

TR202617 Piloting an AI-Enabled Immersive Multi-Agency Traffic Incident Management (TIM) Training Platform



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Abstract

Traffic Incident Management (TIM) depends on coordinated actions among transportation agencies, law enforcement, fire and rescue, emergency medical services, towing and recovery, dispatch, and other partners. This pilot project developed and demonstrated a modular immersive TIM training platform intended to supplement classroom, tabletop, online, and field-based training. The platform was implemented on Meta Quest 3 standalone Virtual Reality (VR) headsets and organized around reusable Virtual Operational Environments (VOEs) that separated persistent roadway settings from scenario-specific incident content. Two VOEs were developed: an Interstate VOE representing multilane, high-speed operations and a Rural Highway VOE representing a two-lane, two-way roadway with opposing traffic and constrained response space. The platform incorporated first-person navigation, selected object interactions, in-application voice communication, rule-based simulated roadway traffic, shared sessions supporting up to four participants, and an initial Unity–OpenAI application programming interface connection that presented model-generated text within the VR application. Three pilot demonstrations were conducted with Missouri Department of Transportation personnel and TIM partners. Demonstration feedback led to further refinement of the Rural Highway VOE and implementation of an injured-driver avatar and related animation. Additional updates involving towing and recovery, participant orientation, scenario content, structured data capture, after-action review, and AI-enabled virtual responders were implemented. The demonstrations supported the technical feasibility and operational relevance of the platform but did not constitute a formal evaluation of training effectiveness. A focused second phase is recommended to expand scenarios, develop validated role-specific virtual responders, implement controlled scenario actions and instructor oversight, and conduct technical, usability, operational-validity, and training-effectiveness evaluations.

Executive Summary

Traffic Incident Management (TIM) requires coordinated actions among transportation agencies, law enforcement, fire and rescue, emergency medical services, towing and recovery, dispatch, and other supporting organizations. Existing classroom, online, tabletop, and field-based training provides important knowledge and experience but differs in realism, interactivity, and logistical demands. This pilot project developed and demonstrated a modular immersive platform intended to supplement these methods with a safe, repeatable, and portable environment for examining roadway conditions, responder positioning, simulated traffic, and multi-agency coordination.

The platform used a Virtual Operational Environment (VOE) framework that separated reusable roadway settings from scenario-specific incident content. Phase I produced two VOEs. The Interstate VOE represented a multilane, high-speed roadway and supported consideration of lane blockages, scene protection, passing traffic, emergency-vehicle positioning, and staged lane reopening. The Rural Highway VOE represented a two-lane, two-way roadway with opposing traffic, limited shoulder space, and constrained responder staging.

The application was developed in Unity and deployed on Meta Quest 3 standalone Virtual Reality (VR) headsets. It incorporated first-person navigation, selected object interactions, participant and session configuration, in-application voice communication, and shared sessions supporting up to four participants. Rule-based simulated traffic provided representative roadway activity, and traffic movement could be enabled or disabled during demonstrations. A tunneling-vignette comfort function helped reduce potential discomfort during virtual locomotion. The traffic system was not calibrated as a microscopic traffic model.

Phase I also implemented an initial Unity–OpenAI application programming interface (API) connection. The application could submit information to an OpenAI model, receive model-generated text, and present the content within an immersive environment. This proof of concept demonstrated the feasibility of incorporating generative artificial intelligence (AI) but did not constitute a validated AI-enabled virtual responder. AI output did not modify Unity variables or trigger scenario conditions.

Three pilot demonstrations were conducted with Missouri Department of Transportation personnel and TIM partners. The first introduced the initial Interstate VOE. Practitioner feedback contributed to further refinement of the Rural Highway VOE and implementation of an injured avatar and related animation. The second reinforced the importance of representing towing and recovery as an active operational role. The third highlighted the need for standardized participant orientation and practice with vehicle-manipulation controls.

The demonstrations provided qualitative feedback regarding technical feasibility, operational relevance, usability, and potential applications. Practitioners recognized value in representing different roadway contexts, sharing incident observations, communicating within a common environment, and discussing responder positioning, traffic control, incident clearance, towing and recovery, and lane reopening. However, the demonstrations were exploratory and did not use standardized surveys, comparison groups, or validated measures of training effectiveness.

Phase I also did not include structured event logging, automated after-action review, fully developed agency-specific interfaces, or formal evaluation of knowledge gain, skill transfer, or long-term retention.

The pilot established a reusable technical and operational foundation rather than a complete training system. Near-term development should prioritize high-value scenarios within the existing VOs, standardized participant orientation, and additional incident elements or agency functions only when they directly support training objectives. A focused Phase II effort should expand the Unity–OpenAI API proof of concept into a limited number of validated, role-specific virtual responders. A structured incident-state model and controlled Unity interface should allow approved AI actions to influence scenario conditions while maintaining traceability and instructor oversight. Structured, time-stamped data should support exercise timelines, selected replay, instructor-led after-action review, and phased evaluation. Initial evaluation should emphasize technical performance, usability, operational validity, AI-agent behavior, and instructor controls. Formal training-effectiveness evaluation should occur after the scenarios, participant roles, AI functions, data-capture procedures, and delivery methods have stabilized.

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List of Abbreviations and Acronyms

3D	Three-Dimensional
AI	Artificial Intelligence
API	Application Programming Interface
EMS	Emergency Medical Services
FHWA	Federal Highway Administration
MoDOT	Missouri Department of Transportation
NHI	National Highway Institute
TIM	Traffic Incident Management
VOE	Virtual Operational Environment
VR	Virtual Reality

1. Introduction

1.1 Background

Traffic incidents disrupt roadway operations and expose both responders and travelers to serious risks of secondary-crash and struck-by incidents. Nationwide, roadside responder fatalities rose sharply from 46 in 2020 to 65 in 2021 before declining to 50 in 2022 (FHWA 2025). These nationwide statistics underscore that struck-by crashes remain a constant threat across emergency disciplines, claiming the lives of one towing and recovery operator each week, one law enforcement officer each month, and five firefighters each year (MoDOT 2025).

Training is an important means of preparing responders to manage these risks. Current Traffic Incident Management (TIM) training commonly includes classroom courses, videos, case studies, tabletop discussions, and field exercises. These approaches introduce accepted practices, agency responsibilities, terminology, and operational principles. However, classroom activities provide limited opportunities to experience the spatial and operational complexity of an active roadway incident, while full-scale exercises require substantial coordination, personnel, equipment, roadway access, and safety controls.

Because TIM operations rely on coordinated actions among law enforcement, fire and rescue, emergency medical services (EMS), transportation agencies, towing and recovery operators, communications personnel, and other supporting organizations, effective training should also provide opportunities for interdisciplinary collaboration. In practice, however, organizing joint exercises involving multiple agencies is resource-intensive and logistically challenging. As a result, responders often have limited opportunities to practice communication, situational awareness, coordinated traffic control, responder protection, incident clearance, and the timely restoration of roadway operations in a shared operational environment.

Virtual reality (VR) offers a practical means of supplementing existing training methods by providing safe, repeatable, and modifiable representations of roadway incidents. Within a shared virtual environment, participants can experience incident conditions from different first-person perspectives, rehearse coordinated operations, and evaluate decisions without disrupting live traffic or requiring extensive field resources.

Although immersive technologies have demonstrated value for emergency response training, relatively few platforms are designed specifically to support collaborative TIM exercises involving multiple agencies across different roadway environments. This need motivates the development of a modular immersive training platform that can accommodate diverse roadway contexts while supporting coordinated responder training.

1.2 Traffic Incident Management Training Needs

Effective TIM training should prepare responders not only to perform agency-specific tasks but also to coordinate decisions and actions across organizations under dynamic roadway conditions. Accordingly, a comprehensive training platform should support several key capabilities.

First, trainees should be able to understand the operational environment by examining roadway geometry, traffic movement, responder locations, emergency-vehicle positioning, lane blockages, available work areas, and evolving incident conditions from within the scene rather than through static diagrams or photographs.

Second, training should promote interagency communication and coordination. Participants should understand how the timing and sequence of agency actions influence responder safety, traffic control, incident clearance, and the restoration of normal roadway operations. Exercises should also facilitate discussion of communication delays, conflicting priorities, and coordination challenges encountered during incident response.

Third, training should support repeated practice with minimal logistical burden. Conventional field exercises require significant personnel, equipment, traffic-control devices, and roadway access, making frequent multidisciplinary training difficult. A reusable training environment can enable repeated exercises while reducing these logistical constraints.

Finally, TIM training should represent the diversity of roadway environments encountered in practice. Interstate incidents involve high-speed, multilane traffic, queues, and complex lane closures, whereas rural two-lane highways present opposing traffic, limited shoulders, constrained access, and fewer diversion opportunities. A comprehensive training platform should therefore support multiple roadway contexts rather than a single fixed incident scenario.

1.3 Opportunities for Immersive and Collaborative Exercises

Immersive technologies, such as VR, are well suited to addressing these training needs. By placing participants within a three-dimensional (3D) incident scene, VR enables users to observe roadway geometry, traffic movement, responder locations, vehicle positioning, and traffic-control arrangements while directly experiencing the operational context of an incident. This immersive perspective strengthens the connection between roadway conditions and decisions related to scene protection, traffic management, responder safety, vehicle recovery, and lane reopening.

Multi-user VR environments further enable collaborative exercises involving participants from different agencies within the same incident scene. Such environments support role-based communication, information sharing, coordinated decision-making, instructor observation, and structured post-exercise debriefing, providing training experiences that are difficult to achieve through classroom training alone.

The pilot platform also included a limited connection between Unity and the OpenAI Application Programming Interface (API). The integration allowed the VR application to submit information to an OpenAI model, receive generated text, and present that content within the immersive environment. This implementation demonstrated the technical feasibility of incorporating externally generated Artificial Intelligence (AI) content into the platform. The Phase I implementation did not include a fully developed AI-enabled virtual responder. The generated content was not yet based on a validated agency-specific role, comprehensive incident-state information, or an adaptive interaction framework. In addition, AI outputs did not

trigger scenario variables or modify incident conditions within Unity. These capabilities remain priorities for future development.

1.4 Scope of the Pilot Project

This pilot project focused on developing and demonstrating a modular immersive TIM platform. The platform was implemented through two Virtual Operational Environments (VOEs): an Interstate VOE based on the I-70 operating context and a Rural Highway VOE representing a two-lane, two-way roadway.

The pilot included shared multi-user participation, simulated roadway traffic, incident-scene elements, first-person immersive participation, and a limited Unity–OpenAI API integration. The AI integration allowed model-generated text to be received and presented within the VR application. Three pilot demonstrations were conducted to assess the platform’s feasibility, operational relevance, usability, and potential applications.

2. Literature Review

2.1 Traffic Incident Management Responder Training and Current Practices

Recognizing the risks associated with roadway incident response and the need for coordinated multi-agency operations, the Federal Highway Administration (FHWA) established the National TIM Responder Training Program (FHWA 2025). The program promoted common practices and core competencies related to responder safety, safe and quick clearance, and prompt, reliable, interoperable communications. As of October 2025, more than 800,000 responders had completed the national program, and many fire, EMS, and law-enforcement academies had incorporated it into their curricula.

