A Vision for Transformative Intersections

Yuankai He and Weisong Shi

***Abstract*—The rapid evolution of connected and autonomous vehicles (CAVs) is ushering in a transformative era for transportation, challenging the adequacy of traditional intersection designs. Conventional intersections, which rely heavily on static traffic signals and human input, are ill-equipped to meet the demands of CAV technologies that require dynamic, real-time communication and coordination to enhance traffic flow and improve safety significantly. This paper introduces OpenIntersection, an active framework that re-imagines intersection design by modulating workload, integrating sensor systems, such as camera and LiDAR sensors, Vehicle-to-Everything (V2X) communication, and heterogeneous computing platforms. OpenIntersection is designed to support the rapid development, validation, and deployment of adaptive intersection systems that meet the complex demands of CAVs, thereby optimizing both traffic efficiency and road safety.**

I. Introduction

The emergence of connected and autonomous vehicles (CAVs) marks a transformative period in transportation, compelling a reevaluation of existing intersection designs. Traditional intersections, primarily governed by automated traffic signals, are proving inadequate in the era of CAVs that demand dynamic, real-time communication and coordination. As vehicles evolve to become more interconnected and autonomous, the existing infrastructure, which facilitates static and predetermined traffic management, falls short of supporting the sophisticated needs of modern transportation technologies.

Existing intersections are designed with dual objectives: regulating traffic flow and ensuring the safety of all road users. They control the movement of vehicles and pedestrians through intersecting paths, optimizing for efficiency and safety. However, in the context of rapid technological advancements where software-defined capabilities are prevalent, traditional intersections remain largely hardware-dependent, limiting their adaptability and the ease with which they can integrate technological upgrades.

This limitation is critical as emerging technologies that could significantly enhance safety and operational efficiency continue to develop. These advancements often depend on the capabilities of connected intersections, which are integral to intelligent transportation systems (ITS). ITS employs Vehicle-to-Everything (C-V2X) technology to facilitate robust wireless communication between vehicles, infrastructure, and other road users, supporting functionalities such as signal phase and timing (SPaT), collision avoidance, and cooperative autonomous driving.

Despite these advancements, current intersection systems remain passive and non-programmable, failing to fully meet the evolving demands for transportation efficiency and safety. This paper introduces OpenIntersection, a transformative framework that re-envisions intersection design by incorporating and modularizing advanced technologies such as camera systems, LiDAR sensors, Vehicle-to-Everything (V2X) communication, and a heterogeneous computing platform. OpenIntersection is designed to support the rapid development, validation, and deployment of adaptive, software-defined intersection systems to optimize traffic flow and enhance road safety effectively. It takes into account the entire architecture of connected intersection systems, including their components, functions, interfaces, and performance requirements, thus offering a comprehensive and visionary approach to future intersection designs.

Furthermore, this paper aims to interest OEMs, researchers, and policymakers in the development and deployment of these advanced intersection systems. It validates the proposed design through prototype and simulation test results, explores the inherent limitations of current designs, and proposes future directions for the evolution of intersection technologies.

This paper is presented as follows: Section II offers important background information on connected and autonomous vehicle technologies, the design of intersections and state-of-the-art technologies for intersections, and related works; Section III summarizes our motivation to create the OpenIntersection reference design; Section IV takes a deep dive into the details of OpenIntersection; Section V demonstrates a prototype and how OpenIntersection opens up the door to Software-Defined-Intersection, and finally Section VI concludes the paper and discusses on future works.

II. Background Information

A. The Intersection is Dangerous

According to NHTSA [1], almost one-third of the annual traffic *fatalities* involves an intersection, averaging ***10389*** in the past five years. The number is even more significant for non-fatal traffic accidents. This statistic not only underscores the inherent risk associated with intersections but also highlights the urgent need for innovative solutions to mitigate such risks.

Emerging technologies like connected vehicles and smart intersection systems present a viable avenue for enhancing road safety. Connected vehicles, equipped with advanced communication capabilities, facilitate real-time information exchange between vehicles and surrounding infrastructure, augmenting situational awareness and enabling preemptive responses to potential hazards.

B. Connected and Autonomous Vehicles (CAV)

Connected and Autonomous vehicles have increased safety levels when compared to non-connected vehicles. This is because connected vehicles can also leverage information from surrounding vehicles and infrastructure. Information such as the traffic light signal phase and the time until the next phase can help the driver decide whether to speed up or slow down. Pedestrian detection information helps drivers avoid vulnerable road users when they are in the blind spot zone. Other information, such as the vehicles' heading, speed, and turn signal status, can help surrounding vehicles make driving decisions.

