they were answering. In many cases, respondents provided front- or back-end material on their organization overall and then responded to specific RFI questions. Most responses received from vendors/private sector and academia followed the RFI questions.

Overall, respondents were more likely to respond to RFI questions in section (A) General Technical Considerations and section (B) System Installation and Deployment than the other sections. Questions A1 (on overall feasibility), A2 (on perception, vision, and fusion technologies), A5 (on new/emerging technologies), A7 (on types of VRUs and vehicles), and B4 (on modes of connectivity) received the greatest number of direct responses. Questions C2 (on human factors), C6 (on performance data), C7 (on measurement/statistical approaches), D1 (on schedule and cost), D2 (on equity), and D5 (on lifecycle considerations) received the fewest number of direct responses.

Table 1. Number of Direct Responses Received to the 27 RFI Questions

Question Section	RFI Question	# Responses Directly to that Question
(A) General Technical Considerations	1. What is the overall feasibility of developing an effective intersection safety system for vulnerable road users (VRUs) based on existing and emerging mobile (vehicle) automation technologies (including other complementary technologies) as described in this RFI?	26
	2. What perception, machine vision, and sensor fusion technologies (and other sensing modalities or combinations) are best suited to an effective intersection safety and VRU and vehicle warning system?	24
	3. What real-time image and data analysis techniques are best suited to provide the required machine vision and perception for an effective intersection safety system?	21
	4. What techniques are most effective in providing real-time vehicle and VRU path planning and prediction capabilities at fixed roadway intersections?	23
	5. What new and emerging technologies can enhance machine-based decision making at intersections—including determining potential vehicle-VRU conflicts, incidents, dilemma zones, and encroachment in real-time?	24
	6. What is the potential role of AI and/or ML in perception, image analysis, data analysis and decision-making at intersections, both in real-time and asynchronously? What is the potential for real-time learning and group learning across a number of similarly-equipped intersections?	23
	7. How could such a system work effectively with all types of VRUs (pedestrians, bicyclists, wheel-chair users, users of electric scooters, etc.) and all types of vehicles (cars, trucks, vans, transit buses, commercial vehicles, etc.)?	25
(B) System Installation and Deployment	1. How can the required installation, setup and calibration requirements for a perception and decision-making based intersection safety system be minimized?	22
	2. What pedestrian and VRU alerting and warning methodologies and systems would be most useful, including for example, visual (or projected), audible, haptic, connected, other?	22
	3. What vehicle driver alerting and warning systems would be most useful, to alert drivers in real-time of impending conflicts at intersections?	23
	4. What potential modes of connectivity, such as V2X (V2N, V2P, V2V, V2I . . .), cellular or Wi-Fi, for connecting vehicles, infrastructure, signals, and VRUs, would be most useful and effective to assure the greatest degree of accessibility for all intersection users?	25

Question Section	RFI Question	# Responses Directly to that Question
	5. What industry standards, best practices, processes, protocols, and interoperability requirements and capabilities are needed or best suited for the development of an effective intersection safety system?	23
	6. How can interfaces with traffic signal controllers and traffic management systems be best implemented? What data storage and curation of the system performance history (on-board, at the edge or in the cloud) are required?	20
	7. How can issues related to reduced visibility (e.g., night-time, low light, bad weather) be addressed and mitigated during both the development and deployment of an effective intersection safety system?	23
	8. Are there any existing research and development efforts, deployments, or pilot demonstrations underway that aim to provide some or all of the capabilities described in this RFI?	23
(C) Human Factors and Performance Measurement	1. What human behavioral considerations are most important in the implementation of an intersection safety system to ensure maximum VRU and driver compliance with the warnings and alerts provided?	18
	2. What are the most relevant human factors, cognition and human-machine interface (HMI) considerations for both VRUs and drivers to ensure the maximum efficacy of an intersection safety system?	16
	3. What metrics, key performance indicators, and measures of success are important for determining the performance and efficacy of an intersection safety system?	22
	4. How would testing and validation of an intersection safety system best be accomplished before full system deployment at active intersections?	20
	5. How can a testing and validation plan be devised that would balance testing and development safety with the ultimate real-world performance of an intersection safety system?	20
	6. What performance data would be required to validate the testing and efficacy of an intersection safety system, and how could that performance data be generated?	15
	7. What measurement and statistical approaches are applicable to real-time decision-making at intersections? How can decision or warning errors be minimized (e.g., through reducing false positives and/or false negatives)?	15
(D) Development Costs and Time to Deployment	1. What is the potential schedule and cost to develop an effective intersection safety system? What are the potential future hardware and software "stack" costs for a system that can be deployed at the scale of (for example) 100,000 commercial installations after 3-5 years of development?	15

Question Section	RFI Question	# Responses Directly to that Question
	2. What equity considerations factor into the potential testing, implementation, and deployment of an effective intersection safety system?	16
	3. What team composition of development, commercialization and deployment partners would be required to achieve the successful commercialization and deployment of such a system?	19
	4. For what proportion of intersections (signalized and/or unsignalized) would such a system be well-suited? What characteristics or measures are important in determining whether a specific intersection is well-suited for the implementation of an effective intersection safety system? How could such a system be further developed or adapted for use in rural areas?	17
	5. What are the installation, calibration, training, maintenance, and operating considerations for deployment of such a system across its full life-cycle by a range of potential end-users, including State, local, Tribal and territorial DOTs, cities and towns?	14

3 General Technical Considerations

The RFI presented seven (7) questions which sought to collect information on general technical considerations regarding enhancing the safety of vulnerable road users at intersections. For the purposes of this report, the technical responses to these questions have been categorized into five main topics including (1) AI, Machine Vision, and Sensor Fusion Technologies; (2) Sensor Types for Detection and Perception; (3) Data Considerations; (4) Considerations for Real-Time Applications and (5) Other Technical Considerations. Most of the information presented on this topic were obtained from responses from vendors, academic institutions, State/Metropolitan Planning Organization (MPO)/City/Local agencies, and other transportation organizations. A few private citizens also provided input on this topic. Note that although some responses did not provide direct answers to questions in the RFI, they did provide information which are categorized under the five topic areas. The summary presented in this chapter includes emerging/available technical capabilities and/or solutions, insights about technologies, and thoughts, concerns, and suggestions that pertain to general technical considerations.

3.1 AI, Machine Vision, and Sensor Fusion Technologies

A substantial number of responses provided information on AI, machine vision, and sensor fusion technologies that can be used to improve or enhance the safety of pedestrians, bicyclists, and other vulnerable road users at or near roadway intersections. The AI, machine vision, and sensor fusion technologies discussed in these responses range from technologies which are still in their conceptual stage of development to technologies which are readily available on the market for deployment. Additionally, other discussions focused on general considerations in the use of these technologies. Overall, responses advocated for the use of AI, machine vision, and sensor fusion technologies and highlighted their ability to offer new opportunities for enhanced detection, classification, and localization to improve safety for pedestrians, bicyclists, and other vulnerable road users at or near roadway intersections. The following bullets summarize relevant responses pertaining to this topic.

<u>Emerging and Readily Available AI, Machine Vision, and Sensor Fusion Technologies</u>

- AIWaysion has a solution called the Mobile Unit for Sensing Traffic (MUST). According to AIWaysion, the MUST is a comprehensive sensor fusion and edge computing device with all-in-one sensing, analysis, and communication capabilities. The company has also developed several impact preprocessing algorithms to help address the challenge of detection under low light and other low visibility conditions.

- Smart Roadside Unit (SmartRSU) is an emerging technology that can enhance machine-based decision. SmartRSU combines communication with significant edge processing capability to support processing sensor data to identify and track the movement of objects, predict movement, and identify potential conflicts or crashes. This technology is being developed by the Institute of Automated Mobility in Arizona.
- Velodyne LiDAR has Bluecity, an AI software that combines AI (deep learning) and LiDAR to create “actionable road usage and safety information”. The company states that their system “reliably detects all road users in any weather or lighting condition without raising privacy concerns” and has the capability to analyze near misses. Furthermore, their system classifies pedestrians, cyclists, passenger vehicles, buses, trucks, and some vehicle subclasses. They intend to further develop classification of micro mobility devices.
- Velodyne LiDAR also has the Intelligent Infrastructure Solutions (IIS) which includes VLP-32 LiDAR sensors, edge processor, perception software, software application layers (e.g., digital twin, traffic actuation, V2X integration), communication capabilities, and data telemetry (e.g., user dashboard, APIs, communication with traffic controller). The system leverages embedded Graphic Processing Unit (GPU) processing to “convert raw LiDAR data into traffic metadata in real-time at the intersection without requiring high bandwidth network infrastructure or costly cloud computing.”
- Robert Bosch LLC has cameras embedded with AI neural networks. The company states that the system detects vehicles and vulnerable road users at a 95% accuracy and is effective under all weather and lighting conditions including in high wind, heavy rain, snow, daytime, and nighttime.
- Robert Bosch LLC is developing technologies that will enable bicycles to broadcast their trajectory as a V2X message, agnostic of the broadcasting communication technology.
- Intel has an opensource OPENVINO software framework, coupled with on-premise edge computing. The company stated that the software is well-suited for managing the computing resources needed during inferencing to perform AI classification in real-time. It is suggested that this software framework works with all major opensource AI classification models.
- Intel stated that its Geti software framework has the capability of bringing together five steps of AI model training into a single workflow. The five steps include data collection, data labeling, model selection and training, model optimization, and deployment.
- Derq USA Inc. has developed an analytics platform that aggregates data from various sources, runs video analytics, sensor fusion, and behavior prediction algorithms powered by AI to detect, track, classify, and predict the intent of surrounding road users in real-time. Additionally, they have developed a unified representation concept, for which it was granted a patent (Aoude et al., Derq Inc., Early warning and collision avoidance, US 10,565,880 B2, 2020-02-18) and which enables greater performance in detecting, tracking, and classifying road

users by using multiple types of sensors and redundant (overlapping) sensor views.