The National TIM Responder Training addressed notification and scene size-up, safe vehicle positioning, scene safety, command responsibilities, traffic management, special circumstances, and clearance and termination. FHWA offered the program through several free delivery formats, including a four-hour in-person course, instructor-led virtual training, online self-paced training, and a train-the-trainer program. The self-paced options included the integrated National Highway Institute (NHI) Course (NHI Course 133126A) and 10 modular courses offered through the Responder Safety Learning Network. This range of formats established a strong national foundation for providing consistent and accessible TIM training across responder disciplines.

Missouri implemented the national program through the Missouri Department of Transportation (MoDOT)'s TIM Responder Training Program. MoDOT offers a free four-hour condensed course designed to develop core competencies in responder safety, safe and quick clearance, and interoperable communications. The program targeted personnel from public works, law enforcement, fire and rescue, EMS, towing and recovery, emergency management, communications, and highway and transportation agencies. MoDOT also provided mechanisms for practitioners to register for scheduled courses, request classes, and become TIM instructors, supporting continued statewide delivery of the program.

In addition, Missouri has used full-scale simulated exercises to support realistic multi-agency practice. MoDOT and partner agencies conducted a simulated multi-vehicle crash involving law enforcement, fire and rescue, EMS, towing and recovery, and transportation personnel (Naughton 2023). Participants practiced traffic control, extrication, triage, crash investigation, recovery operations, and interagency communication, followed by debriefing and after-action review. Full-scale exercises provide valuable operational experience; however, they require significant personnel, equipment, facilities, and coordination, making them impractical to conduct at every TIM training session.

Together, the FHWA and MoDOT programs provided a well-established foundation for conventional TIM training. In-person courses brought personnel from different disciplines together, while virtual and self-paced options expanded access to standardized content. FHWA's instructor-led virtual format also incorporated interactive map-based exercises in which

participants assumed different responder roles and positioned vehicles, signs, and traffic-control devices.

However, these formats provided limited opportunities to experience an incident from a first-person, 3D perspective or to observe moving traffic, sight-distance constraints, responder work areas, and emergency vehicle positioning within a shared roadway environment. The immersive platform developed in this pilot project was therefore intended to supplement—not replace—the established FHWA and MoDOT training programs by providing an additional setting for spatial awareness, operational decision-making, and multi-agency coordination.

2.2 Data-Driven Case Studies and After-Action Review

Incident data and after-action reviews provide an important foundation for developing realistic TIM exercises. They allow practitioners and system developers to examine how roadway geometry, traffic conditions, responder arrival patterns, vehicle positioning, communication, traffic control, and clearance activities influenced incident outcomes. Because actual incidents involve uncertainties and operational constraints that are difficult to reproduce in generic classroom examples, data-driven cases can improve both the realism and operational relevance of immersive exercises.

Overall et al. (2025) developed a repository of 267 TIM after-action reports based on incidents that occurred in Indiana between June 2020 and March 2025. The researchers combined crash reports, roadway camera footage, dispatch audio, connected vehicle data, and other operational information to document incident characteristics, queue development, traffic impacts, responder activities, and lessons learned. Together, these data sources provided a more complete representation of the incident lifecycle than any individual source alone.

The project team used a similar data-driven approach to support platform development. With assistance from MoDOT, the team obtained access to incident information and roadway camera observations through MoDOT traffic management resources. The Purdue incident database and associated after-action reports provided an additional source of documented incidents and operational lessons. These resources helped the team identify representative roadway conditions, agency interactions, response sequences, traffic impacts, and critical decision points.

The incident information supported the development of realistic VOEs and associated exercises. Rather than reproducing each incident exactly, the project team identified transferable elements that could be incorporated into reusable environments. For example, the Interstate VOE can support incidents involving disabled vehicles, lane-blocking crashes, commercial-vehicle rollovers, hazardous-material events, and secondary crashes without requiring a separate roadway model for each event.

These data sources can also support future development of AI-enabled virtual responders. Documented communications, agency actions, response timelines, and incident-state changes can inform the definition of agency roles, expected behaviors, decision rules, and scenario progression. They can also provide reference cases for validating whether virtual responders communicate and act consistently with accepted TIM practices. In future phases, recorded

trainee actions and communications could be compared with documented incident timelines and operational benchmarks during after-action review.

2.3 Immersive and Collaborative Emergency-Response Simulation

VR has increasingly been used to represent hazardous, complex, or infrequently occurring emergency situations. Its principal advantages include providing repeatable conditions, allowing participants to experience situations that would be unsafe or costly to reproduce, and enabling exercises without disrupting actual operations.

Heldring et al. (2024) reviewed 17 studies involving high-fidelity VR for mass-casualty incident training. The review found that VR provided a safe and repeatable learning environment and could allow exercises to be conducted more frequently than live simulations. Participants generally reported increased confidence, engagement, and preparedness. The authors emphasized, however, that VR should supplement rather than replace live exercises and that usability, reliability, and ease of operation strongly influenced its training value.

Bugli et al. (2023) evaluated a VR exercise for public-health emergency responders that emphasized interpersonal communication, competing priorities, and decision-making in an unfamiliar emergency setting. Participants generally viewed the exercise as immersive and relevant. The study demonstrated that VR can address nontechnical competencies such as communication and decision-making, rather than focusing only on physical procedures.

Li, Wang, and Huang (2025) conducted a randomized controlled trial involving emergency physicians and residents. Participants assigned to immersive VR training performed better than the comparison group in immediate measures of scene assessment, triage accuracy, and transportation decision-making and also reported greater satisfaction and confidence. Although the study addressed medical management of traffic-injury casualties rather than roadway TIM operations, it demonstrated the potential of VR to support decision-making in complex traffic-incident environments.

Research specifically addressing traffic-incident response remains limited. Alsuwaidi et al. (2026) evaluated a 3D traffic-incident simulation involving police cadets. The simulation incorporated branching narratives, time pressure, virtual communication, procedural tasks, and performance feedback. The study demonstrated the potential value of meaningful decision points, adaptive consequences, and performance recording. However, it primarily focused on one responder discipline and did not represent a head-mounted, multi-user environment for coordinated participation among transportation, law-enforcement, fire, emergency medical, towing, and communication personnel.

Collaborative and multi-user studies provide additional lessons for TIM applications. Lerner et al. (2020) developed a shared VR environment in which two emergency physicians interacted through synchronized avatars and virtual equipment. Neher et al. (2024) evaluated an interprofessional VR exercise involving medical and nursing participants, while Choi and Kim (2024) examined a team-based mixed-reality emergency exercise. Collectively, these studies indicated that shared virtual environments could support communication, role coordination,

confidence, situational awareness, and collaborative decision-making. They also showed that technical problems, unfamiliar controls, excessive cognitive workload, and poor usability can reduce the benefits of immersion.

Industry-developed platforms also demonstrate the increasing availability of configurable VR tools for emergency-response training. Jacobs developed RealScene, an immersive XR training platform that included six-degrees-of-freedom movement, more than 100 objects and characters, drag-and-drop scene creation, animated traffic, adjustable weather and lighting, and six base environments (Jacobs 2026). These capabilities illustrate how reusable environments, configurable assets, dynamic hazards, and instructor-facing scene-development tools can support the efficient creation and modification of immersive exercises. However, the publicly available product description does not report a formal evaluation of learning outcomes or provide sufficient information to assess TIM-specific multi-agency role coordination, structured performance measurement, or AI-enabled virtual responders. As such, RealScene provided a relevant example of current commercial XR capabilities.

The literature indicates that TIM exercises should involve meaningful operational decision-making rather than serve solely as visual demonstrations. Commercial platforms such as RealScene further demonstrate the value of configurable asset libraries, dynamic environmental conditions, animated traffic, and reusable scene-development tools; however, these technical capabilities should be combined with clearly defined roles, operational decision points, collaborative participation, and structured evaluation when applied to TIM training. Participants should be able to assume different agency roles while maintaining a shared understanding of incident conditions through first-person participation from different positions within a common virtual environment. Additionally, the literature highlights the limitations of VR-based training. Therefore, the platform was designed to complement, rather than replace, existing classroom, tabletop, online, and full-scale TIM exercises.

2.4 AI-Enabled Virtual Responders and After-Action Support

Emergency-response simulations have commonly incorporated virtual patients, scripted dispatch messages, and non-player characters to increase scenario realism. However, these components typically rely on predetermined dialogue and actions, limiting their ability to respond to unanticipated trainee decisions or changing incident conditions.

Recent advances in AI provide opportunities to create more interactive and adaptive virtual responders. For TIM training, AI-enabled responders could help address the practical difficulty of providing human participants to represent every agency required for a multi-agency exercise. Potential virtual responder roles include law enforcement, fire and rescue, EMS, transportation agencies, towing and recovery, dispatch, and traffic management center personnel.

Each virtual responder would need to operate within a defined agency role. Its configuration should specify responsibilities, available information, resources, communication expectations, permitted actions, decision authority, and operational limitations. The virtual responder would also need access to relevant incident-state information, such as lane blockages, emergency-vehicle locations, agency arrival status, traffic-control deployment, hazard or patient conditions,

towing progress, completed tasks, and outstanding requests. These requirements distinguish an operational virtual responder from a general-purpose text-generation system.

The pilot project implemented an initial connection between Unity and OpenAI API. Through this integration, the VR application could submit information to an OpenAI model, receive model-generated text, and present the resulting content within the virtual environment. This proof-of-concept implementation demonstrated the technical feasibility of incorporating generative AI content into the immersive TIM platform.

The Phase I implementation did not constitute a complete AI-enabled virtual responder. The generated content was not yet grounded in validated agency-specific roles, comprehensive incident-state information, or defined operational decision boundaries. Additional configuration, knowledge grounding, testing, and practitioner validation are needed before an AI agent can provide realistic and operationally appropriate interactions with trainees.

The Phase I integration also did not allow AI output to modify Unity variables, manipulate virtual objects, or change incident conditions. Future development could connect role-specific AI agents to a controlled scenario-management interface. Through this interface, an agent could issue a structured request to perform an approved action, such as updating an agency's arrival status, reporting completion of a recovery task, activating a traffic-control element, changing a lane-blockage condition, or advancing the exercise to another stage. The Unity application would validate the request against the agent's assigned role, permitted actions, and current incident state before changing the scenario. Instructor monitoring and override functions would remain necessary, particularly during initial development and evaluation.

AI could also support after-action review. Barker et al. (2026), for example, developed a multi-user VR system that used a large language model to analyze recorded team communications during debriefing. The system organized information related to communication patterns, leadership behaviors, and information flow, although the researchers characterized the findings as preliminary and emphasized the need for expert validation.

A similar approach could support future TIM training. Participant communications, operational decisions, vehicle positions, traffic-control actions, agent responses, and incident-state changes could be recorded and time-stamped during an exercise. AI could help organize these data into a chronological timeline, identify delayed or unresolved requests, and prepare preliminary discussion prompts. These outputs should support, rather than replace, instructor interpretation and the judgment of qualified TIM practitioners.

2.5 Literature Synthesis and Research Gap

The literature demonstrates that FHWA, MoDOT, and other transportation organizations have established a comprehensive foundation for TIM training through classroom training, online courses, tabletop exercises, after-action reviews, and full-scale field exercises. Each training method offers distinct advantages. Classroom and online training provide consistent delivery of foundational knowledge, while tabletop and full-scale exercises promote discussion, coordination, and practical application of TIM procedures. However, classroom and online

formats provide limited opportunities for participants to experience the dynamic and spatial nature of roadway incidents, whereas full-scale exercises require substantial personnel, equipment, facilities, and coordination, making them impractical to conduct frequently.