Talebpour's work [14] in 2016 argues that connected vehicles can improve traffic stability and throughput. Rana's survey work [12] discusses the impact of CAVs on transportation performance. The paper lists road safety as the most important benefit among highway capacity, mobility, environmental, and economic benefits. Deng's work [4] in 2019 and Dong's work on the vision and challenge for collaborative autonomous driving [6] in 2020 demonstrated that V2X-based cooperative collision avoidance scheme performs better than traditional GNSS-based collision avoidance. Yu's work [16] in 2022 demonstrated that autonomous driving vehicles that share sensing or perception data via broadcast-based V2X technologies have improved safety. Talebpour, Dong, and Yu all support the idea that connected vehicles can increase road safety.

C. Recent Advancements in Intelligent Transportation Systems (ITS)

In addition to recent advancements in CAVs, Ran's work [11] in 2019 is one of the first to propose CAVH ITS to work cooperatively with automated vehicles. Aldakkhelallah's work [2] in 2021 investigated the role of autonomous vehicles in intelligent transportation systems. Wu's work [15] in 2022 proposes an ITS to manage unprotected left-turn vehicles when the driver's view is blocked. In Zhang et al.'s work [17], the authors proposed a perception system in the most dangerous roundabout in the state of Michigan. In [7], He et al. push V2X beyond its intended design to guide connected vehicles to stay in lane with infrastructure cameras. Companies, such as Ouster [9], have developed their own ITS systems to support connected and autonomous vehicles. In addition, many others have reviewed and proposed many designs for CAVs and ITS [3], [5], [8], [10], [13]

However, despite years of research and government pilot studies, due to the high-barrier to entry and inconsistent standards, CAVs and ITS are far from widespread.

III. Motivation

The emergence of connected and autonomous vehicles (CAVs) necessitates a profound transformation in intersection infrastructure design to support their advanced technological and communication capabilities. Traditional intersection infrastructure, often slow to evolve, struggles to keep pace with the rapid advancements in CAV technologies. This mismatch highlights the need for intersection designs that are not only adaptable but can also be rapidly implemented and upgraded as technology evolves.

OpenIntersection introduces a software-defined reference design aimed at revolutionizing intersection management. This framework is designed to be highly adaptive, allowing for quick updates and flexibility to integrate with new technologies as they emerge. It is structured to ensure intersections can efficiently respond to the dynamic demands of modern transportation, facilitating smoother traffic flow and enhanced safety. By proposing a model that emphasizes proactive adaptability and technological integration, OpenIntersection seeks to lead the transformation towards smarter, safer, and more efficient traffic systems.

IV. System Design

OpenIntersection introduces a novel software-defined framework for intersection management, specifically designed to integrate with and enhance modern traffic systems by actively adapting to real-time conditions. This section details the system's architecture, highlighting its responsiveness, flexibility, and ability to deploy and validate technological advancements quickly. OpenIntersection is crafted to meet the diverse needs of stakeholders within different traffic ecosystems: **Original Equipment Manufacturers (OEMs)** benefit from standardized V2X communication protocols, ensuring seamless vehicle-system compatibility and easier integration of new automotive technologies; **Autonomous Mobile Robots (AMRs)** leverage customized communication channels and real-time data processing for optimized operational efficiency; **Vulnerable road users** benefit from an active intersection infrastructure in terms of increased safety and reliability; **City Traffic Authorities** utilize the system's flexible architecture to tailor traffic management solutions to their specific needs, enhancing traffic flow and safety across diverse environments.

To accomplish this, OpenIntersection approaches from ***three*** different perspectives: *1) Intersection and Transportation 2) Connected and Autonomous Vehicles 3) Other connected vulnerable road users*

A. Intersection and Transportation

Intersections are critical nodes within transportation networks where multiple roads meet. Traditionally managed by static signals like traffic lights and stop signs, these intersections have primarily focused on minimizing accidents and regulating flow. However, with the surge in vehicle ownership over recent decades, these traditional systems are proving inadequate, struggling to adapt to the dynamic and increasingly complex traffic patterns of modern traffic environments. To address these challenges, some intersections now incorporate technologies like ground activation circuits that adjust signal timing based on real-time traffic conditions. Despite such advancements, the need for a more adaptable solution remains pressing. OpenIntersection introduces a software-defined approach that transforms intersection management. Converting traditional traffic control challenges into software programming opportunities enables a flexible, scalable platform that can adapt to future traffic behaviors and technologies. This system not only manages current traffic efficiently but also integrates advancements in vehicle technology and traffic management strategies, enhancing the safety and efficiency of urban transportation.