- Some respondents advocated for the use of deep Learning models, such as You Only Look Once version 4 (YOLO4), which have been proved to detect and classify objects in video streams.
- According to the Institute of Automated Mobility, vehicle path prediction can be done by using deep learning algorithms such as Long Short-Term Memory (LSTM) or simple extrapolation along the normal roadway paths.
- One company has a collection of ML devices and a software development kit that brings computer vision to internet protocol cameras." The company stated that this could allow the DOT to enable ML features like object detection using existing intersection camera technology.
- National Electrical Manufacturers Association (NEMA) stated that it, together with its member companies, continues to invest in the research, development, and commercialization of Cellular Vehicle-to-Everything communication technology ("C-V2X"). This innovative communication technology is expected to play a significant role in enabling increased vulnerable road users' safety.
- According to the University of Michigan, Ann Abor, there are two main approaches for sensor fusion: (1) sensor fusion on the raw data level and (2) sensor fusion on the object level. There are multiple sensor fusion methods that range from simple Kalman Filters to Dynamic Occupancy Grid Maps and ML-based systems, as well as hybrids of these methodologies.

General Considerations in the Use of AI, Machine Vision, and Sensor Fusion Technologies

- Vision-based systems with AI are advancing rapidly in their ability to classify various types of vulnerable road users. Additionally, wireless communication systems enable vulnerable road users to broadcast their types (pedestrians, scooter riders, wheelchair users, people with hearing disabilities, or cyclists traveling in a platoon, etc.). The number of classes that can be reliably distinguished with machine vision depends on the training data for the neural network and the size of the network.
- Some respondents, such as Kapsch, were of the view that the use of AI deep learning is the only proven method of detection at an intersection that could provide effective safety messaging with minimal latency. However, as mentioned by the University of Michigan, Ann Arbor, problems could arise when something that the deep neural network has not been trained for is encountered, and currently there is no method to ascertain that they perform correctly in all situations.
- Although sensor fusion has a cost advantage since cheaper sensors can be selected, some respondents such as the Center for Urban Informatics and Progress at University of Tennessee expressed the need for the corresponding AI algorithms to be powerful and robust.
- LiDAR and cameras can effectively detect vulnerable road users, but the AI/ML components of the systems need improvement to be able to consistently and

accurately differentiate between the types of vulnerable road users (e.g., pedestrians, bicyclists, wheelchair users, etc.).

- A respondent suggests that Bayesian reasoning techniques are natural candidates for coping with the inherent uncertainty associated with predicting vulnerable road users' trajectories. According to the respondent, these techniques have performed well in predicting trajectories of all types of vulnerable road users.

3.2 Sensor Types for Detection and Perception

The RFI sought to obtain information on existing and emerging sensor technologies that could potentially be used to develop perception systems to provide a full field of view under all lighting and weather conditions with adequate redundancy. Information regarding resolution, bandwidth, latency, power consumption, and cost considerations were of particular importance to the RFI. Based on the responses, a comparison of the sensor types for detection and perception was made and is presented in **Table 2.** For each sensor type, a list of advantages and disadvantages of the sensor gathered from the responses are shown. It is also worth noting that the attachment to the response from the Texas Department of Transportation titled *Synthesis of Automated Pedestrian Data Collection Technologies* (Haddad et al., 2022) provides a comprehensive analysis of new roadside technologies that can assist in efforts to detecting pedestrians. This attachment discusses the benefits and challenges of sensor types from various vendors deployed by select states and local agencies. Relevant information from the attachment has been included in **Table 2**.

Table 2. Comparison of Sensor Types

Sensor Type	Advantages	Disadvantages
LiDAR	• Works in low light conditions, including at night. • Works in various weather conditions (e.g., snow, rain). • LiDAR based systems can help promote equity in pedestrian-detection systems since it does not differentiate between skin tones. • Creates a 3D representation that has high resolution. • Can accurately measure distance between objects, velocity, and size. • Can distinguish between objects that are close together. • Can detect slow moving and stationary objects. • Can monitor multiple moving objects of various sizes simultaneously.	• Higher cost relative to other sensors. • Newer technology that is less widespread. • More commonly used for collecting roadway data and has not been widely applied to pedestrian detection. • High cost of gathering, storing, and processing more refined/granular pedestrian information. • There are not many vendors on the market. • Agencies are reluctant to invest due to lack of experience with the technology and its accuracy. • The number of classes that can be distinguished is more limited due to lack of color detection and the resolution of the sensor, compared to cameras.

Sensor Type	Advantages	Disadvantages
	• Does not require re-calibration, which reduces set-up, installation, and calibration time/resources. • Inherently protective of privacy, as this sensor type does not record identifiable images of road users. • Can detect at a far distance (some upwards of 200 m).	
Radar	• Outperforms other sensor types at far distances; has an extended range. • Can accurately detect vehicle speed and position without the need for calibration. • Inherently protective of privacy, as this sensor type does not record identifiable images of road users. • Has better inclement weather performance compared to cameras and LiDARs as it works based on radio waves rather than light. • More cost effective than LiDAR-based solutions, with costs steadily falling. • Able to detect pedestrians at distances greater than 160m with a precision of approximately 0.5m.	• Performs best when objects are moving toward or away from the sensor, which is not always the direction of vulnerable road users or vehicles. • The automotive industry has largely moved to 76 GHz radars but currently only 24 GHz radars with a very narrow bandwidth are allowed to be deployed in the infrastructure. • The number of classes that can be distinguished is more limited due to lack of color detection and the resolution of the sensor, compared to cameras.
Camera/Video	• Provides higher level of detail, compared to radar and LiDAR, that can be used to differentiate types of vulnerable road users. • Widespread technology. • Delivers the best object classification performance and the best angular resolution. • Covers a larger area where pedestrians are not confined to a narrow path, such as people crossing midblock. • Raw video files can be used for safety assessment. • Can be integrated with signal detection equipment. • Calibration can be performed automatically with only one variable needed, which is the mounted height of the video sensor. • Agnostic to the method of connectivity. It can be integrated into independent devices that then transmit the alerts with reduced latency. • May be used for several use cases, avoiding the need to deploy multiple	• Some cameras create a 2D representation (rather than 3D). • Performs poorly in low light and adverse weather conditions. • Weather (fog, glare) can thwart devices. • Long picture readout times needed for high-resolution images. • Long-term deployment feasibility heavily depends on cost, power source availability, and number of cameras. • High recurring costs for data storage and processing. • Not protective of privacy, as this sensor type records identifiable images of road users.

Sensor Type	Advantages	Disadvantages
	single purpose sensors at an intersection.	
Infrared	• Works in any lighting conditions, including low light conditions. • Performs well in some weather conditions, such as rain and fog. • Lower equipment costs compared to other methods.	• Cannot determine the number of objects detected. • Cannot distinguish different types of vulnerable road users. • Environmental conditions such as heavy rain and snow may trigger false detections. Worse performance at temperatures approaching that of a human body, due to difficulties distinguishing people from the background. • Poor performance on wider facilities due to a higher incidence of occlusion. • Cannot capture pedestrian roadway crossings and vehicular intersection turning movements. • Fall under International Traffic in Arms Regulations (ITAR). • Currently expensive relative to some other sensor types.
Thermal Imaging	• Detects multiple user types. • Tracks paths and routes within the sensor area. • Counts multiple methods of travel. • Can detect in harsh weather conditions. • More accurate than video technology in dark/nighttime conditions and the presence of occlusion.	• Not tested extensively. Needs more testing. • Limited operating temperatures of the equipment; could struggle when the surrounding areas are warmer than a human body. • Lack of user familiarity. • Limited detection range. • Costly. • Accuracy is not well established.
Fiber Sensing	• Can detect any presence on the road by picking up the vibrations in the ground caused by vehicles, pedestrians, cyclists, and even small animals.	• Still in early stages of research.
Wi-Fi and Bluetooth Sensing	• Captures the hardware media access control (MAC) address of discoverable mobile devices. • Critical supplement to vision-based detection, especially for the detection and tracking of vulnerable road users in non-line-of-sight environments and dark conditions.	• Only senses discoverable mobile devices. • Often limited by the penetration rate.

Additionally, some responses provided insights, thoughts, concerns, and suggestions that pertain to sensors for detection and perception. The responses are summarized as follows.

- Combining inputs from multiple sensors (video, radar, LiDAR etc.) improves accuracy but may not be cost effective. This presents a tradeoff between cost and performance. For example, combining data from radars, which are sensitive to speed, with the vision ability of video cameras is effective in distinguishing between vehicles, bikes, and pedestrians, but may present some cost challenges. However, if data from low-cost sensors are fused together, this could potentially overcome this challenge.
- Some respondents suggested that during preliminary implementations, it may not be necessary to differentiate specific types of vulnerable road users (e.g., wheelchair, scooter) and are of the view that detecting vulnerable road users as a whole can provide safety benefits.
- Utilize already installed sensors (radar, LiDARs and cameras) in urban areas and along highways. Connecting these sensors to V2X roadside units can allow inclusion of non-connected road users in the V2X ecosystem.
- Some respondents suggested that a rating system for ADAS and ADS systems based on ability to accurately detect and respond to vulnerable road user is developed. Mandate inclusion of ADAS and ADS systems that meet basic safety standards in new vehicles.
- Other respondents advised the DOT to focus on vehicle-based detections and collision avoidance technology since they are more versatile.
- The most basic perception capability needed at the intersection is the ability to distinguish travel modes of detected traffic (e.g., pedestrians, bicyclists, scooters, trucks, passenger vehicles, etc.). Multiple commercially available detection technologies provide this capability, and this capability can provide a starting point for a vulnerable road user warning system.
- Use low size, weight, power, and cost (SwaP-C) mmW radars at intersections to detect, classify, localize, and track vulnerable road users both in day and night and in all weather conditions.
- Some respondents expressed concern that many intersection technologies focus on using existing sensors, but these are designed to detect vehicles, not vulnerable road users.
- One company has an ML monitoring system that uses sensors to capture vibration and temperature data and is equipped with gateways to automatically transfer data to the cloud. According to the company, this system could “potentially reduce the need to purchase more expensive physical vehicle detection equipment.” the company also has a software that can identify objects, people, text, scenes, and activities in images and videos.
- To improve vision-based detection, it is suggested that data is pre-processed (e.g., using de-hazing, de-noising in low light conditions) to reduce the effects of weather, glare, and low-light conditions. Also, to address the challenge of positional accuracy, real-time kinematic (RTK) positioning was mentioned as one viable positional enhancement solution.