Research in emergency response training further suggests that immersive simulation can provide a safe, repeatable, and engaging environment for practicing decision-making, communication, teamwork, and situational awareness. Collaborative virtual environments have also demonstrated the potential to support multi-user interaction and interagency coordination. Nevertheless, most published studies have focused on medical emergencies, triage, public health response, fire services, or disaster management, with relatively little attention given to roadway TIM.

Commercial VR platforms demonstrate that reusable environments, configurable assets, dynamic hazards, animated traffic, and environmental variability can be integrated into accessible scene-development systems. However, publicly available descriptions of these platforms provide limited evidence regarding TIM-specific multi-agency collaboration, agency-role representation, structured incident-state management, AI-enabled virtual responders, and formal training-effectiveness evaluation.

The literature reveals several important research gaps related to immersive TIM training. First, few virtual training platforms realistically integrate the dynamic characteristics of roadway incidents, including moving traffic, lane closures, emergency vehicle positioning, temporary traffic control, and coordinated participation among multiple responder agencies within a shared environment. Existing traffic incident simulations are generally limited to a single responder discipline, predefined serious-game scenarios, or non-immersive desktop applications. Second, relatively little attention has been given to developing reusable virtual roadway environments that support multiple training scenarios. Most existing systems are designed around a single exercise, whereas a VOE allows a persistent roadway network to support a wide range of incident types, responder roles, traffic conditions, and training objectives without rebuilding the environment for each exercise. Finally, although recent advances in AI have introduced opportunities for intelligent virtual teammates and automated after-action analysis, current applications remain in their early stages. Existing studies primarily rely on scripted virtual characters or AI-assisted debriefing, while autonomous, agency-specific virtual responders capable of interacting naturally with trainees have not yet been fully developed or validated for TIM training.

These remaining needs guided the modular, collaborative, and AI-ready design of the pilot platform. To address the identified gaps, the project developed an immersive TIM training platform centered on reusable VOEs. The platform included Interstate and Rural Highway VOEs, supported collaborative multi-user participation through first-person immersive interaction, and provided a flexible framework for developing multiple incident scenarios within the same virtual roadway environment. The project also implemented a limited Unity–OpenAI API connection through which model-generated text could be presented within the VR application. This implementation established an initial AI-integration pathway; however, additional development is needed to create validated role-specific virtual responders, incorporate comprehensive

incident-state information, support adaptive trainee-agent interaction, and connect approved AI actions to Unity scenario variables and conditions.

3. System Design and Architecture of the Immersive TIM Platform

3.1 Design Objectives

The platform design was guided by the operational characteristics of TIM and the pilot nature of the project. The primary goal was to create a reusable technical foundation that could support collaborative incident-response exercises across different roadway contexts. Four principal design objectives were established.

1. Support immersive representation across reusable roadway contexts

The platform needed to provide a 3D environment in which participants could observe roadway geometry, moving traffic, emergency vehicles, responders, lane blockages, and incident-scene conditions from a first-person perspective. The environments also needed to be reusable. Rather than developing each exercise as a separate virtual application, the roadway environment and incident content were structured so that additional incident scenarios could be added without rebuilding the entire system. The pilot demonstrated this approach through both a high-speed interstate environment and a rural two-lane, two-way highway environment.

2. Support collaborative participation

Multiple participants needed to enter the same virtual environment and observe a common incident scene. This shared setting provided the foundation for representing multi-agency communication, role coordination, information exchange, and collaborative decision-making. The platform was designed to support participants representing different TIM agencies. The shared-session structure also provided a foundation for future exercises involving combinations of human trainees and AI-enabled virtual responders.

3. Maintain practical usability

The platform needed to operate on commercially available standalone VR equipment and provide interactions that participants could learn through a relatively brief orientation. System stability, straightforward navigation, clear visual presentation, and portability were prioritized because technical difficulty or excessive interface complexity could distract participants from the TIM exercise.

4. Establish an AI-ready architecture

The platform established a communication interface between the Unity application and an external AI service. During Phase I, Unity was integrated with the OpenAI API, enabling AI-generated text responses to be exchanged and displayed within the VR environment. The integration was designed as a foundation for future AI capabilities beyond text generation, including role-specific virtual responders, incident-state awareness, natural-language interaction, structured scenario control, automated data capture, and after-action review. Phase I demonstrated reliable connectivity between the VR platform and the external AI service, but it did not implement validated agent behaviors or AI-driven scenario progression.

3.2 Platform Development Approach

The project followed an iterative design and development process that progressed from identifying TIM operational needs to defining priorities for future platform expansion. The process included eight major stages: identification of operational needs, platform and VOE design, VR environment development, shared-session and interaction development, technical testing, pilot demonstrations, practitioner feedback, and preparation of a future development roadmap.

The process began with identifying the roadway conditions, incident-response activities, multi-agency coordination needs, and practical limitations that the platform should address. The project team then developed the overall system concept and separated the reusable VOEs from scenario-specific incident content. This structure allowed different incidents to be implemented within the same roadway environment without rebuilding the entire platform.

The Interstate and Rural Highway VOEs were subsequently developed with roadway geometry, roadside features, incident objects, emergency-response assets, and simulated traffic paths. Participant navigation, first-person interaction, and shared-session functions were then incorporated to allow multiple users to occupy the same incident environment.

Technical testing was conducted throughout development to evaluate headset compatibility, navigation, scene loading, traffic movement, visual clarity, network synchronization, and standalone-system performance. Three pilot demonstrations were conducted after the principal platform functions had been implemented. Practitioner comments and project-team observations were used to identify platform refinements and establish priorities for future development.

Table 3-1 summarizes the principal stages and outcomes of the development process. Although the stages are presented sequentially, technical testing and refinement occurred throughout the project as new environments and functions were implemented.

Table 3-1. Platform Development Process

Stage Number	Development stage	Principal activities and outcomes
1	Identification of TIM operational needs	Identified relevant roadway conditions, incident-response activities, multi-agency coordination needs, and limitations of existing exercise formats.
2	Platform and VOE design	Defined the overall platform architecture and separated reusable VOEs from scenario-specific incident content.
3	VR environment development	Developed the Interstate and Rural Highway VOEs, including roadway geometry, roadside features, emergency-response assets, incident objects, and simulated traffic paths.
4	Shared-session and interaction development	Implemented participant navigation, first-person interaction, and shared-session functions that allowed multiple users to occupy the same incident environment.
5	Technical testing	Evaluated headset compatibility, navigation, scene loading, traffic movement, visual clarity, synchronization, and standalone-system performance.
6	Pilot demonstrations	Presented the platform during three demonstrations to assess feasibility, operational relevance, usability, and potential applications.
7	Practitioner feedback	Documented practitioner comments and project-team observations regarding platform strengths, limitations, and recommended improvements.
8	Future development roadmap	Identified priorities for continued development, including AI-enabled virtual responders, scenario-state management, instructor controls, data capture, and after-action review.

3.3 Overall System Architecture and Technology Framework

The immersive TIM platform was designed as a modular system that integrated standalone VR hardware, reusable VOEs, incident-scene components, simulated traffic, participant interaction, shared-session functionality, and scenario-management functions. These components worked together to provide a common virtual setting in which multiple participants could experience and discuss roadway incidents from first-person perspective.

The Phase I platform included the Interstate and Rural Highway VOEs, simulated roadway traffic, incident and emergency-response vehicles, participant navigation, selected object interactions, and shared multi-user sessions. The VOEs provided persistent roadway and roadside settings,

while scenario-specific content defined the incident vehicles, lane blockages, emergency-response resources, traffic-control elements, and participant starting conditions. This separation allowed additional incident scenarios to be developed within an existing VOE without reconstructing the complete roadway model.

The platform was developed using Unity 6000.3.13f1. Unity served as the primary development environment for creating 3D roadway environments, incident objects, simulated traffic, participant interactions, multiplayer functions, and application logic. The VR interface used OpenXR to support headset tracking, controller input, participant navigation, and object interaction. Multiplayer networking incorporated Netcode for GameObjects, Unity Multiplayer Services, and a Distributed Authority architecture. Under this architecture, responsibility for synchronizing networked objects and application states was distributed among connected clients rather than assigned to a dedicated server. Unity cloud services supported session connectivity and management, while session-management responsibility could transfer if the initial session owner disconnected. Unity Vivox provided voice communication within the application. During the pilot, shared sessions supported up to four simultaneous participants.

The hardware platform was deployed exclusively on Meta Quest 3 standalone VR headsets. This standalone configuration improved portability and eliminated the need for external computers, cables, or dedicated gaming hardware during training and demonstrations. However, the hardware also imposed performance constraints related to model complexity, texture resolution, lighting, shadows, active traffic vehicles, physics, animation, and network synchronization. Consequently, the platform was optimized to ensure stable performance, clear representation of roadway conditions, and intuitive participant interaction rather than pursuing photorealistic reproduction of every roadway and roadside feature.

The platform also incorporated an initial connection between Unity and the OpenAI API. Through this integration, the Unity application could submit information to an OpenAI model, receive model-generated text, and present the resulting content within the VR environment. This proof-of-concept function demonstrated the technical feasibility of incorporating generative AI content directly into the immersive platform. The Phase I AI implementation was limited to communication between Unity and the external AI service and the presentation of model-generated content. It did not include a validated, role-specific AI responder capable of maintaining an agency identity, interpreting comprehensive incident-state information, or engaging in operationally realistic dialogue. The AI output also did not modify Unity variables, manipulate virtual objects, or trigger changes in roadway and incident conditions.

The principal hardware, software, networking, communication, roadway-environment, and AI-integration components of the TIM platform are summarized in Table 3-2.

Table 3-2. Principal Platform Components

Component	Pilot implementation	Function
Development environment	Unity 6000.3.13f1	Supported environment development, interaction, networking, simulated traffic, and application logic.
VR interface	OpenXR	Connected the application with supported VR hardware and interaction functions.
Networking	Netcode for GameObjects, Unity Multiplayer Services, and Distributed Authority	Supported cloud-connected shared sessions and synchronization among participants.
Voice communication	Unity Vivox	Supported voice communication within the application.
Head-mounted display	Meta Quest 3	Provided standalone immersive visualization and user input.
Roadway environments	Interstate and Rural Highway VOEs	Represented two distinct TIM operating contexts.
Initial AI integration	Unity connection to the OpenAI API	Allowed the application to exchange information with an OpenAI model and receive model-generated text.

As shown in Figure 3-1, the system architecture provided flexibility for future development. The primary future AI application is the development of virtual responders that can represent unavailable agencies, communicate with trainees, provide status updates, and perform defined role-specific actions. Additional future capabilities may include natural-language interaction, adaptive scenario progression, instructor controls, performance-data capture, scenario replay, and after-action review.