B. Connected and Autonomous Vehicles

Connected and autonomous vehicles (CAVs) represent a significant evolution in automotive technology, often described by Original Equipment Manufacturers (OEMs) as the key to extending vehicle functionality and lifespan through ongoing updates. These advancements facilitate the rise of autonomous driving technologies. At intersections, CAVs leverage Vehicle-to-Everything (V2X) technologies, transforming intersections into dynamic systems that enhance safety through extensive data sharing. This connectivity overcomes the limitations of traditional single-agent systems by augmenting a vehicle's sensory information with broader situational awareness provided by V2X, which enhances safety features traditionally managed by Advanced Driver Assistance Systems (ADAS). The deployment of V2X has been slow due to its reliance on specific hardware, leading to interoperability issues and high costs associated with varying manufacturer systems. OpenIntersection proposes a software-defined approach, advocating for standardized APIs that ensure hardware compatibility and reduce installation complexities. By adhering to protocols like J2735 V2X standards, OpenIntersection facilitates a more integrated and efficient transportation network, minimizing hardware constraints.

C. Other Connected Vulnerable Road Users

While V2X communications have traditionally focused on vehicle-to-vehicle and vehicle-to-infrastructure interactions, OpenIntersection extends this connectivity to encompass all road users, including pedestrians, cyclists, and even pets. This inclusive approach ensures that not just vehicles, but any participant in traffic can be integrated into the safety network. Pedestrians often carry smartphones that can provide precise movement data through built-in gyroscopes, while bicycles and motorcycles can be connected through associated mobile devices. OpenIntersection harnesses these connections, allowing for a comprehensive flow of situational data among all road users. This system uses cameras and other sensors to augment data accuracy further, enhancing real-time responsiveness.

D. Design Overview

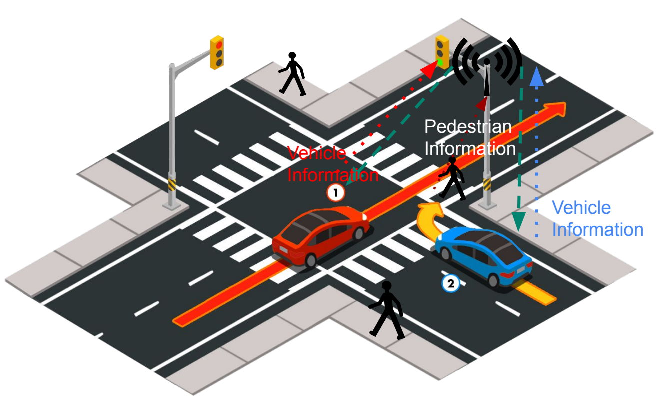

Fig. 1. Example Communication Between OpenIntersection Users. In this scenario, a pedestrian is running a red light and the driver fails to see the pedestrian, leaving the ultimate decision to the vehicle's ADAS system to detect and stop the vehicle.

Fig 1 depicts an example scenario at an intersection where a pedestrian is running a red light, but the drivers fail to observe the pedestrian. Existing solutions involve the vehicle taking over to ensure road user safety. Infrastructure-based solutions improving road-user safety are hard to deploy en masse using current infrastructure design paradigms. This creates issues with development, validation, and deployment.

OpenIntersection consists of **five** layers: The Computing layer combines high-performance processors (CPUs and GPUs) for intensive tasks such as object detection and tracking with low-power embedded systems designed for high efficiency and low latency operations, allowing for different applications to be developed. The Containerization layer allows different applications developed on different computing platforms and software versions to co-exist. The Communication layer handles V2X communications and communications between the sub-modules, allowing for data synchronization. The Interface layer establishes a universal language, ensuring that devices from different manufacturers and with varying capabilities can communicate effectively, making interoperability possible. It also makes developing new safety-critical applications much easier. Last, the Application layer invites all stakeholders to develop, deploy, and validate their safety-critical applications.

The rest of this section breaks down and explains OpenIntersection's system design into the following: *1) hardware requirements 2) software requirements 3) intersection programming interface (IPI) 4) scalability 5) data processing and analysis 6) push and pull services 7) security-enhanced V2X message format 8) coverage requirements 9) safety requirements.*

E. Hardware Design Requirements

The Sensor hardware needs to see and perceive the scene to identify potential accidents and reduce risks. Most of the existing technologies revolve around cameras, and some also revolve around LiDARs. Camera and imaging technologies have matured to satisfy the need for reliability and long lifespan. While LiDARs do not have a long lifespan, some technologies require precise locations. With a reliable range of 100 meters, OpenIntersection includes a camera and a LiDAR as two must-have sensors. Additional functionalities may require additional sensors, such as an audio receiver, to detect noise levels.