3.3 Data Considerations

As stated in the RFI, it is anticipated that developers of vulnerable road user and vehicle warning systems will benefit from the collection of large amounts of data from the operation of a real-world roadway intersection for the development, training, validating, and testing of machine learning (ML) algorithms. Further, this data could be processed, fused, and shared to accelerate the parallel development of effective solutions. In that regard, the RFI presented questions which sought information on emerging and available technologies for data analysis, data handling and storage, data privacy protections, and data transfer capabilities best suited to provide the required machine vision and perception for an effective intersection safety system. Summarized below are data considerations which include insights, thoughts, concerns, and suggestions gathered from the responses.

<u>Emerging and Readily Available Technologies</u>

- Iteris has a platform with year-round multimodal data that are automatically collected by sensors. Planners can use this platform to identify where dollars can best be spent to prioritize projects.
- Velodyne LiDAR publishes their vulnerable road users' data in real-time through an application programming interface (API). Other safety collaborators/systems can access this data (e.g., Commsignia RSU, Verizon Virtual RSU, pedestrians warning visual/audio beacons).
- AIWaysion developed in-house AI algorithms using YOLO V5 for object detection and Deep SORT for object tracking. The algorithms are trained with publicly available datasets (e.g., COCO and TinyPerson) and their own labeled datasets for specific types of road users with field data collected by the MUST devices.
- One company has a collection of services which can provide data storage, data mining, and data analytics to deploy highly scalable and centralized data lakes that store intersection data and create useful insights.

<u>Other General Data Considerations</u>

- Crowdsourced imagery data (e.g., dashcams which make it more feasible in rural areas) can help in real-time analysis, incident detection and pavement condition analysis (e.g., fading crosswalks, streetlight outage).
- Use of Data-Driven Safety Analysis (DDSA) techniques can inform State, local, Tribal, and territorial DOTs to make more targeted implementation of infrastructure investments that improve safety and equity.
- Incorporate objects detected by vehicle front and rear cameras into V2X data flow to improve the detection of vulnerable road users and allow for cross-comparison of objects detected by infrastructure-based sensing, vehicle-based sensing, and V2X.
- Develop data reporting and sharing protocols for vulnerable road users and vehicle detection at intersections. Data standards should be akin to DOT's Work Zone Data Exchange (WZDx) protocol.

- Deep learning with supervised learning requires large amounts of annotated data. Recent self-supervised learning techniques reduce annotated data requirements.
- Sensor Data Sharing Messages (SDSMs) could also be transmitted to vehicles after detecting vulnerable road users if the equipped intersection is also outfitted with a roadside unit (RSU).

3.4 Considerations for Real-Time Applications

The RFI envisages that a vulnerable road users and vehicle intersection safety system will require capabilities such as real-time data sharing, “crowd-sourced” vehicle-based real-time imaging and information sharing, real-time data analysis, real-time safety and warning alerts, and real-time decision-making. As such, questions were posed in the RFI which sought to garner information regarding the availability of real-time technological capabilities. Real-time applications related to machine-based decision making, machine vision and perception, path prediction, and group learning were of particular importance. Summarized below are emerging/available real-time application technologies and other considerations which include insights, thoughts, concerns, and suggestions gathered from the responses.

Emerging and Readily Available Technologies

- Velodyne LiDAR has a system that uses embedded GPU processing to convert raw LiDAR data into traffic metadata in real-time at the intersection, which saves on costly cloud computing and does not require high bandwidth network infrastructure. However, GPU processing is not inexpensive either.
- Cellular network technologies have evolved to the point where they can deliver latency performances appropriate for time-sensitive applications.

Other Real-Time Application Considerations

- Edge computing has many advantages including low latency, privacy protection since it does not require raw data storage or transfer, and implementation and scaling ease due to the lack of substantial infrastructure support requirements (e.g., high bandwidth internet for data transfer).
- On-premises edge computing in the roadside unit is needed for performing near real-time computation and to create a digital twin of the intersection or road segment.
- Infrastructure needs sufficient computing power to process the data, which includes detection, classification, sensor fusion, and tracking of objects with a high refresh rate of ideally 10 Hz or better, according to the University of Michigan, Ann Arbor.
- Extend real-time V2X to micromobility vehicles to notify drivers of potential safety hazards.

- For pedestrian tracking, coupling a wearable application with Ultra-Wideband (UWB) beacons installed at the intersection provides a simpler, less expensive alternative way of detecting vulnerable road users.

3.5 Other Technical Considerations

This section presents a summary of responses which could not be directly affiliated to any of the questions under general technical considerations but were nonetheless relevant to the overall objective of the RFI and can be categorized as technical considerations. It should be noted that most of the responses from private citizens were found to belong under this topic. A general trend was observed in the responses of private citizens. Most of these responses suggested that the DOT should direct its efforts and resources towards improvements to the existing roadway infrastructure, focusing on physical improvements such as road diets, enhance crosswalk visibility, relocation of traffic signal heads, traffic signal retiming, turn restrictions, installation of bicycles lanes, and daylighting intersections, among others. Further, some responses referred the DOT to examples of successful case studies from European countries. A recurring example in the responses was the Dutch Intersection design. The following are other technical considerations gathered from the responses.

- Consider the following technologies that have reached commercial viability:
- Speed limiter technology to cap vehicles speeds against posted speed limits on roadways. Maximum speed could be adjusted based on presence of and number of vulnerable road users.
- Ignition interlock system to prevent impaired drivers from operating vehicles.
- Contrary to the RFI requirement of maintaining baseline performance of the intersections, implementation of ITS systems may require the adjustment of vehicular speed, throughput, and capacity of an intersection. Appropriate trade-offs between efficiency and safety performance should be the goal.
- It is anticipated that infrastructure owners and operators (IOOs) will be reluctant to move out of their traditional role of providing roadway infrastructure and information for drivers to make informed decisions, to a role of being involved in the driving task more deeply.
- Regulate weight of vehicles and design features. An IIHS study shows for vehicles traveling above 20mph, SUVs are more likely to cause death compared with sedans.
- Latency, Global Positioning System (GPS) accuracy, infrastructure required for connectivity, and interoperability between systems are the factors that should be considered before selecting the CV communication technology (e.g., V2X, cellular, Wi-Fi).
- Provide Leading Pedestrian Intervals (LPI) for traffic signals in densely settled areas. Retime traffic signals should prioritize vulnerable road users and provide pedestrian actuated signals.

- Be cautious about the increasing complexity of the system and ergonomics. Focus on implementation of simple technologies and algorithms.
- Provide long cycle length at intersections with high volume of vulnerable road users. Permissive left-turn movements lead to severe crashes. Also, focus should be put on intersections with frequent occurrence of vehicular red light running.
- Emphasize the importance of lighting as a key element to enhancing safety and visibility at intersections. Smart lighting systems can utilize cameras/sensors to report information such as functionality and incidents.
- Implement vehicle safety performance standards based on crashes and fatalities per 100 million miles of travel.

4 System Installation and Deployment

In pursuit of Vision Zero, many agencies are looking to utilize new data sources leveraging connected vehicles and the Internet of Things (IoT) to move from reactive data decisions to proactive data decisions based on identifying and addressing unsafe conditions before crashes occur. This approach is consistent with DOT's Safe System Approach.

The RFI presented eight (8) questions which sought to collect information on types of alerting and warning methodologies and systems, modes of connectivity, and relevant industry standards and considerations for interoperability for potential intersection safety systems. Information presented in this section were obtained from responses from vendors, academic institutions, State/ Metropolitan Planning Organization (MPO)/City/Local agencies, and other transportation organizations. Few private citizens also provided input on these topics. However, the majority of responses from private citizens supported traditional safety countermeasures and policies, and not a necessarily a technological solution.

4.1 Suggested Use Cases / Scenarios

Respondents suggested strategies for identifying use cases as well as specific applications that could benefit from an intersection safety system. A key theme was that respondents supported the development of various targeted strategies aimed at mitigating risk for vulnerable road users rather than attempting to develop a one-size-fits-all intersection safety system. Depending on the context, multiple strategies may be appropriate, so it is important to maintain flexibility for the practitioner. Some responses suggested identifying use cases based on a preliminary safety assessment and/or a site survey during both peak and off-peak hours to determine the feasibility and potential impacts (e.g., power source, sensor availability, connectivity, vulnerable road user behavior). Candidate sites for surveying include signalized intersections with high incident rates and signalized intersections with long cycle lengths where vulnerable road users are likely to cross against the signal.

In general, many responses advocated for improved intersection design and policies, and not necessarily the development and implementation of vulnerable road user and vehicle warning systems. Several comments were received about reducing lane width, reducing turning radii, reducing vehicle sizes, removing right turn on red, removing the permissive left turn, and mandating speed governors to improve intersection safety. Another common comment received was in favor of converting more intersections to roundabouts to reduce the complexity of pedestrian/vehicle interactions. However, specific applications mentioned in the responses that could be addressed by an intersection safety system relied on real-time detection of imminent conflict. Examples of identified intersection safety use cases and applications are listed in **Table 3** and **Table 4**, respectively.