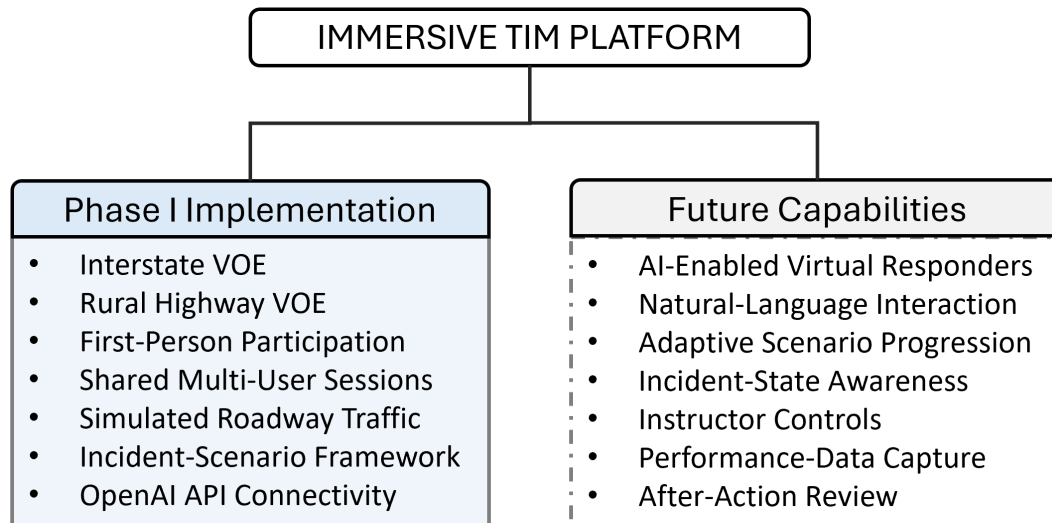


Figure 3-1. Current and Future Platform Architecture

3.4 Modular VOE and Scenario Framework

Modularity was a central design principle of the platform. The system separated persistent roadway environments from scenario-specific incident content so that roadway assets, traffic paths, participant interactions, and networking functions could be reused across multiple exercises.

A VOE is a reusable immersive digital setting representing a particular roadway and operating context. Persistent VOE components included roadway geometry, pavement markings, roadside features, environmental conditions, participant navigation areas, and simulated traffic paths. Scenario-specific components included involved vehicles, emergency-response resources, lane blockages, traffic-control devices, participant starting conditions, and exercise objectives.

This structure allowed the incident configuration to be modified without reconstructing the entire virtual environment. It also supported two forms of expansion. Additional roadway contexts could be created as new VOEs, while new incidents could be added within an existing VOE. For example, an urban arterial or work-zone VOE could be added to the platform, while the existing Interstate VOE could be expanded with disabled-vehicle, rollover, hazardous-material, vehicle-fire, or secondary-crash scenarios.

3.4.1 Interstate VOE

As shown in Figure 3-2, the Interstate VOE represented a multilane, high-speed roadway based on the general operating context. It provided a reusable foundation for exercises involving high-speed approaching traffic, multiple travel lanes, lane blockages, emergency vehicle positioning, traffic-control deployment, responder exposure, vehicle recovery, and staged lane reopening.

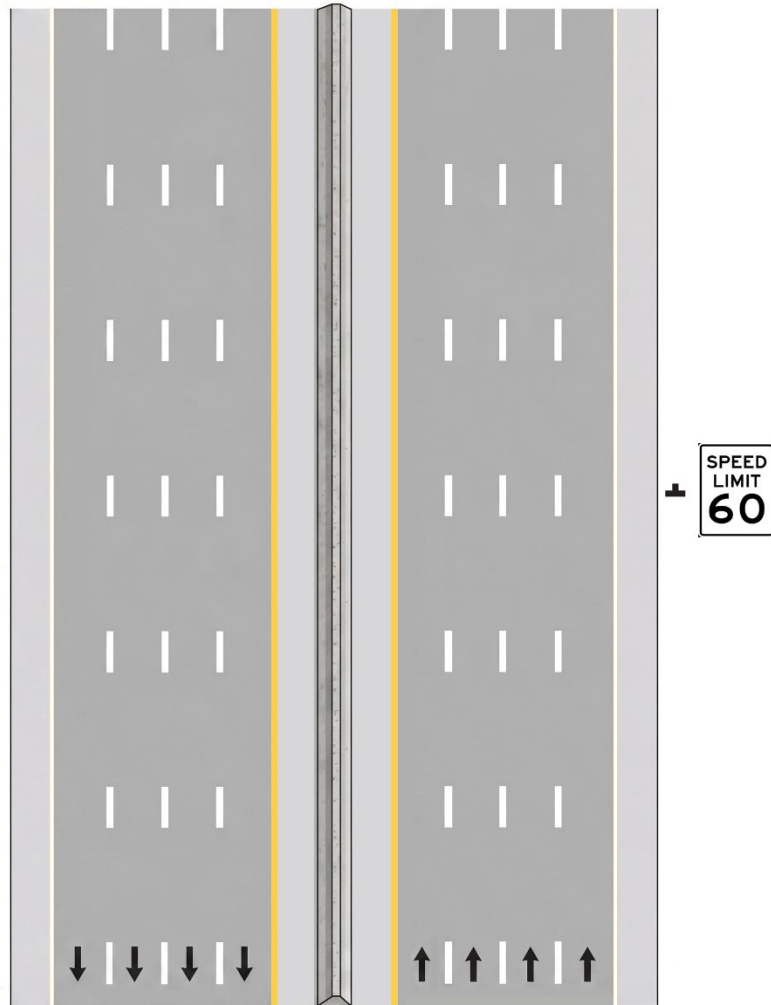


Figure 3-2. Interstate VOE Roadway Configuration

The environment supported consideration of scene protection, emergency vehicle placement, responder safety, traffic management, incident clearance, and secondary-crash risk. Additional incident configurations can be incorporated without reconstructing the underlying interstate roadway environment.

3.4.2 Rural Highway VOE

As shown in Figure 3-3, the Rural Highway VOE represented a two-lane, two-way roadway with opposing traffic. It provided a reusable foundation for incidents involving limited roadway width, constrained shoulder space, restricted responder access, temporary traffic stoppage, alternating traffic control, and limited opportunities for traffic diversion.

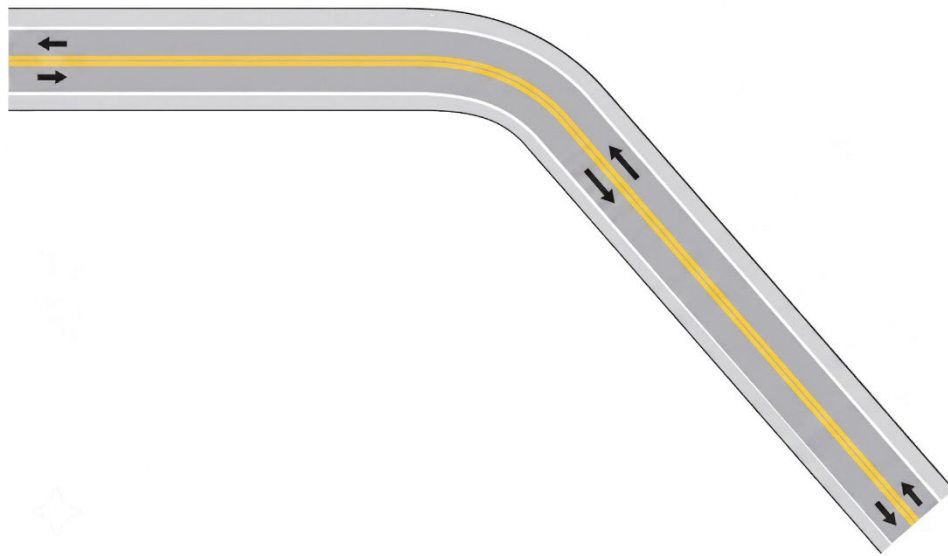


Figure 3-3. Rural Highway VOE Roadway Configuration

The rural roadway context introduced operating conditions that differed substantially from those of the Interstate VOE. Emergency vehicle staging and temporary traffic control needed to account for approaching traffic from both directions and the limited space available for response and recovery activities.

Table 3-3. Operational Characteristics of the Pilot VOE

Characteristic	Interstate VOE	Rural Highway VOE
Roadway configuration	Multilane divided roadway	Two-lane, two-way roadway
Traffic pattern	High-speed traffic moving in the same direction within each roadway	Opposing traffic within a shared roadway corridor
Primary traffic-management concerns	Lane blockage, merging, queues, and secondary-crash exposure	Alternating traffic, temporary full closure, and limited diversion opportunities
Responder-positioning concerns	Upstream protection and exposure to high-speed traffic	Constrained staging and exposure from both directions
Potential future incidents	Lane-blocking crash, commercial-vehicle rollover, hazardous-material incident, or vehicle fire	Rear-end crash, head-on crash, roadway obstruction, equipment incident, or weather-related event

3.5 Collaborative Participation and Role Framework

TIM operations depend on coordination among agencies with different responsibilities, information, resources, and operational priorities. To support collaborative training, the platform incorporated shared-session functionality that allowed multiple participants to enter the same VOE, experience a common incident scene, and communicate directly within the application.

During the pilot project, shared sessions supported up to four participants using Meta Quest 3 headsets. Participant positions, networked avatars, and supported interactions were synchronized so that users observed the same roadway and incident conditions from their respective first-person perspectives. Integrated Vivox voice communication enabled participants to communicate naturally without requiring a separate conferencing or radio application.

The collaborative environment was designed to promote shared situational awareness, interagency communication, coordinated decision-making, and instructor-led discussion. Participants could assume representative TIM roles, including law enforcement, fire and rescue, EMS, transportation agencies, towing and recovery, dispatch, incident command, and instructor or facilitator. The pilot implementation emphasized collaborative interaction rather than detailed simulation of agency-specific procedures, equipment, or operational authority.

Although the initial implementation provided only a basic role structure, it established a framework that can be expanded in future versions. A more comprehensive implementation could assign each participant a role-specific starting location, available information, communication channels, accessible resources, permitted actions, operational objectives, and

decision authority, allowing training scenarios to more closely reflect real-world agency responsibilities.

The role framework also established the foundation for future mixed human–AI exercises. When human participants are unavailable to represent every responding organization, AI-enabled virtual responders could assume selected agency roles. Each virtual responder would operate with a defined agency identity, responsibility set, information boundary, communication behavior, available resources, permitted actions, and decision authority, enabling realistic multiagency exercises even when all roles cannot be staffed by human participants.

3.6 Initial AI Integration and Future Agent Architecture

The platform included an initial connection between Unity and the OpenAI API. This integration allowed the application to exchange information with an OpenAI model and present model-generated text within the VR environment. The architecture was also designed to support future expansion into role-specific AI-enabled virtual responders, incident-state-aware interaction, controlled scenario actions, instructor oversight, and after-action review.

A complete TIM exercise may involve law enforcement, fire and rescue, EMS, transportation agencies, towing and recovery, dispatch, and other supporting organizations. Because providing a human participant for every role is often impractical, future AI-enabled responders could supplement collaborative exercises by representing selected agencies. Each virtual responder would operate according to a defined agency role, responsibility set, information boundary, available resources, permitted actions, communication behavior, and decision authority.

Phase I established the architectural foundation for these capabilities through reusable VOEs, shared-session networking, role-based participation, configurable scenarios, incident objects, and in-application communication. However, the pilot did not implement autonomous conversational agents, adaptive AI decision-making, AI-controlled scenario progression, or automated performance assessment.

Future development will require a structured incident-state model that maintains the evolving operational status of the exercise. The incident state may include lane closures, responder and vehicle locations, traffic-control deployments, agency arrival status, hazard and patient conditions, towing progress, completed actions, elapsed time, communications, and outstanding requests. Human and AI participant actions would update this shared state, allowing subsequent decisions and scenario progression to reflect current incident conditions.