Computing Platform: To effectively handle the diverse computational demands of a modern intersection, OpenIntersection proposes a heterogeneous computing platform. This platform combines high-performance processors (CPUs and GPUs) for intensive tasks such as object detection and tracking, with low-power embedded systems designed for high efficiency and low latency operations. Embedded systems are particularly suited for managing routine tasks like traffic signal control and emergency interventions, ensuring rapid response capabilities that are critical in traffic management.

The Communication hardware needs to conform to a set of design standards, including operating temperature range, deterministic latency, and coverage. It also needs to conform to a set of commonly accepted software programming APIs—critical for maintaining continuous system improvements and compatibility with new technologies.

The Traffic control actuator: At the core of the hardware suite is the traffic control actuator, a vital component that serves as the ultimate fail-safe mechanism. This actuator ensures that even in the event of software anomalies or calculation errors, no conflicting traffic signals are issued, thereby preventing accidents. This design principle underscores OpenIntersection's commitment to safety and reliability, ensuring that intersection controls remain secure and effective, even under unexpected conditions.

F. Software Design Requirements

OpenIntersection embodies the principles of a Software-Defined Intersection (SDI), focusing on flexibility and rapid deployment across different hardware setups. This software-centric approach ensures that OpenIntersection remains adaptable and scalable, regardless of the specific hardware in use. The key aspects of this design are:

- Hardware-Software Decoupling: By separating hardware dependencies from software operations, OpenIntersection ensures that its software can be deployed across various hardware platforms. This flexibility allows for greater innovation in hardware choices without compromising the functionality or efficiency of the system.
- Rapid Deployment and Validation: The software design is engineered to facilitate quick updates and improvements, enabling faster validation and deployment of new safety applications. This capability is crucial for responding to emerging traffic management challenges and integrating the latest advancements in safety technology effectively.

G. Infrastructure Programming Interface

The Infrastructure Programming Interface at OpenIntersection facilitates communication across diverse vehicle types and traffic management systems, enhancing scalability and interoperability. By adopting Software Defined Network (SDN) principles, these interfaces allow for dynamic network management and configuration, ensuring devices from various manufacturers can interact effectively. This setup fosters a collaborative environment among stakeholders such as vehicle manufacturers, software developers, and urban planners, which is crucial for refining API standards that accommodate a broad spectrum of needs, from enhancing vehicle safety to optimizing traffic flow. The iterative process of testing, feedback, and updates inherent to SDN is crucial for adapting to challenges like data privacy and the integration of increasingly autonomous vehicles, ultimately crafting a resilient, adaptable transportation ecosystem.

H. Scalability

The Software-Defined Intersection concept emphasizes infrastructure compatibility, customization, and extensibility. Its design incorporates SDN capabilities to facilitate smooth integration with existing road infrastructure and allows for tailored solutions that meet specific local needs without extensive modifications. This extensible framework supports current traffic management technologies and is poised to incorporate future innovations, maintaining relevance as traffic dynamics evolve. Additionally, OpenIntersection is designed to accommodate new participants in traffic, such as autonomous mobile robots, ensuring long-term viability and adaptability.

I. Data Processing and Analysis

Effective data handling and analysis are crucial for managing the complex dynamics of modern intersections. The system's software-defined architecture enables it to seamlessly process and analyze diverse data streams from connected and autonomous vehicles (CAVs), sensors, and other infrastructure elements. This capability allows real-time traffic management and decision-making, adapting to changing traffic conditions. The scalable data architecture efficiently handles increasing data volumes, facilitating predictive analytics for traffic flow optimization and safety enhancements. By integrating advanced data analysis tools, the system can continually learn and adapt, supporting smarter, safer, and more efficient traffic management.

Furthermore, OpenIntersection can be viewed as an *extensible edge*. It harnesses edge computing to process data near traffic intersections, reducing latency and bandwidth use, crucial for real-time traffic management. Its scalability allows for easy expansion to meet increasing demands, while its extensibility supports integrating new technologies, making it a dynamic, adaptive solution for mobility challenges.