Table 3. Identified Intersection Safety System Use Cases

Intersection Type	Suggested Use Case
Signalized	Permissive left turn (i.e., left turn on green)
Signalized	Red-light violation
Signalized	Right turn on red
Signalized	Long Cycle Lengths (>60 seconds)
Unsignalized	Roundabouts
Signalized / Unsignalized	Transit Stops
Signalized / Unsignalized	School Zones
Signalized / Unsignalized	Work Zones

Table 4. Identified Intersection Safety System Applications

Intersection Type	Suggested Application
Signalized	Red-light Running Detection
Signalized	Pedestrian in Crosswalk Detection
Signalized	Illegal Crossing Detection
Signalized / Unsignalized	Speeding Detection
Signalized / Unsignalized	Transit Stop Boarding / Alighting Notification
Signalized / Unsignalized	Work Zone Intrusion Detection
Signalized / Unsignalized	Wrong Way Driving Detection
Signalized / Unsignalized	Near-miss analysis

4.2 Considerations for Alerts / Warnings

There are many considerations about alerts, including the modality, format, and timing. The three main modes of alerts include audio alerts (audible tone or “chirp”), visual alerts (display or interface), and haptic alerts (vibrations). Respondents tended to support intersection safety systems that incorporated a combination of warning types for vulnerable road users. Regardless of the alert type, timeliness of the alerts is critical for vehicles and vulnerable road users to have time to respond. Additionally, the amount of information that is provided through these modes and the frequency of alerts needs to be considered. Warnings must be delivered in a way that reinforces safe behavior and optimizes user attention, without risking alert fatigue through too high a quantity or complexity of warnings and alerts.

Personal devices were recommended for delivery of alerts from both a cost and functional perspective, considering the ubiquity of smart phones these days. However, one challenge stated is the specificity of the alert on a personal device. Unless the VRU registers the device with the infrastructure in some way, it may be difficult to send a warning to a specific user. While a stationary alert device in the infrastructure would be highly visible, it would be unspecific.

Table 5 provides a summary of the three alert types and respondents' perception of each.

Table 5. Identified Intersection Safety System Alert/Warning Types

Alert/Warning Type	Advantages	Disadvantages	Example Use case
Haptic	• Not disruptive to others.	• Difficult to distinguish alerts.	A steering wheel that provides a vibratory cue when the vehicle is approaching an impending conflict at an intersection.
Audio	• Effective in attracting attention.	• Hard to hear in a noisy environment. • Not suitable for the hearing impaired	An onboard device that sounds a warning tone when the vehicle is approaching an impending conflict at an intersection.
Visual	• Effective for conveying complex information (such as spatial information).	• Distracts users' eyes from the scene. • Not suitable for the visually impaired.	An onboard display that flashes a warning when the vehicle is approaching an impending conflict at an intersection.
Standard Messages via Mobile Device	• Most adults own smartphones.	• May not see the message in a timely manner.	A user receives a warning message on their mobile device when approaching an impending conflict at an intersection.

4.3 Modes of Connectivity

There was consensus that connected vehicle technology and V2X communications will likely play a pivotal role in any future intersection safety and warning system where vehicles communicate with both infrastructure and vulnerable road users. Respondents mostly supported the pairing of infrastructure-based perception systems from Section 3.2 with V2X infrastructure to communicate this information to vehicles and drivers to further prevent non-line-of-sight crashes. One promising use case for V2X technology for vulnerable road users is vehicle-to-pedestrian (V2P) communication. V2P applications would allow for communication between vehicles and pedestrians, bicyclists, and other vulnerable road users to exchange information to enable collision alerts or warnings to drivers and, in some cases, pedestrians.

However, respondents cited the many challenges facing V2X, including regulatory uncertainty, insufficient spectrum resulting from the 2021 Federal Communications Commission (FCC) ruling to open up the 5.9 GHz Safety Band, and the potential for harmful interference from unlicensed devices. Many cited the need for more dedicated spectrum to allow intelligent intersection infrastructure to function without interference. With only 30 MHz now dedicated to ITS uses in the 5.9 GHz range, additional spectrum is needed to allow the full capabilities to be maximized.

Several respondents highlighted the promise of a cellular network-based approach (e.g., cellular 5G network with multi-access edge computing (MEC)). Using Virtual RSUs (vRSU), detected data can be backhauled over a wireless network to the MEC for processing and eventual delivery of an alert. As mentioned in several responses, Verizon has recently partnered with Honda, Nissan, Cisco, AI Wayison, TELUS and Stellantis to further demonstrate the ability for MEC to support V2X technology.

In addition to Cellular, Dedicated Short-Range Communications (DSRC) and Wi-Fi, Ultra-wideband (UWB) technology was also commonly cited due its high-precision localization. For example, adding UWB beacons at the corners of intersections could detect movement outside of the crosswalk and signal corrective action to help even vision impaired pedestrians.

Note that it should not be assumed that data will move only wirelessly. Backbone fiber optic cable is required to create the broadband network to support robust network enabled road safety and advanced capabilities.

Table 6 lists the connectivity modes identified in the responses.

Table 6. Identified Intersection Safety System Connectivity Modes

Mode of Connectivity	Advantages	Disadvantages
DSRC	• Low latency • Extensively tested	• Not cost effective (requires additional-DSRC infrastructure) • Insufficient dedicated spectrum.
Cellular (LTE, 5G)	• High Range • Cost Effective (uses existing cellular infrastructure)	• Latency can be a limiting factor • Not extensively tested
Wi-Fi	• Fast performing • High bandwidth	• Limited coverage • Difficult to provision and set-up devices
UWB	• UWB chip embedded in smart phones • Allows high-precision localization	• Not extensively tested

4.4 Standards and Considerations for Interoperability

The development and use of standards are critical for ensuring compatibility and interoperability. Interoperability will be more critical than ever before with the implementation of connected and automated vehicle systems as system interdependencies increase, not only in number but also in complexity. Standards and architectures must continue to evolve to reflect technological advancements and maintain the required backward compatibility and interoperability.

Several existing industry standards currently benefit V2X communications. Respondents expressed the industry standards that they think will be best suited for the development of an effective intersection safety system, including the 3GPP Release 14, IEEE 1609, SAE J2735 (specifically the Personal Safety Message (PSM)), and SAE J3224, which have already proven their effectiveness. Additionally, interoperability standard IEEE 2945, which simplifies interactions between different pieces of technology, was referenced regularly.

For systems that integrate physically with traffic signal control, it was recommended that standard protocols like National Transportation Communications for Intelligent Transportation System Protocol (NTCIP) be used, with the caveat that NTCIP interfaces were not designed for multiple/concurrent system interfaces and present both operational and cybersecurity challenges. A need for modernizing these interfaces was expressed for both greater publication of localized datasets as well as manageable control over external systems' desired inputs to traffic control. In addition to protocols, APIs were also frequently mentioned for implementing various interfaces with traffic signal controllers and traffic management systems as they allow for a broad range of public and private sector needs to be met, such as effective data storage and curation.

Others mentioned revisiting the design standards and practices in the Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD) to ensure protection of vulnerable road users, the safe testing and integration of automated vehicle technology, and appropriate use of variable message signs. The Infrastructure Investment and Jobs Act directs DOT to update the MUTCD by no later than May 15, 2023, and at least every 4 years thereafter to promote the safety, inclusion, and mobility of all road users.

Table 7 lists the Intersection Safety System relevant industry standards identified in the responses.

Table 7. Identified Intersection Safety System Relevant Industry Standards

Organization	#	Name	Purpose	Status
SAE	J2945/9	Vulnerable Road User Safety Message Minimum Performance Requirements	Provides safety message minimum performance requirements between a Vulnerable Road User and a vehicle.	Issued
SAE	J2735	V2X Communications Message Set Dictionary	Specifies a message set, and its data frames and data elements, for use by applications that use V2X communications systems.	Revised
SAE	J3224	V2X Sensor-Sharing for Cooperative and Automated Driving	Defines message structure, requirements, and information elements to describe detected objects to facilitate sensor sharing to enable RSUs and V2X1 vehicles to share information about their localized driving environment.	Issued
IEEE	1609 family	Standards for Wireless Access in Vehicular Environments (WAVE)	Defines the architecture, communications model, management structure, security mechanisms and physical access for wireless communications in the vehicular environment.	Stabilized
IEEE	P2945	Technical Requirements for Face Recognition Systems	Specifies an architecture and defines the functional, performance, and security requirements for face recognition systems.	Work in progress
3GPP	Release 14	3rd Generation Partnership Project	Specifies LTE telecommunications technologies, including radio access, core network and service capabilities for V2x services.	Issued
NTCIP	1218	Object Definitions for Roadside Units	Identifies and defines how a management station interfaces with a roadside unit, including receipt and transmittal of Radio Technical Commission for Maritime Services (RTCM) GPS correction messages.	Issued
ISO	26262	Road vehicles – Functional Safety	Defines functional safety for automotive equipment applicable throughout the lifecycle of all automotive electronic and electrical safety-related systems.	Issued
ISO/PAS	21448	Road vehicles — Safety of the Intended Functionality	Provides a general framework to ensure the safety of the intended functionality (SOTIF).	Issued
FHWA	-	MUTCD	Provides minimum standards (messages, locations, shapes, sizes and colors) for the use of uniform traffic control devices nationwide.	Stabilized

4.5 Other Installation and Deployment Considerations

Summarized below are other installation and deployment considerations mentioned that, while not directly affiliated to any of the questions, were nonetheless relevant to the overall objective of the RFI.

- Different road and intersection layouts will require different sensor field of view positioning. As a result, over specifying unit geometry layout may be restrictive.
- Depending on the deployment region, the existence of traffic poles with rigid mast-arms capable of supporting rigid sensor mounting may be an issue if span-wire solutions have been preferred. Ensuring existing infrastructure is updated and future ready will go a long way to reducing the complexity of installation.
- Remote monitoring of system health notifications will be particularly important also for the detection of system faults which could affect the integrity of transmitted information (sensor outages, processor health, etc.)
- Compared to more traditional in-ground presence detection systems such as inductive loops or pucks, pole-mounted perception systems require less frequent physical maintenance and replacement, particularly in areas which experience freeze-thaw pavement issues.
- Unsignalized intersections may not have electric power for the equipment available and connectivity to a back-end might only be through 4G or even lower bandwidth connections. Power requirements may be able to be satisfied with solar panels.
- Public education (e.g., demonstration events) should be emphasized before deployment to inform the public about changes in existing technology and environment.
- Data gathered by the infrastructure and traffic participants could be used to support other goals areas than just safety, including to improve traffic flow, get vehicle counts by direction to allow TMCs to precisely estimate demand, optimize signal timing across the network, analyze traffic hazards, etc.