The architecture also supports future implementation of structured events logging for participant positions, communications, object interactions, agency requests, decision timing, and incident-state updates. These data could enable scenario replay, after-action review, and AI-assisted instructor tools for organizing exercise timelines, identifying communication patterns, and generating preliminary discussion prompts. Such capabilities are intended to support, rather than replace, instructor evaluation and should be validated by TIM subject-matter experts.

3.7 Design Boundaries

The platform was developed as a proof-of-concept pilot and therefore reflects several intentional design boundaries. Two VOEes were implemented—an Interstate environment and a Rural Highway environment—rather than a comprehensive library of roadway types and incident scenarios.

Agency-specific tools, interfaces, operational procedures, and decision processes were intentionally simplified. The project emphasized development of a reusable immersive environment, collaborative multi-user participation, and an extensible system architecture rather than detailed simulation of every responder function.

Simulated traffic provided realistic roadway context but was not intended to serve as a calibrated microscopic traffic model. Future development may incorporate more advanced traffic demand, queue formation, merging behavior, diversion strategies, driver compliance, and emergency vehicle interactions for scenarios focused on traffic operations.

Shared sessions were demonstrated with up to four simultaneous participants. Larger participant groups, alternative network conditions, and scalability beyond the pilot configuration were outside the scope of Phase I.

Similarly, Phase I did not include structured event logging, autonomous AI-enabled responders, adaptive scenario progression, or automated performance assessment. Platform demonstrations relied primarily on screen recordings and observer feedback rather than time-stamped operational data.

Finally, the pilot demonstrations were intended to evaluate technical feasibility, operational relevance, usability, and practitioner acceptance. The project did not include controlled studies of knowledge acquisition, skill transfer, or long-term learning outcomes.

These boundaries were consistent with the pilot scope and established clear priorities for continued development. Section 4 describes the implementation of the platform and the two VOEes, while Section 6 presents the recommended roadmap for AI-enabled virtual responders, instructor tools, structured data capture, and formal evaluation.

4. Platform Implementation

4.1 Implementation Overview

The platform was implemented as a standalone VR application based on the hardware and software architecture described in Section 3. The application integrated roadway environments, incident vehicles, emergency-response assets, traffic-control devices, simulated traffic, participant navigation, shared-session networking, and in-application voice communication into a unified training environment.

Implementation was guided by four primary objectives. First, the roadway environments and incident scenes were designed to realistically represent the operational conditions encountered during TIM activities. Second, the application was optimized to operate reliably on Meta Quest 3 standalone headsets. Third, roadway environments, incident objects, and supporting assets were developed as modular, reusable components to facilitate the creation of additional scenarios without requiring substantial redevelopment. Finally, the user interface and interaction design were intended to minimize the learning curve for practitioners with little or no prior VR experience.

Table 4-1 summarizes the principal capabilities implemented in the Phase I pilot platform.

Table 4-1. Principal Implemented Functions

Function	Pilot implementation
Immersive participation	First-person observation and navigation within the incident environment
Collaborative participation	Shared sessions with up to four participants
Communication	Voice communication within the application
Roadway environments	Interstate and Rural Highway VOE
Incident representation	Incident vehicles, emergency-response vehicles, lane blockages, selected traffic-control elements, and an injured avatar with related animation.
Roadway traffic	Rule-based simulated vehicle movement
Participant interaction	Navigation, scene observation, selected object interaction, and a tunneling-vignette comfort function
Documentation	Screen recordings of representative platform functions
Initial AI integration	Unity–OpenAI API connection and presentation of model-generated text within the VR application

The implementation was intended to demonstrate the technical feasibility of an immersive, collaborative TIM training platform while providing a foundation for future expansion. Consistent with the proof-of-concept scope, the platform emphasized reusable architecture and collaborative functionality rather than detailed simulation of every agency-specific procedure, equipment configuration, or operational decision.

4.2 VOE and Incident-Scenario Construction

The implementation separated the persistent roadway environment from scenario-specific incident content. This approach allowed roadway geometry, roadside features, traffic paths, participant navigation areas, and networking functions to remain available while the incident configuration was modified.

Persistent VOE components included the roadway alignment, lane configuration, pavement markings, shoulders, roadside terrain, vegetation, environmental lighting, simulated traffic

paths, and participant navigation areas. These components defined the roadway context in which incident scenarios could be conducted.

Scenario-specific components included involved vehicles, disabled or damaged vehicles, emergency-response vehicles, lane blockages, traffic-control devices, participant starting locations, and exercise-specific object arrangements. These elements could be repositioned or replaced to create additional incident configurations within the same VOE.

Reusable assets were used where practical. Emergency vehicles, service vehicles, cones, signs, incident vehicles, and other roadway objects were configured so that they could be placed in different locations or incorporated into future scenarios. This reduced duplicated development work and allowed testing to focus on the modified scenario content.

Simulated traffic provided a dynamic roadway environment by moving vehicles along predefined travel paths using rule-based behaviors. The implementation represented approaching traffic, lane occupancy, and vehicle movement through the incident area while maintaining acceptable performance on standalone Meta Quest 3 headsets. The traffic model was intended to provide operational context rather than calibrated traffic simulation. More detailed traffic demand, queue formation, merging behavior, driver compliance, emergency-vehicle yielding, and temporary traffic-control operations remain areas for future development.

4.3 Interstate VOE Implementation

As shown in Figure 4-1, the Interstate VOE represented a multilane divided highway based on the general operating context of Interstate 70. It was not intended to reproduce a specific location at survey-level accuracy. Instead, the environment represented the roadway characteristics needed to demonstrate high-speed TIM operations.



Figure 4-1. Interstate 70 VOE Roadway

4.3.1 Roadway Environment

The Interstate VOE included multiple travel lanes, paved shoulders, pavement markings, roadside terrain, and environmental features extending both upstream and downstream of the incident area. The roadway was organized into three functional zones: an upstream approach where simulated traffic travels toward the incident, a central response area where emergency operations occur, and a downstream section where traffic continues beyond the incident scene. Together, these zones provide the spatial context needed to examine lane closures, responder positioning, work-space protection, and interactions with passing traffic.

As shown in Figure 4-2, an adjacent outer road containing a gas station and general store was also incorporated to support future scenarios involving secondary incidents, alternate access routes, or off-mainline emergency response.

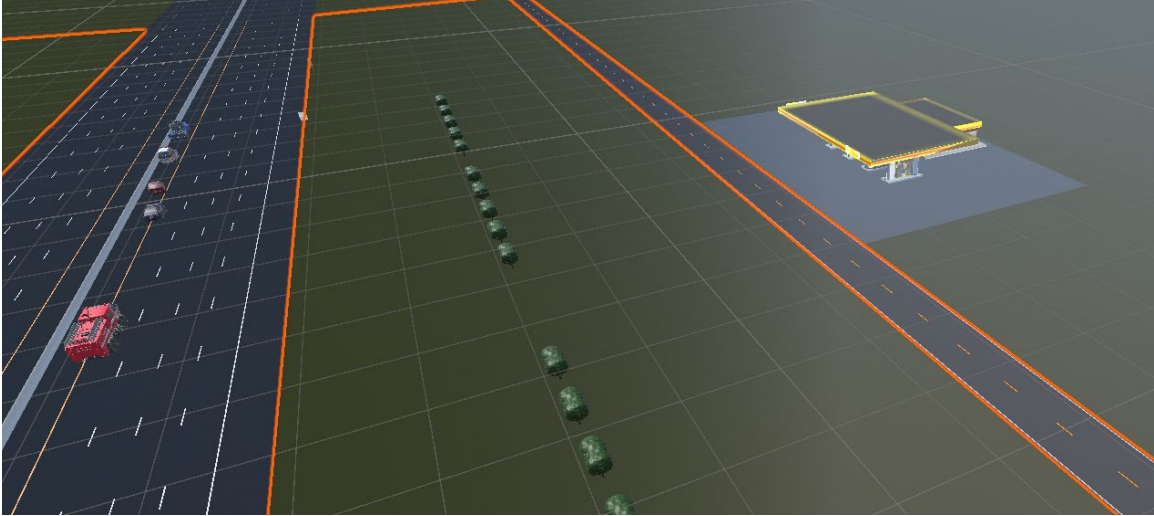


Figure 4-2. Outer Road of Interstate 70 VOE

4.3.2 Incident Configuration

As shown in Figure 4-3, the interstate incident scene included incident vehicles, emergency-response vehicles, and roadway blockages. Vehicle placement was configured to support discussion of scene protection, available travel lanes, responder workspace, and traffic movement through or around the incident.



Figure 4-3. Interstate 70 VOE Incident Scene

The scene also demonstrated how emergency-response activities occupy roadway space and influence the remaining capacity available to traffic. The modular configuration allows future versions to change the number of involved vehicles, blocked lanes, emergency resources, and traffic-control arrangements.

Potential future incidents within the Interstate VOE may include a disabled vehicle, lane-blocking collision, commercial-vehicle rollover, hazardous-material incident, vehicle fire, or secondary crash.

4.3.3 Simulated Traffic

Simulated vehicles traveled through the Interstate VOE using a rule-based traffic system developed with Unity AI Navigation. As shown in Figure 4-4, vehicles were defined to follow designated roadway paths and navigate among a series of waypoints representing the intended travel lanes and movement sequence. Avoidance colliders were incorporated to help regulate vehicle spacing, reduce conflicts among simulated vehicles, and prevent vehicles from entering restricted areas or passing through incident-scene objects.

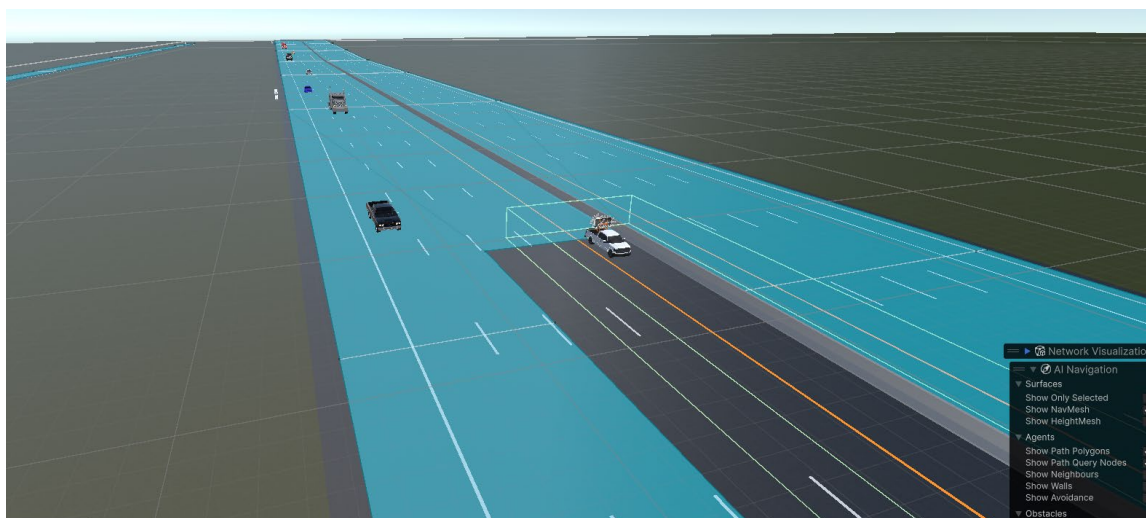


Figure 4-4. Simulated Traffic in Unity

The traffic system was configured to represent vehicles approaching the incident area, traveling through the available lanes, and continuing downstream after passing the response scene. This movement provided visual roadway activity and allowed participants to observe responder exposure to moving traffic, the effects of lane blockages, and the spatial relationship between emergency vehicles and approaching motorists.