J. Push and Pull Services

The integration of push and pull services enriches the communication framework established by existing Vehicle-to-Everything (V2X) technologies. While V2X technologies facilitate foundational real-time interactions between vehicles and their surrounding infrastructure, the nuanced application of push and pull strategies introduces a higher level of information customization and efficiency. Push services preemptively disseminate vital information, ensuring a broad-based situational awareness essential for preemptive traffic management and safety interventions. In contrast, pull services cater to the bespoke information needs of individual users or systems, enabling a more granular level of interaction where data is solicited based on specific, real-time requirements. This dual-faceted approach not only amplifies the utility of the extant V2X communications but also cultivates a more adaptable and user-centric ITS ecosystem. The synergistic operation of push and pull services within such a framework underscores a paradigm shift towards more dynamic, responsive, and personalized intelligent transportation systems, thereby augmenting the overall efficacy and safety of mobility networks.

K. Security-Enhanced V2X Message Format

V2X messages need to ensure security and latency. Existing V2X implementation solely relies on manufacturers for security. Transitioning from ASN.1 to a TCP/IP-inspired V2X message format, may address the dynamic needs of vehicular communications with enhanced efficiency, security, and adaptability. The ASN.1 format, while established, faces challenges in high-density vehicular environments due to its rigidity and limited quality of service differentiation. The proposed structure introduces **Version** and **Header Length** for protocol compatibility and precise payload parsing, which is crucial in fast-changing vehicular scenarios. A redefined Type of **Service** caters to V2X-specific priorities like latency sensitivity, overcoming ASN.1's limitations in service differentiation. **Total Length** and **Message Validity** ensure message integrity and temporal relevance, aligning with the urgent nature of vehicular communications. The **Protocol** field, along with **Source** and **Destination** Addresses, ensures efficient routing of diverse V2X services. **Header Checksum** enhances data integrity at high speeds, and **Security & Data** options provide flexibility for advanced security and application-specific needs, addressing ASN.1's constraints in supporting a wide array of V2X applications.

L. Latency Requirements

The OpenIntersection reference design divides latency into three sections: computational, communication, and actuation. Computational latency is derived from processing sensor data and outputting correct traffic control commands; communication latency stems from V2X communications; and actuation latency is inherently small in embedded systems and simple controllers.

Deterministic latency is crucial when providing real-time safety applications. OpenIntersection views latency as a two-step problem. The first step is to determine whether or not an application can provide the correct response within the acceptable time frame; the second step is to determine whether or not an application can provide the correct response within the acceptable time frame when the resource is scarce. Passing both tests ensures that safety-critical applications are useful in times of crisis.

M. Coverage Requirements

Coverage should also be considered alongside latency requirements. This is especially true for communication. Coverage requirements help answer the question of when communication network resources become so scarce that safety-critical applications can no longer complete their assigned task within the allotted time frame.

N. Safety Requirements

Last but not least, connecting safety-critical infrastructure with other devices may lead to catastrophic outcomes if data safety is ignored. OpenIntersection considers safety from the following scopes: *1) Ensure that the sensor data are reliable 2) Ensure that the V2X messages are legitimate and not ill-intended 3) Protect user data privacy*

Reliability ensures that data can be used for safety-critical applications. Effects such as glaring or low light may render it useless for camera data. These "broken" raw data should not be sent to safety-critical applications. For LiDAR sensors, the distance-measuring algorithm needs to be calibrated. Unreliable LiDAR data may lead to incorrect output, causing catastrophic accidents.

The Legitimacy of V2X messages needs to be verified by the broadcaster and the receiver. If messages are not verified, attackers or ill-intends can exploit this deficiency to create fatal accidents.

User Data Privacy need be protected. Intersections collect hundreds of millions of camera captures per day. The captures may include plate information and facial information. If not protected, this information may be used to track individuals.

O. Limitations

Life expectancy is another reason existing intersections have not all switched to ITS systems proposed by Ouster and others. Because intersections are permanent, once construction is completed, the intersection is expected to operate for decades without major failures. Camera solutions are well adopted because camera imaging and manufacturing technologies have matured. They are inexpensive to manufacture, easy to install, robust, and easy to replace. This cannot be said for LiDARs. The proposed hardware stack in OpenIntersection does not consider the life expectancy of existing technologies because we expect hardware manufacturing to mature over the next decade.

V. Software-Defined-Intersection

OpenIntersection's implementation as a software-defined intersection (SDI) incorporates both theoretical frameworks and practical applications demonstrated through indoor prototype testing. This section details our prototype's development, the scope of indoor testing, and our plans for extending these tests to outdoor environments.