5 Human Factors and Performance Measurement

The RFI presented seven (7) questions which sought to collect information on human factors and performance measurement regarding enhancing the safety of vulnerable road users at intersections. For the purposes of this report, the technical responses to these questions have been categorized into three main topics including (1) Human Factors; (2) Evaluation, Testing, and Validation Considerations; and (3) Potential Performance Measures. Note that although some responses did not provide direct answers to questions in the RFI, they provided information which are categorized under the three topics. The summary presented in this chapter includes insights on human factors relevant to an intersection safety system, equity considerations, considerations for system evaluation, validation, and testing, and potential performance measures, focused mainly on accuracy/effectiveness and safety measures.

5.1 Human Factors

The RFI sought information on human behavioral considerations as well as human factors, cognition, and human-machine interface (HMI) considerations for both vulnerable road users and drivers to ensure maximum compliance with warnings and maximum efficacy of an intersection safety system.

Human Factors for Alerts/Warnings:

As mentioned by various RFI respondents, obtaining road users' attention at the appropriate time and via effective means is important for enhancing safety at intersections. But gaining their attention is a challenge, especially since they are operating in an increasingly distracting world with many connected devices, and different road users have different needs. Specific insights with respect to human factors for alerts/warnings include:

- Cognitive load is a key human factor for an intersection safety system. New alerts/warnings could increase cognitive load and the potential for distraction. Devices add to the complexity of urban mobility as well, especially for people who are vision impaired.
- While it is important to keep human cognitive load in mind and limit undue distraction when possible, it is also important to have alerts of various types to effectively reach different users, including multi-modal means of conveying safety warnings (e.g., ADS, C-V2X, and audio-visual alerts). For example,

AlWaysion developed both web and mobile based applications to support device management, data analysis and visualization, and communication with road users. They offer a light mobile app for general information dissemination as well as a web version with more detailed functionality for transportation agencies.

- Some respondents mentioned the importance of standardizing alerts/warnings for vulnerable road users and using existing standards as a foundation for alerting drivers. For example, Ohio State University mentioned that audio and visual alerts should be standardized by "a government body like DOT in the MUTCD," and having standardized audio-visual alerts at an intersection will help ensure that all intersection users can respond to safety alerts. On the vehicle side, P3Mobility argued that "DOTs should not prescribe how an ADAS/ADS responds to vulnerable road user proximity messaging." Instead, OEMs will develop their own alerting and response mechanisms that balance driver cognitive load and integrate with their overall vehicle design. OEMs are considering messaging standards (e.g., SAE J2735) in their design process to incorporate external sources of information for driver alerts.
- It is difficult to predict vulnerable road user paths due to their erratic nature, wide range of speeds, and tendency to not always follow traffic rules. Since vulnerable road user behavior can be inconsistent and unpredictable, this makes it difficult to deliver accurate alerts/warnings.
- Alerts need to be timely (i.e., allow enough time for perception and reaction), reasonably accurate (e.g., low number of false positives), and appropriately tuned for the severity of the warning. For example, according to Autotalks, only the endangering driver and vulnerable road user at risk should be warned, and a warning should not be issued more than 4 seconds in advance. As mentioned by Autotalks, the European New Car Assessment Programme (Euro NCAP) estimates it takes 1.218 seconds for a driver to make a decision with an additional 0.5 seconds to take action. Consequently, a driver should not be warned if the potential risk is closer than 1.719 seconds to prevent distracting attention from the risk.
- Warnings alone may not bring sizeable safety benefits. Control actions (e.g., automatic emergency braking (AEB), speed limiters, signal changes) can better protect vulnerable road users. For example, Equiticity mentioned that "technological requirements for the vehicle may have a more pervasive safety benefit than intersection technology." The North Central Texas Council of Governments advocated for prioritizing in-vehicle technology improvements (e.g., collision avoidance) over giving more information to vulnerable road users. Additionally, many private citizens mentioned focusing on driver behavior rather than vulnerable road user behavior for the greatest potential safety benefit.

<u>Equity Considerations:</u>

Many respondents emphasized the importance of equity when designing and implementing an intersection safety system, but few provided specific equity considerations. Vulnerable road user socio-economic status, connectivity and technology access (i.e., smartphone), race, and abilities/needs (e.g., wheelchair use) were a few potential equity areas mentioned. A few specific equity considerations that were mentioned are summarized below:

- One private citizen emphasized that “in order to be equitable, any solution for enhancing the safety of vulnerable road users at intersections must not require additional investment or cost on behalf of the vulnerable road user.”
- LiDAR vendors emphasized that LiDAR is privacy protective and can help promote equity, since it does not differentiate between skin tones.

5.2 Evaluation, Testing, and Validation Considerations

Many respondents provided general evaluation considerations in their response to this section of the RFI. Some also provided more specific testing and validation considerations. Evaluation, testing, and validation insights are summarized below:

- A handful of respondents expressed concern when the RFI mentioned that the goal is to prevent crashes “while facilitating normal traffic flows and vulnerable road user movements.” An intersection safety system that has no adverse impact on vehicle flows through intersections may overly limit the system’s ability to improve safety.
- There are tradeoffs between detection accuracy, latency, and cost. For example, while fusing inputs from multiple sensors (e.g., LiDAR, cameras, radar) is likely to improve detection accuracy, it is also likely to increase latency and cost.
- A phased approach is key for system testing and validation to ensure safety. This phased approach could start with testing in a virtual lab or simulation environment, then progress to controlled environment testing, and finally move to limited deployment testing on public roads, as suggested by Honda and Ohio State University. A systems engineering process (i.e., V-model) can be a useful approach for validation, as suggested by Ohio State University.
- Respondents mentioned the importance of having high-quality labeled ground truth data to validate and refine AI/ML models, including high fidelity location data of object-actors. For example, Velodyne LiDAR mentioned that the most dependable ground truth would be a video system real-time manual analysis; loops and physical count systems could also be effective for data comparisons. P3Mobility mentioned that system maintainers should routinely assess software/algorithm/model performance using a ground truth reporting device (e.g., OBU) to reconcile the system’s perception and alerting capabilities.
- It is expected that trained models will be updated during testing, validation, and evaluation. For example, Velodyne LiDAR mentioned that if performance issues are discovered during the evaluation process, their team can record and annotate the raw LiDAR data and use it to re-train the deep learning models, which can then be deployed remotely on all sensors.
- Numerous respondents mentioned that reproducing the traffic environment on a server as a digital twin could help track attributes of road users and predict traffic

safety risks. Some respondents from the private sector mentioned their specific approaches to creating and using a digital twin (e.g., Honda, Intel).

- According to P3Mobility, many partners bear some responsibility for system performance and its ability to forewarn of the presence of a vulnerable road user, including governments, hardware manufacturers, software developers, and system integrators. For example, according to P3Mobility, post installation calibration and testing should be conducted by the system integrator followed by acceptance testing conducted by (or on behalf of) the receiving government authority.
- A robust testing and validation plan includes many components. According to Velodyne LiDAR, in addition to performance criteria (e.g., classification accuracy), a test plan should include system hardware reliability, maintenance, calibration, and upgrade requirements as well as operations and maintenance costs. Michelin Driving Data to Intelligence (Michelin DDi) recommends building a robust testing and validation plan that compares performance between two groups of intersection safety systems: one equipped and the other unequipped.

5.3 Potential Performance Measures

The RFI sought metrics, key performance indicators, and measures of success that are important for determining the performance and efficacy of an intersection safety system. **Table 8** summarizes key accuracy/reliability performance measures as well as safety performance measures mentioned by RFI respondents.

Table 8. Potential Performance Measures Mentioned by RFI Respondents

Accuracy/Reliability Measures	Safety Measures
• Accuracy of detection and classification of road users • Accuracy of alerts • Accuracy of tracking and localizing objects • False positives, false positive rate • False negatives, false negative rate • Reliability measures (e.g., performance in various environmental conditions and times of day) • System latency	• Number/frequency of crashes, conflicts, crash severity, near-misses, injuries, fatalities • Post encroachment time (PET), time-to-collision (TTC), gap time, time advantage • Number/frequency of red-light violations • Number/frequency of safer driver behaviors - e.g., reduced lane changing, reduced speed, increased looking behavior of drivers and vulnerable road users to potential safety issues • Smoothness of driving measures - e.g., speeding, sudden acceleration, hard braking, hard steering • Change in vulnerable road user intersection crossing time and crossing delays

Other evaluation and performance measure insights are summarized below:

- Various respondents mentioned the need to break performance measures into components. For example, P3Mobility suggested two major performance components: 1) what information the safety system provides, and 2) what the vehicle operator does with the information, to help decouple the intersection safety system from the appropriateness of the use of its information.

- Generally, AI-enabled intersection safety systems are first assessed on their algorithm's performance (e.g., accuracy, number of false positives) during development and testing in a simulated or closed environment.
- Some respondents mentioned their minimum requirements for detection and classification accuracy. For example, Velodyne LiDAR has used the following minimum requirements for accuracy: 95% vehicle count accuracy and 80% pedestrian presence detection accuracy.
- Beyond algorithm performance, key safety performance measures mentioned include but are not limited to the number/frequency of crashes, near-misses, injuries, fatalities, and red-light violations, as well as smoothness of driving metrics, such as speeding, sudden acceleration, and hard braking. However, many of these safety measures require a before and after period of study.
- In addition to accuracy/effectiveness and safety performance measures, RFI respondents mentioned mobility, customer satisfaction, and other measures. These include, but are not limited to: compliance rate, wait time for vulnerable road users, system scalability and range, improved equity (no specific measures were mentioned), reduced stress level of vulnerable road users, and increased ability to stay within the crosswalk for vision-impaired pedestrians.
- Many of the safety measures mentioned require long-term studies before and after deployment. For example, according to Ohio State University, the "gold standard for evaluation" would be widespread system deployment in various geographical areas, evaluating safety at the intersection for a long duration prior to and post deployment.
- However, long evaluation timeframes are not always feasible. To help address this time concern, "as part of the Safe System approach, FHWA has noted the need to use proactive tools to identify and address safety issues at intersections. Towards that end, proactive approaches for evaluating treatments (such as analysis of conflicts using video analytics) that do not require the use of long-term (three to five years) collision data need to be more broadly applied," which the American Society of Civil Engineers (ASCE) mentioned in their RFI response. System benefits could be proactively estimated (e.g., estimated reduction in intersection conflicts, predicted crash frequency).