A dedicated traffic-control input was also added to enable or disable simulated vehicle movement during demonstrations. This function allowed the project team to pause traffic when introducing the environment, explaining application controls, repositioning incident-scene elements, or discussing a specific operational condition. Traffic movement could then be reactivated when participants were ready to observe the incident under active roadway conditions. The control improved demonstration flexibility and reduced potential distractions during orientation and facilitated discussion.

The pilot traffic system was intended to provide representative roadway movement rather than reproduce traffic operations at a detailed analytical level. It was not calibrated as a microscopic traffic simulation and did not reproduce the full range of traffic-demand variation, queue formation and dissipation, merging behavior, diversion, driver compliance, or emergency-

vehicle yielding associated with a major interstate incident. Future development could incorporate configurable traffic volumes, additional vehicle types, more responsive lane-changing behavior, and traffic reactions to temporary traffic-control devices and changing incident conditions.

4.4 Rural Highway VOE Implementation

The Rural Highway VOE represented a two-lane, two-way roadway intended to capture the operational characteristics of rural TIM. Unlike the Interstate VOE, the rural environment emphasized constrained roadway geometry, opposing traffic, limited recovery space, and reduced opportunities for traffic diversion, all of which influence responder operations and traffic control.

4.4.1 Roadway Environment

As shown in Figure 4-5, the Rural Highway VOE included one travel lane in each direction, centerline and edge markings, roadside terrain, vegetation, and limited shoulder or roadside recovery space. The rural setting provided a visually distinct environment while maintaining the roadway features most relevant to incident operations.



Figure 4-5. Rural Highway VOE Roadway

The two-way roadway configuration exposed responders to traffic approaching from both directions and provides few opportunities for vehicles to pass the incident without temporary traffic control or controlled use of the opposing lane. As a result, the environment highlights the operational constraints commonly encountered during rural incident response.

4.4.2 Incident-Scene Configuration

The initial rural scenario positions incident vehicles and emergency-response vehicles within the travel lanes to create a constrained work area. As shown in Figure 4-6, the arrangement illustrates how even a relatively small incident can occupy a substantial portion of the available roadway, affecting traffic flow in both directions.

The scenario supports discussion of emergency-vehicle staging, responder work-space protection, towing and recovery access, temporary traffic stoppages, alternating one-way traffic operations, and circumstances that may require complete roadway closure.

The modular design also provides a foundation for developing additional rural incident scenarios, including rear-end and head-on collisions, roadway departures, overturned vehicles, farm-equipment incidents, fallen trees, utility emergencies, flooding, and other roadway obstructions. These scenarios represent a range of operational conditions that require different traffic-control strategies, responder coordination, and incident-management procedures.



Figure 4-6. Rear-end Crash Incident in Rural Highway VOE

4.4.3 Simulated Traffic

Simulated vehicles approached the incident area from both directions. This two-way traffic pattern created operating conditions that differed from those in the Interstate VOE. The traffic movement provided a visual basis for discussing upstream and downstream traffic control, restricted passing opportunities, exposure from opposing traffic, and the conditions required before the roadway could be reopened.

Table 4-2. Implemented Characteristics of the Two VOEs

Implementation element	Interstate VOE	Rural Highway VOE
Roadway type	Multilane divided highway	Two-lane, two-way highway
Traffic approach	Same-direction traffic within each roadway	Traffic approaching from both directions
Incident-space characteristics	Multiple lanes with high-speed exposure	Limited roadway and shoulder space
Emergency vehicle configuration	Positioned within or adjacent to blocked travel lanes	Positioned within a constrained two-way roadway
Traffic representation	Vehicles approaching and moving past the incident	Vehicles approaching from opposing directions
Principal operational context	Lane blockage, scene protection, and high-speed traffic	Restricted access, opposing traffic, and temporary control

4.5 Participant Interaction and Shared-Session Operation

Participants experienced the platform from a first-person perspective. Headset tracking allowed users to look around the incident scene naturally, while controller input supported movement, menu selection, and interaction with available virtual objects.

The interaction design was intentionally limited to the functions required for the pilot demonstrations. Using Unity’s Input System, controller inputs were mapped to a defined set of VR input actions, including navigation, view control, object selection, and object manipulation (Figure 4-7). These actions allowed participants to move within designated areas, observe roadway and incident conditions, examine emergency-response vehicle placement, monitor simulated traffic, and interact with selected virtual objects. For example, participants could select, move, and reposition traffic-control devices such as cones using the assigned controller actions. This input-action framework demonstrated the potential to support more detailed traffic-control deployment, equipment handling, and responder-task interactions in future versions.

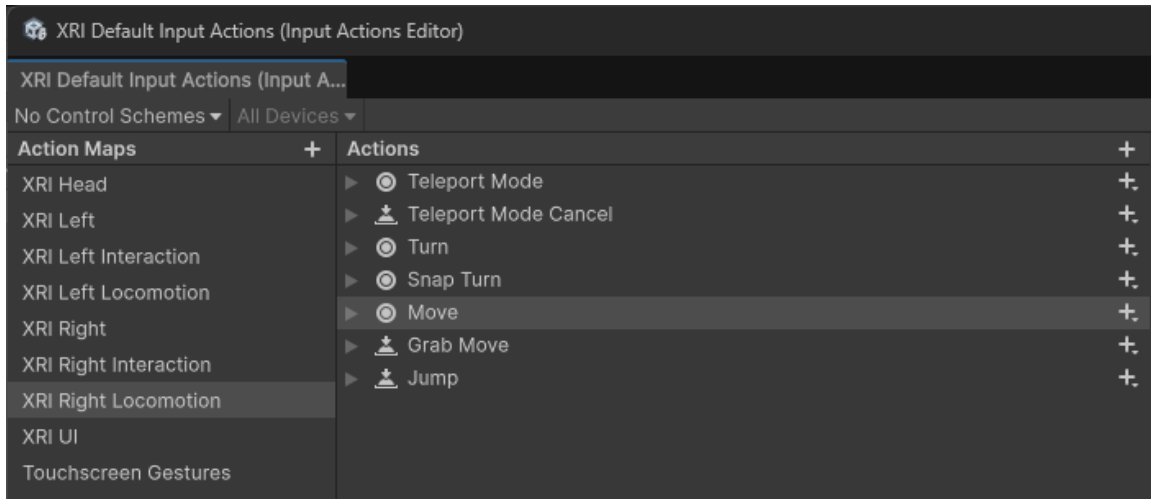


Figure 4-7. Unity Input Actions for VR Training

A tunneling vignette comfort function was incorporated to reduce potential discomfort during virtual locomotion (Figure 4-8). When activated, the function gradually reduced the participant's peripheral field of view by darkening the outer portion of the display while maintaining a clear central viewing area. This visual effect was intended to help mitigate motion discomfort during movement, and the vignette parameters could be adjusted based on participant feedback and individual comfort preferences.

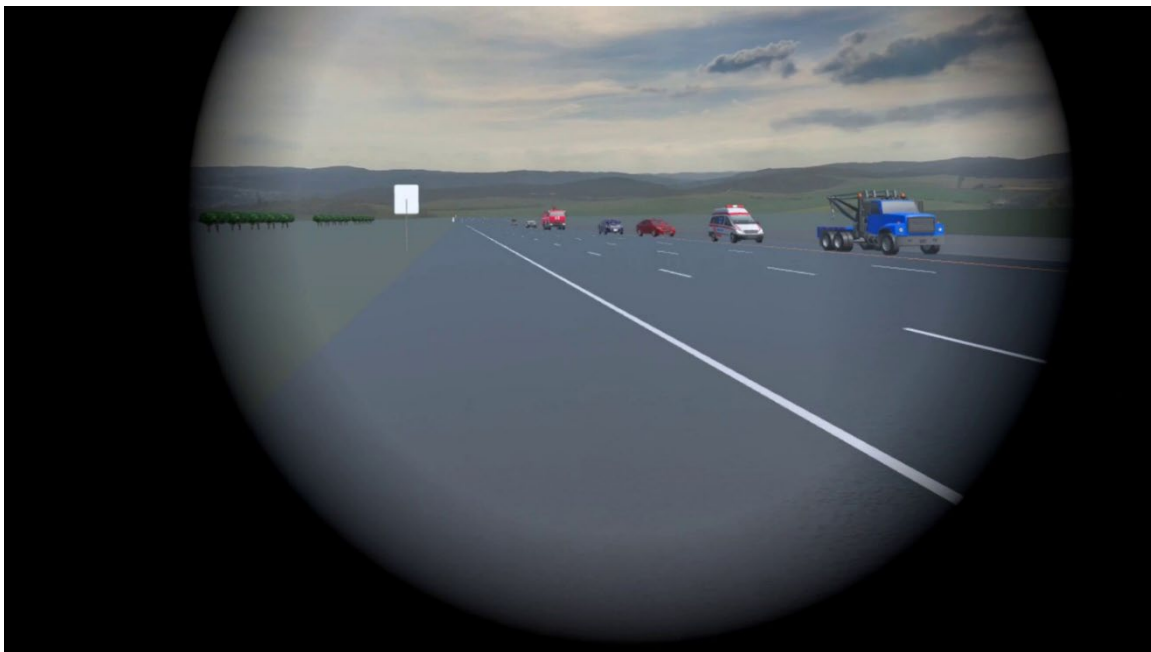


Figure 4-8. Tunneling Vignette Comfort Function

The platform also included interfaces for creating or joining multiplayer sessions, selecting participant configurations, and moving between the available VOs. Participants used the Shared-Session and Participant Configuration Interface shown in Figure 4-9 to enter a common

environment. Once connected, their virtual representations, positions, and supported interactions were synchronized across the participating headsets.

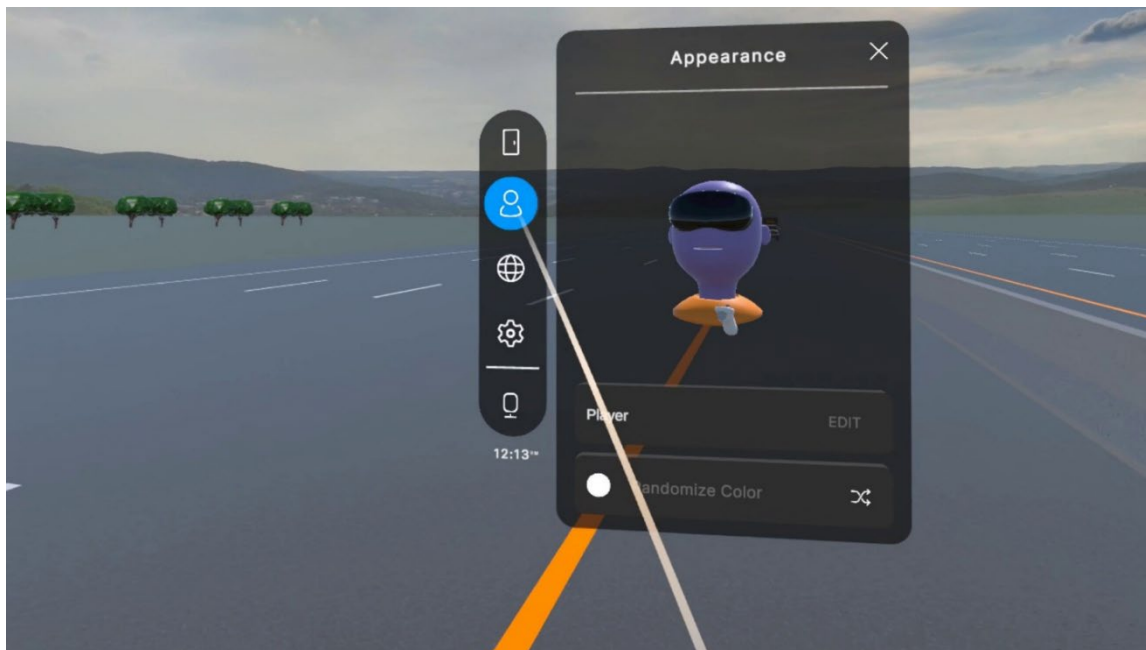


Figure 4-9. Shared-Session and Participant Configuration Interface

Shared sessions supported up to four participants simultaneously. Each participant used a Meta Quest 3 headset and experienced the incident from an individual first-person position. Unity Vivox provided voice communication within the application, allowing participants to communicate without using a separate conferencing or radio system.

The shared environment supported common observation and discussion of roadway and incident conditions. It also established the technical foundation for future role-based exercises in which participants may represent law enforcement, fire and rescue, EMS, transportation agencies, towing and recovery, dispatch, or other TIM partners.

The pilot did not implement detailed permissions, information access, or agency-specific interfaces for every participant role. Participants primarily used the same navigation, observation, communication, and object-interaction functions. Future versions may provide role-specific starting locations, operational information, resources, permitted interactions, and training objectives.

4.6 Pilot Configuration and Implementation Boundaries

All three pilot demonstrations used Meta Quest 3 standalone headsets. The pilot configuration was supported with up to four participants in a shared session and included in-application voice communication among connected users.

Screen recordings were used to document representative platform operation. The recordings captured first-person navigation, incident-scene observation, simulated traffic, selected object

interactions, operation of the tunneling-vignette comfort function, multiplayer-session interfaces, participant configuration, and transitions between the Interstate and Rural Highway VOEs.

The recordings documented what participants could see and do within the platform but did not constitute structured performance data. Phase I did not include a dedicated logging system for automatically recording participant locations, communications, decisions, object interactions, or scenario-state changes as time-stamped data. Consequently, the recordings could support general review of platform functions but could not provide a complete or readily searchable record of participant activities.

The pilot also implemented an initial connection between Unity and the OpenAI API. This integration allowed model-generated text to be received and presented within the VR application. The function represented a technical proof of concept and did not include validated agency-specific AI agents, comprehensive incident-state awareness, AI-triggered changes to Unity variables or scenario conditions, or adaptive scenario progression.

The Phase I implementation emphasized technical feasibility, portability, reusable roadway environments, shared participation, and representative TIM conditions. It did not reproduce every agency-specific procedure, tool, information source, or decision authority. Simulated traffic provided roadway activity and moving-vehicle exposure but was not calibrated as a detailed traffic model. The pilot also did not evaluate larger multiplayer sessions, substantially different network conditions, or long-duration training use.

5. Pilot Demonstrations and Practitioner Feedback

5.1 Demonstration and Feedback Approach

The pilot demonstrations were conducted to evaluate the technical feasibility, operational relevance, usability, and potential applications of the immersive TIM platform. Rather than serving as formal training evaluations, the demonstrations introduced practitioners to the VOEs, collaborative participation capabilities, and interactive features developed during Phase I while providing opportunities to obtain feedback for continued platform development.

Each demonstration generally included an overview of the project objectives, orientation to the Meta Quest 3 headset and application controls, presentation of the available VOEs, and discussion of potential TIM training applications. Participants were encouraged to explore the virtual environments and comment on roadway representation, incident realism, participant interaction, collaborative functionality, and opportunities for future enhancement.

Feedback was collected through participant discussion and observations documented by the project team. No standardized survey or formal assessment instrument was administered. Consequently, the findings presented in this section represent qualitative practitioner feedback rather than statistically generalizable evaluation results.

The demonstrations addressed the following questions:

- Were the roadway and incident environments understandable and operationally relevant?
- Could participants use the VR platform after a brief orientation?
- Did practitioners identify potential applications for TIM training and multi-agency exercises?
- What roadway environments, incident elements, or interactions should be added or improved?
- Which capabilities should be prioritized in a future phase?

5.2 Overview of Pilot Demonstrations

Three pilot demonstrations were completed during Phase I. Together, they provided opportunities to present the evolving platform to transportation practitioners, emergency responders, and multidisciplinary TIM partners while obtaining feedback to guide subsequent development.

Table 5-1 summarizes the dates, locations, participants, and principal objectives of the three demonstrations.

Table 5-1. Summary of Pilot Demonstrations

Demonstration	Date	Location and format	Participants	Principal purpose
MoDOT TIM VR Training Demonstration	April 30, 2026	Lafferre Hall E1510, University of Missouri, Columbia, MO	MoDOT Research and Emergency Management staff	Review the initial platform and obtain feedback on roadway and incident content
I-70 TIM Coalition Meeting	May 26, 2026	Boone County Emergency Communication Center, Columbia, MO	I-70 TIM Coalition members and partner organizations	Present the platform to a multidisciplinary TIM audience and discuss potential applications
MoDOT Stand Up for Safety Day	July 16, 2026	3211 Masonic Court, Jefferson City, MO	MoDOT personnel	Demonstrate the pilot platform to a broader safety-focused practitioner audience

5.3 Demonstration Findings

5.3.1 Pilot Demonstration 1: MoDOT TIM VR Training Demonstration

The first pilot demonstration was conducted on April 30, 2026, in Room E1510 of Lafferre Hall at the University of Missouri in Columbia, Missouri. Participants included MoDOT Research and Emergency Management staff.

The demonstration introduced the initial Interstate VOE, first-person immersive interaction, multiplayer functionality, and the overall concept of VR-based TIM training. Practitioner feedback identified the need to strengthen the representation of rural two-lane, two-way highway conditions. Participants noted that rural incidents involve distinct operational challenges, including opposing traffic, limited shoulder space, constrained responder staging, and fewer opportunities for traffic diversion. This feedback informed further refinement of the Rural Highway VOE during Phase I.

Participants also recommended improving incident realism by adding an injured virtual person and associated animation. The project team subsequently implemented an injured avatar and related animation during Phase I (Figure 5-1). These elements improved the representation of responder priorities and emergency activities within the incident scene.



Figure 5-1. Injured Avatar Added to TIM Training Platform

The first demonstration therefore established two major development priorities: expanding roadway environments and improving incident representation.

5.3.2 Pilot Demonstration 2: I-70 TIM Coalition Meeting

The second pilot demonstration was conducted on May 26, 2026, during the I-70 TIM Coalition Meeting at the Boone County Emergency Communication Center in Columbia, Missouri. Representatives from multiple organizations involved in TIM planning and response attended the meeting, including transportation agencies, emergency responders, and towing and recovery personnel.

The demonstration presented both the Interstate and Rural Highway VOs, collaborative multiplayer capabilities, and modular platform architecture.

Participants expressed strong interest in the platform's potential to support multidisciplinary TIM training. Input from towing and recovery representatives was particularly valuable because recovery activities play a significant role in incident clearance while often receiving limited attention during conventional training exercises.

Feedback from this demonstration reinforced the importance of representing towing and recovery as an active operational participant. Future scenarios should therefore incorporate defined towing roles, communication exchanges, recovery progress updates, and lane-clearance activities as integral components of collaborative exercises.

5.3.3 Pilot Demonstration 3: MoDOT Stand Up for Safety Day

The third pilot demonstration was conducted on July 16, 2026, during MoDOT Stand Up for Safety Day at 3211 Masonic Court in Jefferson City, Missouri. Participants experienced the platform using Meta Quest 3 headsets and explored both VOEs.

Unlike the earlier demonstrations, practitioner feedback focused primarily on usability. During an emergency-vehicle positioning activity, one participant initially experienced difficulty rotating a selected vehicle before discovering that the right-hand controller thumbstick controlled vehicle rotation.

This observation indicated that the interaction capability had been successfully implemented but was not immediately intuitive for first-time users. Future demonstrations and training sessions should therefore include a brief orientation covering navigation, controller inputs, object selection, movement, and rotation before operational exercises begin. Short practice activities or on-screen guidance could further reduce the learning curve and allow participants to focus on TIM decision-making rather than interface controls.

5.4 Synthesis of Practitioner Feedback

The three pilot demonstrations generated qualitative feedback concerning roadway context, incident representation, multidisciplinary participation, usability, and potential future applications. Although the feedback was not collected through a standardized survey, it identified several practical priorities for continued platform development.

Representation of Roadway Contexts

Practitioners emphasized that effective TIM training should represent multiple roadway environments rather than a single interstate setting. Further refinement of the Rural Highway VOE addressed this feedback and demonstrated the flexibility of the modular platform architecture.

Incident Representation

Practitioner feedback identified the need for more complete incident representation. In response, the project team implemented an injured avatar and related animation during Phase I. Participants also identified opportunities to incorporate additional responder activities, patient conditions, hazards, and dynamic scene elements in future scenarios.

Collaborative Multi-Agency Training

Participants viewed the shared virtual environment as one of the platform's greatest strengths. The ability for multiple agencies to observe the same incident, communicate in real time, and coordinate operational decisions was considered a valuable capability that is difficult to achieve through classroom training alone.

Platform Usability

Practitioners generally adapted to the VR platform after a brief orientation. Feedback nevertheless indicated that first-time users benefit from structured orientation covering navigation, object manipulation, and controller functions before beginning operational exercises.

Opportunities for AI-Enabled Virtual Responders

Participants also recognized the potential value of AI-enabled virtual responders for representing agencies that cannot be staffed during collaborative exercises. Transportation agencies and towing and recovery personnel were identified as practical initial applications because their communications and operational decisions directly influence traffic control, recovery activities, and roadway reopening.

5.5 Evaluation Limitations

The pilot demonstrations were qualitative and exploratory. They were conducted to assess technical feasibility, operational relevance, usability, and potential applications rather than to measure formal learning outcomes.

The demonstrations did not include a standardized survey, pretest – post-test assessment, comparison group, or validated measures of knowledge gain, skill transfer, or long-term retention. The findings should therefore be interpreted as preliminary practitioner observations rather than statistically generalizable results.

Participants represented selected MoDOT personnel and TIM partner organizations rather than a representative sample of all Missouri responders. The number of individuals who directly used a headset during each demonstration may also have differed from the total number attending the associated meeting or event.

The platform continued to evolve between demonstrations. Participants may have reviewed different roadway environments, incident elements, or interaction functions. This iterative development approach was appropriate for the pilot but limits direct comparison of feedback across the three demonstrations. The demonstrations also did not evaluate larger multiplayer sessions, extended training use, varied network conditions, or independent delivery by instructors who were not involved in platform development. These issues should be considered in a future structured evaluation.