6 Development Costs and Time to Deployment

The DOT acknowledges in the RFI that beyond the cost of construction of an intersection safety system, there may be significant additional ‘soft' costs including permitting, installation, testing, calibration, operation, training, maintenance, integration with other existing systems, and R&D costs. It is the aim of the DOT to reduce the cost of providing advanced safety systems by a factor of 10-100x through the targeted application of automation technologies. The reduction in cost would facilitate the development of a new, standardized vulnerable road user warning system that could significantly benefit system end-users, including State, local, Tribal and territorial DOTs and jurisdictions. Additionally, DOT desires that such systems should have the potential of rapid commercialization and deployment within 3 to 5 years. The RFI presented five (5) questions which sought to gather information on potential schedule and cost to develop an effective intersection safety system. Also, the questions requested information regarding equity considerations, commercialization and deployment partners, and genericness of such a system. For the purposes of this report, the technical responses to these questions have been categorized into three (3) main topics including (1) Timeline (2) Partners and (3) Costs. Note that although some responses did not provide direct answers to questions in the RFI, they provided information which are categorized under the three (3) topics. The following sections present a summary of key insights, thoughts, concern and suggestions related to the development cost and time to deployment of intersection safety systems.

6.1 Timeline

Some responses provided information on the potential timeline from development to deployment of intersection safety systems. Timelines provided ranged from 3 to 7 years. Although some responses expressed doubt about the deployment of such systems in the near term, others indicated that some components of the system could be deployed early. Below is a summary of responses providing potential timelines for the development and deployments of intersection safety systems.

- Some respondents suggest that it is unrealistic to expect a substantial number of intersections outfitted with a robust intersection safety and warning system in the near term. For example, according to Velodyne there are foundational safety issues that require resolution before an effective intersection safety system can be widely deployed. These issues include the need for performance standards for many of the underlying collision avoidance technologies and the need for improved oversight of the testing of automated vehicles.

- Autotalks suggests that when using channel 183, V2X can be deployed in 2026/7 model-year vehicles without additional cost. This functionality can be added over-the-air using a firmware update to deploy V2X vehicles. Additionally, they stated that V2X can be integrated into eBikes and eScooter from Year 2025 or 2026.
- Velodyne are of the view that the goal of $10K stack within a 5-year timeframe is reasonable at scale. This is with expectation that cost of LiDAR will continue to drop. For example, VLP-32 has reduced by 26% in its MSRP in the last 2 years.
- Continental has reliable and cost-effective radar-based sensors that can be deployed today.
- Derq USA Inc. suggest that at scale, a system that includes an edge device, a panoramic camera and software licenses for the real-time safety solution supported for a period of 5-7 years can already cost under $10,000 today.

6.2 Partners

To achieve the successful commercialization and deployment of intersection safety systems, the RFI anticipates that teams and partnerships composed of vendors, academic institutions, State/ Metropolitan Planning Organization/City/Local agencies, and other organizations would be required. Below are existing and proposed partnerships/team compositions gathered from the responses.

- Honda and AIWaysion have partnered with Verizon for 5G MEC.
- LG Electronics partnered with Verizon and another company for its next generation V2X platform, using Verizon's 5G network and the other company's compute and storage services to ensure fast, smooth, and reliable data capture and display, while cloud-based processing and distribution moved data in real time.
- Verizon partnered with Nissan to complete a proof-of-concept, demonstrating how 5G and MEC can help drivers in situations where it may be difficult to see vulnerable pedestrians or oncoming traffic emerging from behind visual obstructions.
- Verizon and Cisco capitalized on existing V2X and MEC, partnering on a demonstration in Las Vegas where the companies used Verizon's 5G MEC to enable autonomous driving solutions without using physical roadside units.
- Velodyne suggested a few "value-added collaborators":
  - Consultants and engineering groups can help agencies understand the advantages of intersection safety systems.
  - Traffic system distributors can help with installation and maintenance of intersection safety systems.

  - System integrators can help establish the link between available data from the system and the numerous vehicle warning solutions.
  - Universities and research centers can help understand capabilities, issues, use cases for intersection safety systems components.
- National Electrical Manufacturers Association (NEMA) has partnered with several organizations for the development and deployment of CV, C-V2X, and pedestrian/bicyclist safety applications. These organizations include Audi, Virginia Department of Transportation (VDOT), the Virginia Tech Transportation Institute (VTTI), Blue Bird, Fulton County School System (in Georgia), Spoke Safety, Tampa Hillsborough Expressway Authority (THEA), and Florida Department of Transportation (FDOT).
- With regards to team compositions, Derq USA Inc suggests that internal teams should typically compose of systems engineers, computer vision and research scientists, full-stack engineers, product managers, and business development and marketing experts.

6.3 Costs

A considerable number of responses provided information on cost considerations and estimates for the development and deployment of intersection safety systems. While some respondents provided suggestions on how to reduce costs, other respondents advised the DOT not to make cost reduction the focus as that could compromise safety. Below is a summary of cost related responses.

- The DOT should assess the potential tradeoff between safety improvements due to sensors at an intersection and the costs of installing those sensors. This information could inform allocation of resources that considers the overall system impact on safety and the associated opportunity costs.
- The installation costs of intersection safety systems can be minimized by leveraging the existing infrastructure, such as traffic poles, to mount sensors and equipment.
- Minimize wherever possible the cabling, connection, and sensor needs of a perception system to reduce cost.
- Costs should not be the driving force for safety since that could lead to substandard systems or use of existing equipment not meant for new task.
- The DOT should use its considerable influence and leverage embedded in competitive grant programs to pressure state and local governments to adopt inclusive and safe facility designs when spending federal funds.
- The Center for American Progress advised that the DOT should advance President Biden’s Justice40 Initiative by ensuring that at least 40 percent of the benefits from safety improvements and complete streets flow to disadvantaged communities.

- Use a mix of low-tech and high-tech interventions to find most-cost effective safety solutions.
- Currently, OEMs sell vehicles regardless of safety performance at intersections because DSRC onboard equipment add cost and risk. The DOT must address the incentive structure guiding transportation stakeholders to install DSRC V2X roadside and vehicle onboard equipment.
- Public sector agencies receive DOT funding without regard to safety performance of intersection. The DOT is advised to condition eligibility for grant application on demonstrated improvement of safety performance of roadways.
- Using MEC would anticipate fee based on a subscription-based model. The cost of service would largely depend on the scale of deployment.
- Cloud technology can help control costs by minimizing expenditures for IT infrastructure.
- Public funding can accelerate the V2X penetration by sponsoring retrofit safety devices in low-income communities.
- It is anticipated that intersection safety systems equipment is expected to be replaced every 10 years with routine maintenance cost and electric bills. For example, a traffic light has a yearly average of $8K in maintenance cost and $1.5K in electric bills.
- Cellular phones are the lowest cost option for detection of vulnerable road users, requiring zero deployment cost or delay. LiDAR and cameras may be used for detection, but costs may be high.

7 Key Takeaways

To better understand the feasibility and potential application of technologies that could enhance intersection safety, the DOT published the "Enhancing the Safety of Vulnerable Road Users at Intersections; Request for Information (RFI)" on September 16, 2022. The RFI closed two months later, on November 16, 2022. DOT received 221 responses to the RFI, with 152 from private citizens, 25 from vendors/private sector companies, 19 from transportation organizations, 10 from other organizations, 7 from academia, and 4 each from state DOTs and MPOs/cities/local agencies. Please see Appendix A for a complete list of the respondents by organization type.

This chapter summarizes high-level key insights overall (Section 7.1) and by each of the four major question categories from the RFI questionnaire: General Technical Considerations (Section 7.2), System Installation and Deployment (Section 7.3), Human Factors and Performance Measurement (Section 7.4), and Development Costs and Time to Deployment (Section 7.5). Insights from the RFI responses will help inform DOT initiatives aimed at improving intersections safety.

7.1 Key Takeaways – Overall

- **Overall Feasibility:** Respondents generally suggested that it is feasible to develop an intersection safety system for vulnerable road users based on the technologies mentioned in the RFI, specifically including machine vision and sensor fusion. However, a number of non-trivial challenges remain to near-term, widespread implementation.
- **Challenges:** While the system building blocks or components of the proposed intersection safety system concept mostly exist, important challenges remain. For example, technical challenges include the need for improved position accuracy and latency concerns for real-time safety applications. Other challenges include the need for standards development and adoption, communications/spectrum uncertainty, and sustainability of a public-private partnership model.
- **Broader Safety Context:** Many responses, especially those from private citizens and advocacy organizations, emphasized the criticality of vulnerable road user safety within a holistic context combining technology with policy measures and traffic calming. Additionally, numerous responses noted that warnings alone may not bring sizeable safety benefits. Control actions (e.g., automatic emergency braking, signal changes) can better protect vulnerable road users and drivers.

- **Real-Time Operations:** Low latency is critical for real-time safety applications, with tradeoffs between latency, detection accuracy, and cost. Edge computing offers promise to reduce latency, protect privacy, and scale readily.
- **Sensors:** Cameras, radar, and LiDAR were the most frequently mentioned modes of perception in RFI responses. Using existing sensors at intersections can help save on costs but could require additional calibration since existing sensors are generally designed to detect vehicles, not vulnerable road users.
- **Key Technologies:** AI and machine vision, multi-access edge computing (MEC), 5G, and V2X could be important emerging technologies for enhancing safety.
- **Costs:** Costs are highly dependent on the solution proposed and the availability of supporting infrastructure in actual deployments. Reducing costs will be an important factor in driving deployment of these systems at scale.

7.2 Key Takeaways – General Technical Considerations

- **Technical Feasibility:** Many, especially vendors/private sector companies, emphasized that deep learning-based and V2X-enabled intersection safety systems are feasible and ready for near-term deployment, but some technical and broader implementation challenges remain.
- **Sensing:** Different modes of perception have their pros/cons. Combining techniques (e.g., radar; LiDAR; Wi-Fi/Bluetooth sensing; infrared, visible, stereo vision, event and thermal cameras) improves accuracy.
- **Detection:** Improvements in AI/ML/computer vision offer new opportunities for vulnerable road user detection. Non-learning based decision-making methods can supplement AI/ML based perception systems for robust deployment.
- **Processing:** Weather, glare, and low-light conditions can reduce the accuracy of vision-based detection. Pre-processing algorithms (e.g., de-hazing, de-noising in low light conditions) can help improve vision-based detection. Additionally, positional accuracy is a challenge. Real-time kinematic positioning (RTK) was mentioned as one viable positional enhancement solution.
- **Differentiating Vulnerable Road Users:** Given the current state of technology, simple forms of vulnerable road user classification (e.g., pedestrian and bicyclist) may be cost-effective and represent an important first step. Detecting vulnerable road users as a whole can provide safety benefits, even if the system cannot yet differentiate a wheelchair from a scooter (but recognizes both as vulnerable).
- **Real-Time Operations:** Minimal delay/latency is critical for safety. Sensor fusion, detection, communication, and warning must happen within seconds and give road users sufficient time to respond (i.e., providing alerts roughly 2 seconds in advance). Cellular networks could experience delay from contemporaneous communications traffic on the network. Therefore, there may be a need for direct communications for safety applications. Edge computing offers promise to reduce latency, protect privacy, and scale readily.

7.3 Key Takeaways – System Installation and Deployment

- **Use Cases:** RFI respondents suggested strategies for identifying use cases as well as specific use cases that could benefit from an intersection safety system. For example, some suggested identifying use cases based on a preliminary safety assessment and/or a site survey to determine the feasibility and potential impacts (e.g., power source, sensor availability, connectivity, vulnerable road user behavior). Example suggested use cases include signalized intersections with permissive left turns, signalized intersections with long cycle lengths where vulnerable road users are likely to cross against the signal, intersections with a high incidence of red-light violations, right turns on red, unsignalized intersections, and roundabouts.
- **Vulnerable Road User Groups:** Not all vulnerable road user groups exhibit the same behaviors. Therefore, it is important to consider high-risk vulnerable road user groups and occupations in system development and testing, such as lower socio-economic groups, first responders, law enforcement, construction workers, tow-truck operators, and occupants leaving disabled or stopped vehicles. Capturing a wide range of potential vulnerable road user behaviors is important in algorithm training, but the trained algorithm does not necessarily have to be able to classify each individual vulnerable road user group to bring safety impacts, so long as it can classify them all as vulnerable.
- **Alert Types:** It is important to have multiple alert types for different vulnerable road users and drivers (e.g., visual, audio, haptic, smartphone-based), but be wary of overly distracting them. A combination of visual and audible warnings was most commonly suggested, in part because they can be easily integrated into existing intersection infrastructure. Regardless of the alert type, timeliness of the alerts is critical for vehicles and vulnerable road users to have time to respond.
- **Modes of Connectivity:** Some respondents highlighted the promise of a cellular network-based approach (e.g., cellular 5G network MEC-based V2X/V2N) for an intersection safety system. This approach may not require dedicated hardware in the vehicle or with the vulnerable road user, agreement on a common communication technology, nor a clear line-of sight to work. Additionally, this approach can work in highly congested environments, does not rely on having dedicated spectrum, puts the onus of network operation on the wireless carrier rather than the road operator, and is scalable at lower cost. Other respondents disagreed, citing latency, reliability, accessibility, and standardization concerns of cellular or Wi-Fi based approaches. Given mixed views on the most desirable mode of connectivity, RFI respondents seem to be exploring a variety of connectivity modes for their intersection safety systems.
- **Standards:** RFI respondents pointed to a variety of existing and new standards applicable to intersection safety systems that could support interoperability, including but not limited to SAE J2945/9 Vulnerable Road User Safety Message Minimum Performance Requirements; J2735 V2X Communications Message

Set Dictionary, especially the Personal Safety Message (PSM); and J3224 Sensor-Sharing for Cooperative and Automated Driving, which includes a new Sensor Data Sharing Message (SDSM). Additionally, respondents pointed to the MUTCD as the closest thing to a national standard for communication with non-connected vehicles. Finally, respondents mentioned the important role of government in collecting best practices and the needs of users to support interoperability.

7.4 Key Takeaways – Human Factors and Performance Measurement

- **Vulnerable Road User Behavior:** Predicting the pace, direction, and path of vulnerable road users with high precision may be difficult. Vulnerable road users progress at a wide range of speeds, tend to make rapid changes in direction, and do not always follow intersection control rules. Obtaining road users' attention is a challenge, especially since different road users have different communication needs. Additional devices and/or apps add to the complexity of urban mobility.
- **Performance Tradeoffs:** There are performance tradeoffs between detection accuracy and system latency. For example, while fusing inputs from multiple sensors (e.g., LiDAR, cameras, radar) is likely to improve detection accuracy, a system dependent on multi-sensor fusion may also have increased latency.
- **Testing and Validation:** A phased approach is key for system testing and validation to ensure safety, starting with testing in a virtual lab or simulation environment, then progressing to controlled environment testing, and finally moving to limited deployment testing. A systems engineering process (i.e., V-model) can be a useful approach for validation. Respondents also mentioned the importance of having high-quality labeled ground truth data to validate and refine AI/ML models.
- **Test Conditions:** It is important to test the system in various conditions to ensure it behaves as intended. For example, rain, snow, shadow, darkness, fog, glaring sunlight, extremely hot and cold weather, etc., were all mentioned by RFI respondents.
- **Key Performance Measures:** Generally, AI-enabled intersection safety systems are first assessed on their algorithm's performance (e.g., accuracy, number of false positives). Some respondents mentioned their minimum requirements for detection and classification accuracy. Beyond algorithm performance, key safety performance measures mentioned include but are not limited to the number/frequency of crashes, conflicts, near-misses, injuries, fatalities, and red-light violations, as well as smoothness of driving metrics, such as speeding, sudden acceleration, and hard braking. However, many of these safety measures require a before and after period of study.

- **Expected Impacts:** Warnings alone may not bring sizeable safety benefits. Control actions (e.g., AEB, speed limiters, signal changes) can better protect vulnerable road users.

7.5 Key Takeaways – Development Costs and Time to Deployment

- **Cost Considerations:** Costs are highly dependent on the nature of the solution and available supporting infrastructure. For example, using MEC, which wireless carriers provide as a service, would likely bring a fee based on a subscription-based model.
- **Potential Cost-Effective Approaches:** Sensor fusion could be a cost-effective approach since inputs from multiple, cheaper sensors can be combined. Additionally, using existing infrastructure sensors (e.g., cameras) could save on sensor costs. However, both approaches could come with latency and/or performance tradeoffs.
- **Deployment Cost Estimates:** According to Maryland DOT, these technology deployments are often less than $50K in cost assuming existing infrastructure is available. However, costs could range from $150K to $250K in more rural regions.
- **Sensor Cost Estimates:** Commercial thermal cameras with >90% effective vulnerable road user identification may be under $100 each, according to the thermal sensing system vendor, Veoneer. The current cost to the buyer of a level 2 ADAS with radars, cameras, and processing is below $2,000. However, if LiDAR are required, the cost of the installation will rise substantially, according to Mcity and UMTRI at the University of Michigan.
- **Deployment Timeline:** Responses were mixed on the timeline for deploying intersection safety systems. For example, the National Transportation Safety Board (NTSB) responded that it is “unrealistic” to expect a substantial number of intersections will be outfitted with robust intersection safety systems in the near term. Conversely, some vendors argue a $10K software and hardware stack can be deployed within 5 years or fewer at scale.
- **Deployment Partners:** Intersection safety system deployments tend to follow a public-private partnership model involving a variety of partners, including but not limited to technology vendors, consultants and engineering groups, traffic system distributors, system integrators, OEMs, agencies, and universities or research centers. Additionally, new partners are entering the conversation, such as wireless service providers (e.g., Verizon).

8 References

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Appendix A. List of RFI Respondents

A total of 221 RFI responses were received, as assessed by the reviewers. However, the docket shows more comments than that posted under “Browse All Comments” at 222 since some appear to have come from the same entity. Additionally, the “Docket Details” page of the RFI shows the total number of comments received at 256, but this number appears to count all attachments (even those within the same comment post) as separate comments, making the value higher than the actual. Since some of the responses appeared to originate from the same entity, they were consolidated in the total number. Details of the reviewers’ assumptions for individual responses are summarized below:

- Emergency Safety Solutions, Inc. posted one response on 10/20/22 and a slightly revised response on 11/1/22 to correct an incorrect date on the comment originally submitted. Since these two comments came from the same vendor, they were consolidated.
- BikeWalkNC posted four comments back-to-back on 11/14/22. Therefore, these were assumed to come from the same organization and were consolidated.
- Private citizen, Jerry Schippa, posted two brief comments back-to-back on 11/3/22. Therefore, these were assumed to come from the same person and were consolidated.
- Six transportation organizations together posted a request for a 30-day RFI deadline extension on 10/11/22. These six transportation organizations—Intelligent Transportation Society of America (ITS America), Alliance for Automotive Innovation (Auto Innovators), American Association of State Highway and Transportation Officials (AASHTO), 5G Automotive Association (5GAA), Motor & Equipment Manufacturers Association (MEMA), and National Electric Manufacturers Association (NEMA)—later submitted individual responses. Originally, the combined response posted on 10/11/22 requesting an extension was treated as one response from a Transportation Organization. Following the RFI closure, the six individual responses were counted separately and the original request for an extension was removed from the overall total to avoid double counting.
- Comments were posted from “anne dicker” on 11/14/22 and “Anne Dicker” on 11/15/22. Since these comments were posted on different days, they were not assumed to have come from the same person, and were, therefore, kept separate.
- Comments were posted from “Isabella Chu” on 10/4/22 and 11/14/22. Since they were posted on different dates, they were not assumed to have come from the same person, and were, therefore, kept separate.