6. Conclusions and Next Steps

The Phase I pilot established a technical and operational foundation for a modular immersive TIM training platform rather than a complete training system. The project demonstrated reusable VOE, shared multi-user participation, simulated roadway traffic, selected participant interactions, in-application communication, and an initial connection between Unity and the OpenAI API.

This section discusses the principal contributions and potential applications of the pilot and presents conclusions and recommended next steps. The recommendations are organized around three areas: scenario and participant development; AI-enabled virtual responders and instructor oversight; and data capture, after-action review, and evaluation.

6.1 Principal Project Contributions

6.1.1 Modular VOE and Scenario Framework

The principal project contribution was the development of a modular immersive TIM platform rather than a single fixed VR scenario. Roadway environments, simulated traffic, incident vehicles, emergency-response assets, traffic-control devices, participant functions, and networking components were organized so that they could be modified or reused across multiple exercises.

The VOE framework separated persistent roadway and roadside conditions from scenario-specific incident content. Persistent components included roadway geometry, pavement markings, roadside features, participant navigation areas, simulated traffic paths, and environmental conditions. Scenario-specific components included involved vehicles, emergency-response resources, lane blockages, traffic-control devices, participant starting conditions, agency roles, and training objectives.

This structure reduced the need to reconstruct the complete application for each new incident. Additional incident configurations can be developed within an existing VOE, while a new VOE can be added when a substantially different roadway context is needed. For example, the Interstate VOE can support disabled-vehicle, lane-blocking crash, commercial-vehicle rollover, hazardous-material, vehicle-fire, and secondary-crash scenarios without requiring reconstruction of the underlying roadway environment.

The Interstate and Rural Highway VOEs demonstrated the application of this framework across two substantially different roadway contexts. The Interstate VOE represented multilane, high-speed operations, while the Rural Highway VOE represented a two-lane, two-way roadway with opposing traffic and constrained response space. These environments demonstrated that immersive TIM training should account for roadway context rather than rely on a single generic incident setting.

6.1.2 Shared Multi-User Participation

The platform incorporated shared-session functionality that allowed multiple participants to occupy the same virtual incident environment. Shared sessions supported up to four participants using Meta Quest 3 standalone headsets. Participant positions, virtual representations, and supported interactions were synchronized across connected headsets, while Unity Vivox provided voice communication within the application.

This functionality established a foundation for collaborative TIM training. Participants could observe the same roadway and incident conditions from individual first-person positions and discuss scene protection, emergency-vehicle placement, traffic management, incident clearance, responder safety, and roadway reopening.

The Phase I implementation did not include complete agency-specific interfaces, permissions, information access, or task sequences. Participants primarily used a common set of navigation, observation, communication, and object-interaction functions. Nevertheless, the shared-session framework demonstrated the feasibility of developing future exercises in which participants represent law enforcement, fire and rescue, EMS, transportation agencies, towing and recovery, dispatch, and other TIM partners.

6.1.3 Initial Unity–OpenAI API Integration

Phase I implemented an initial connection between Unity and the OpenAI API. Through this connection, the VR application could submit information to an OpenAI model, receive model-generated text, and present the resulting content within the immersive environment.

This implementation represented a technical proof of concept rather than a complete AI-enabled virtual responder. The generated content was not yet grounded in a validated agency-specific role, comprehensive incident-state information, or defined operational decision boundaries. The AI output also did not modify Unity variables, manipulate virtual objects, or trigger changes in roadway and incident conditions.

Nevertheless, the completed integration reduced the technical uncertainty associated with connecting an external generative AI service to the VR application. It established a communication pathway that can be expanded to support role-specific virtual responders, structured trainee-agent interaction, incident-state awareness, controlled scenario actions, and AI-assisted after-action review.

6.1.4 Practitioner-Informed Development

The pilot demonstrations provided practical feedback that influenced both Phase I development and future priorities. The recommendation to represent rural two-lane, two-way roadway conditions led to development of the Rural Highway VOE during Phase I. Participants also recommended adding an injured avatar and related animation to improve the representation of the incident scene. These elements were subsequently implemented during Phase I.

Other recommendations were documented as priorities for future development. These included representing towing and recovery as a more active operational role and improving participant preparation for object and vehicle manipulation.

The demonstrations also showed that an available interaction function may not be apparent to a first-time participant. During the third demonstration, a participant initially experienced difficulty rotating an emergency vehicle but was able to perform the action after learning that the right-hand controller thumbstick directly controlled vehicle rotation. This observation indicated that future training sessions should include standardized control instructions and a short practice activity before participants enter the operational exercise.

6.2 Potential Applications

The platform is designed to supplement existing TIM training methods rather than replace classroom training, tabletop exercises, field exercises, or full-scale simulations. Each delivery method serves a different purpose. Classroom and online training can provide consistent knowledge regarding policies, responsibilities, and recommended practices. Tabletop exercises can support facilitated discussion of agency roles and decision-making. Full-scale exercises can provide experience with actual vehicles, equipment, and roadway operations but require substantial personnel, facilities, and coordination.

An immersive platform could provide an intermediate exercise format. It could represent roadway geometry, moving traffic, incident vehicles, responder positioning, and spatial relationships without requiring a roadway closure or deployment of full-scale equipment. Because the VOs and incident components are reusable, exercises could also be repeated more frequently and modified to address different objectives.

Potential applications include responder orientation, emergency-vehicle positioning, scene-protection discussion, traffic-control planning, multi-agency communication, towing and recovery coordination, lane-reopening decisions, instructor-led case review, and preparation for larger field exercises.

The platform may be particularly useful when participants need to understand how roadway conditions and agency actions relate spatially. It can also allow an instructor to pause an exercise, reposition incident or emergency-response vehicles, compare alternative arrangements, and discuss the potential consequences of different operational decisions.

6.3 Recommended Next Steps

Continued development should focus on a limited number of improvements that build directly on the Phase I platform. Priority areas include scenario and participant development, AI-enabled virtual responders and instructor oversight, and data capture, after-action review, and phased evaluation.

6.3.1 Scenario and Participant Development

Near-term development should prioritize high-value incident scenarios within the existing Interstate and Rural Highway VOs before additional roadway environments are constructed. This approach would reuse the roadway geometry, simulated traffic, navigation, networking, communication, and interaction functions already developed during Phase I. Scenario priorities should be established with MoDOT and TIM practitioners based on operational significance, multidisciplinary training value, and the difficulty of practicing the incident through conventional training.

Each scenario should define its initial conditions, participating agency roles, available information, expected communications, operational decision points, permitted actions, progression criteria, and exercise end state. Additional patient conditions, responder activities, towing and recovery functions, hazards, equipment, and traffic behaviors should be incorporated only when they directly support the training objectives.

Future sessions should also include a standardized participant orientation and short practice activity. The orientation should cover headset use, navigation, communication, object selection, vehicle movement and rotation, and the tunneling-vignette comfort function. This preparation would reduce the likelihood that interface difficulties interfere with the operational exercise.

6.3.2 AI-Enabled Virtual Responders and Instructor Oversight

Phase II should build on the Unity–OpenAI API connection implemented during Phase I by developing a limited number of validated, role-specific virtual responders. Initial development should focus on one priority scenario and one or two agency roles so that the complete interaction process can be tested before expansion to additional agencies and incident types.

Each virtual responder should operate within defined agency responsibilities, available information, permitted actions, communication expectations, decision authority, and operational boundaries. A common incident-state model should provide relevant information concerning lane blockages, vehicle and responder locations, agency status, traffic-control deployment, hazards, patient conditions, towing and recovery progress, completed tasks, and unresolved requests.

Virtual responders should communicate within their assigned operational scope and issue structured requests for approved scenario actions rather than receive unrestricted control of the Unity environment. The Unity application should validate each request against the current incident state, assigned role, permitted actions, and applicable instructor controls before modifying scenario conditions.

An instructor interface should support exercise initiation, participant and virtual-responder role assignment, scenario-event control, review of communications and pending AI actions, intervention, and override. Virtual-responder roles and behaviors should be developed and validated with TIM subject-matter experts. Communications, scenario requests, validation results, and resulting actions should remain traceable, and AI-generated outputs should support rather than replace instructor and practitioner judgment.

6.3.3 Data Capture, After-Action Review, and Evaluation

Future versions should record participant, instructor, virtual-responder, and scenario activities as structured, time-stamped data. Relevant data may include participant locations, communications, vehicle placement, object interactions, agency requests, decision timing, instructor interventions, AI responses, and incident-state changes.

These data could support a chronological exercise timeline, selected scenario replay, and instructor-led after-action review. The review could help participants examine communication sequences, vehicle positioning, traffic-control actions, unresolved requests, and decisions affecting scene protection, clearance, and roadway reopening. AI could assist with organizing the recorded information and generating preliminary discussion prompts, but the instructor should determine the final interpretation of participant performance.

Evaluation should proceed incrementally. Initial testing should emphasize technical performance, usability, operational validity, AI-agent behavior, data capture, and instructor controls. Formal training-effectiveness evaluation should begin only after the scenarios, participant roles, AI functions, and delivery procedures have stabilized.

Table 6-1. Summary of Recommended Next Steps

Priority	Recommendation
Scenario development	Add priority incident scenarios within the existing VOEs before constructing additional roadway environments.
Participant preparation	Provide standardized control instructions and a required practice activity.
Operational representation	Expand the Phase I injury representation by incorporating relevant patient conditions, responder activities, hazards, equipment, animations, and agency-specific functions.
AI-enabled participation	Develop a limited number of validated, agency-specific virtual responders supported by incident-state information and controlled Unity actions.
Instructor oversight	Provide scenario controls, AI-action review, intervention, and override capabilities.
Data and after-action review	Implement structured event logging, exercise timelines, selected replay, and instructor-led review.
Evaluation	Conduct phased technical, usability, operational-validity, AI-agent, and training-effectiveness evaluations.

6.4 Conclusions

This pilot project developed and demonstrated a modular immersive platform for TIM training. The application was deployed on Meta Quest 3 standalone VR headsets and included first-person navigation, in-application voice communication, rule-based simulated roadway traffic, selected object interactions, and shared sessions supporting up to four participants.

Two reusable VOs were developed. The Interstate VO represented multilane, high-speed incident conditions, while the Rural Highway VO represented a two-lane, two-way roadway with opposing traffic and constrained response space. Separating persistent roadway environments from scenario-specific incident content established a flexible structure for developing additional exercises without reconstructing the complete platform.

The project also implemented an initial connection between Unity and the OpenAI API. This proof of concept allowed model-generated text to be presented within the VR application and established a technical pathway for future role-specific virtual responders. Phase I did not implement validated agency-specific agents, comprehensive incident-state awareness, or AI-triggered changes to Unity variables and scenario conditions.

Three pilot demonstrations provided qualitative practitioner feedback regarding technical feasibility, operational relevance, usability, and potential applications. Feedback contributed to development of the Rural Highway VO, implementation of an injured avatar and related animation, and identification of priorities involving towing and recovery, participant orientation, structured data capture, instructor tools, and AI-enabled participation.

The demonstrations indicated that the platform could supplement existing classroom, tabletop, online, and field-based TIM training. However, the pilot did not constitute a formal evaluation of training effectiveness. Overall, Phase I established a reusable technical and operational foundation for continued development through a focused second phase emphasizing scenario expansion, participant preparation, controlled AI-enabled virtual responders, structured after-action review, and phased evaluation.

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