- Six comments were posted by “Anonymous” on 11/4/22, 11/9/22, 11/10/22, 11/14/22 (two comments), and 11/15/22. These six comments were not assumed to have come from the same person, and were, therefore, kept separate. These six comments were included under the “Private Citizen” category in the figures in Section 2.

Most RFI responses were posted to the docket, but some were sent via email and later posted to the docket (or not posted to the docket). For example, one company emailed their response (dated 10/14/22) to the *saferintersections* email, but this response was not posted to the docket. Additionally, the University of Cincinnati Department of Planning, Design, and Construction emailed their response to Tim Klein on 11/16/22, which was posted to the docket a few days later on 11/18/22. Finally, Continental emailed their late submission to Tim Klein on 11/21/22, which was later posted to the docket on 12/6/22.

Table A- 1 through **Table A- 8.** provide a comprehensive list of respondents by category.

Table A- 1. State DOT Respondents

No.	Respondent Name
1.	Georgia DOT
2.	Kansas DOT
3.	Maryland DOT
4.	Texas DOT

Table A- 2. MPO/City/Local Agency Respondents

No.	Respondent Name
5.	Alachua County Board of County Commissioners
6.	City of Houston, TX
7.	City of Portland
8.	North Central Texas Council of Governments

Table A- 3. Academia Respondents

No.	Respondent Name
9.	Duke University – Department of Electrical and Computer Engineering
10.	Colorado State University – Pueblo, Southern Colorado Institute of Transportation Technology (SCITT)
11.	The Ohio State University
12.	University of Cincinnati - Department of Planning, Design, and Construction
13.	University of Michigan & Commsignia Inc.
14.	University of Michigan, Ann Arbor
15.	University of Tennessee at Chattanooga

Table A- 4. Transportation Organization Respondents

No.	Respondent Name
16.	5G Automotive Association
17.	Action Committee for Transit
18.	Alliance for Automotive Innovation
19.	American Association of State Highway and Transportation Officials
20.	American Center for Mobility
21.	American Motorcyclist Association
22.	American Society of Civil Engineers
23.	BikeWalkNC
24.	Institute of Automated Mobility (Arizona)
25.	Insurance Institute for Highway Safety
26.	ITS America
27.	Lidar Coalition
28.	Marin County Bicycle Coalition
29.	Motor & Equipment Manufacturers Association (MEMA)
30.	National Transportation Safety Board
31.	SAE ITC Vulnerable Road User Safety Consortium (VRUSC)
32.	The League of American Bicyclists
33.	Transportation for America
34.	Advocates for Highway and Auto Safety

Table A- 5. Vendor/Private Sector Respondents

No.	Respondent Name
35.	AIWaysion, Inc.
36.	American Honda Motor Co., Inc.
37.	Autotalks
38.	Anonymous
39.	Blyncsy, Inc.
40.	CalypsoAI
41.	Commsignia Ltd.
42.	Continental
43.	Derq USA, Inc.
44.	Emergency Safety Solutions, Inc.
45.	Harman International (a Samsung Company)
46.	Intel Corporation
47.	Iteris, Inc.
48.	Kapsch
49.	Michelin Driving Data to Intelligence (MICHELIN DDi)
50.	National Association of Mutual Insurance Companies
51.	P3Mobility
52.	Panasonic North America

No.	Respondent Name
53.	Pedestrian Safety Solutions, LLC
54.	Qualcomm
55.	Robert Bosch LLC
56.	Sentinel Transportation Systems LLC
57.	Velodyne Lidar Inc.
58.	Veoneer HoldCo, LLC
59.	Verizon

Table A- 6. Other Organization Respondents

No.	Respondent Name
60.	Center for American Progress
61.	CTIA
62.	Disability Rights Education & Defense Fund
63.	Electronic Privacy Information Center (EPIC)
64.	Equiticity
65.	Metropolitan Planning Council, Chicago
66.	National Electrical Manufacturers Association (NEMA)
67.	Pennsylvania Downtown Center
68.	SAE International
69.	Walkable Albany

Table A- 7. Private Citizen Respondents

No.	Respondent Name
70.	Adam Knott
71.	Aio Z.
72.	Alan Gerber
73.	Alasdair Crawford
74.	Alec Perkins
75.	Alex Jacobson
76.	Alexander LaBee
77.	Amy Parzych
78.	Andrej Marich
79.	Andrew Killick
80.	Andy Boenau
81.	Andy Levitz
82.	Angela Crow
83.	Anne B
84.	Anne Dicker
85.	Anne Dicker (2)
86.	Anton Beer
87.	Anton Maes
88.	Arley Lewis
89.	Ashley Heyer

No.	Respondent Name
90.	Aubrey Pullman
91.	Aubrey Pullman (2)
92.	Barbara Lents
93.	Beezy Bentzen
94.	Ben Turndorf
95.	Benjamin Keith
96.	Bill Stencel
97.	Bob T.
98.	Brandt Witt
99.	Brandt Witt (2)
100.	Brent Bovenzi
101.	Brian Bowman
102.	Brian Bowman (2)
103.	Brian Seel
104.	Brian Van Nieuwenhoven
105.	Burton Sutker
106.	Caleb Pan
107.	Cara Murphy
108.	Catherine Windyk
109.	Charles Vann
110.	Cheryl Zalenski
111.	Chris Turek
112.	Cindy McLaughlin
113.	Colin Clarke
114.	Connie Szabo Schmucker
115.	Daniel Fuller
116.	Danielle T.
117.	David M Simpson
118.	David Roederer
119.	Derek Shan
120.	Donal O'Briain
121.	Ed Cotter
122.	Ed Damato
123.	Edward Kantz
124.	Eli Ferrari
125.	Elizabeth Denys
126.	Ellery Klein
127.	Elliott Vanskike
128.	Elliott Wilcoxon
129.	Eric Kraan
130.	Evan Ward
131.	Evangeline Warren
132.	Evangeline Warren (2)
133.	G Galdamez
134.	Giancarlo Rodriguez

No.	Respondent Name
135.	Gordon Watt
136.	Grace Peng
137.	Greg Boris
138.	Heidi Perry
139.	Himanshu Gaur
140.	Hunter Oatman-Stanford
141.	Ian B
142.	Isabella Chu
143.	Isabella Chu (2)
144.	Isabella Tate
145.	Isabella Tate (2)
146.	J Lorenz
147.	J Paul Johnson
148.	Jacob Unterreiner
149.	Jacqualine Grant
150.	James Ingram
151.	Jason Owen
152.	Jerry Schippa
153.	Jessie Hart
154.	Joanna Smith
155.	Joel Kohn
156.	Joey Iuliano
157.	John McWhirter
158.	Joseph Frazier
159.	Josh Goodman
160.	Joshua Peacock
161.	K N
162.	Kathy Park Price
163.	Katie Jones
164.	Kenneth Russell
165.	Kevin Opp
166.	Kieran O'Brien Kern
167.	Kimmie Nguyen
168.	Kristin Tieche
169.	Kyle Krysinski
170.	Laura Clark
171.	Lindsay Philiben
172.	Marissa Borquez
173.	Marissa Borquez (2)
174.	Mason Stark
175.	Matt Magnasco
176.	Matthew Boomhower
177.	Matthew Denys
178.	Maxwell Davis
179.	Meg Robertson

No.	Respondent Name
180.	Melyssa Mendoza
181.	Michael Chen
182.	Michael Grabow
183.	N Magnezi
184.	Neil D.
185.	Nicole Burgess
186.	Pat Dol
187.	Patrick Cierpiot
188.	Patrick Smith
189.	Peter Griesar
190.	Phoebe Ford
191.	Raul Maldonado
192.	Reed Meyer
193.	RL Mann
194.	Robbie Young
195.	Robert Huben
196.	Robert Johnson
197.	Rock Miller
198.	Roy Russell
199.	Sam Anderson
200.	Sam Archer
201.	Sam Harmic
202.	Scot Bents
203.	Shawne Martinez
204.	Shih-Hsuan Liu
205.	Stephanie Reid
206.	Stephen Smith
207.	Steve Piercy
208.	Steven Philips
209.	Thomas Haymore
210.	Thomas Smith
211.	Tom Dijk
212.	Valerie Reishuk
213.	William Meehan
214.	Willow Hamilton
215.	Yang Chong

Table A- 8. Other Anonymous Respondents

No.	Respondent Name
216.	Anonymous (1)
217.	Anonymous (2)
218.	Anonymous (3)
219.	Anonymous (4)

No.	Respondent Name
220.	Anonymous (5)
221.	Anonymous (6)

Appendix B. Acknowledgements

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The authors would also like to thank others from DOT subject matter experts (SMEs) (see **Table B- 1**).

Table B- 1. Core Team and Subject Matter Experts

ID	Name	DOT Office
1.	Aimee Drewry	FHWA Office of Contracting Operations
2.	Alissa Dolan	FHWA Office of Chief Counsel
3.	Brian Cronin	FHWA Office of Safety and Operations Research and Development
4.	Chris Atkinson	OST-R
5.	Eddie Curtis	FHWA Office of Transportation Management
6.	Edward Fok	FHWA Resource Center
7.	Faroog Ibrahim	Volpe
8.	Govind Vadakpat	ITS JPO
9.	Hyungjun Park	ITS JPO
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11.	Jesse Eisert	FHWA Office of Safety and Operations Research and Development
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14.	Rachel James	FHWA Office of Safety and Operations Research and Development
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17.	Wei Zhang	FHWA Office of Safety and Operations Research and Development

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