A. Prototype

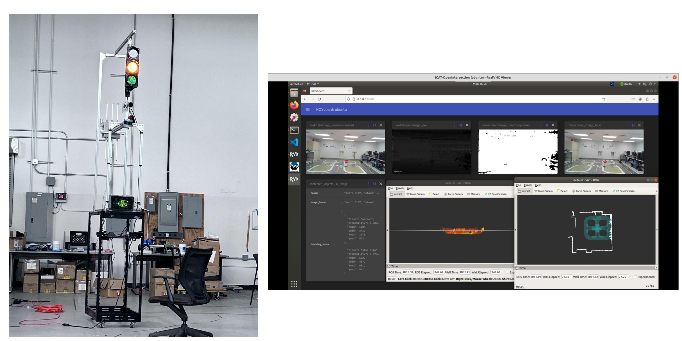

Fig. 2. Left: OpenIntersection Prototype; Right: Management Console for SDI, including RGB camera, depth camera, LiDAR, object detection, and vector map viewer

1) Hardware: Table I lists the hardware setup used in the prototype. For the high-performance computing platform, we chose to use the NVIDIA AGX. The ARM architecture is integrated with the SOAFEE architecture, enabling the vision for Software-Defined-Infrastructure. As for a low-computing device and traffic light actuator, we used a Raspberry Pi 4B. This is specially chosen due to its cost, robustness, and programmability. The traffic light is a commercial off-the-shelf traffic light. It is controlled using the GPIO pins

TABLE I
HARDWARE & SOFTWARE SETUP

Computing Unit	NVIDIA AGX
LiDAR Sensor	Ouster VLP-16
Camera Sensor	RealSense RGB-D Camera
V2X	iSmartWay Roadside Unit
Traffic Light	Standard Traffic Light
Controller	Raspberry Pi 4B
Framework	ARM SOAFEE
Application 1	V2X Hub
Application 2	Object Detection and Classification
Application 3	Object Localization and Tracking
Traffic Light	Standard Traffic Light

on the Raspberry Pi. A Velodyne VLP-16 LiDAR and a RealSense RGB-D camera cover most object detection and object tracking use cases within 50 meters, about twice the size of an average urban intersection. Last but not least, we deployed an iSmartWay roadside unit onto the prototype.

Compared to other ITS systems proposed by Ouster and others, our prototype leverages the heterogeneous computing platform to combine the fast and low overhead benefits of embedded systems and the power of machine learning from high-power computing systems.

Table I also showcases the software and framework deployed in the prototype. The ARM SOAFEE framework enables easy addition, modification, and removal of applications. The V2X hub enables the creation and modification of V2X messages. These messages are sent to the RSU to be broadcast. Object detection, classification, localization, and tracking applications support safety-critical functions such as pedestrian detection and vulnerable road user detection and tracking. Last but not least, a basic traffic rule control algorithm is installed onto the Raspberry Pi.

Adding applications can easily be done with docker containers. Users define the software requirements, create the container, and run their applications.

Modifying applications is also risk-free. Containerization ensures that modifying software version dependencies in one container does not affect the software versions in another container. This allows users to freely modify software without worrying about breaking other applications.

Removing applications is hassle-free. Because each application is only executed in its container, removing an application does not affect other applications.

B. Prototype Development and Indoor Testing

The OpenIntersection prototype was tested in an indoor controlled environment that simulates urban traffic scenarios. This setting allowed us to closely monitor system performance and accurately measure crucial metrics such as latency—the time taken from sensor data capture to action execution. Latency was specifically measured to ensure the system's capability for real-time response, with our tests showing a response time well within the necessary thresholds for traffic management applications. The indoor environment provided a stable platform to debug initial system setups, optimize sensor integration, and refine communication protocols without the variables in an outdoor setting.

Several tests were designed and carried out on OpenIntersection to evaluate some key functionalities:

- **Offload Testing:** We conducted tests where path planning tasks, traditionally handled by individual autonomous vehicles, were offloaded to the infrastructure. OpenIntersection plans a new path for the indoor vehicle to follow. This demonstrates the system's ability to reduce on-vehicle computational loads and improve overall traffic efficiency. The communication latency between OpenIntersection and the indoor vehicle averages to 30 ms. With this latency, we can plan new routes in real time.
- **Shared Perception:** The prototype showcased shared perception capabilities, where data collected by individual vehicles or sensors were shared across the network, enhancing situational awareness across all system participants. In this test, OpenIntersection uses V2X messages defined in the J2735 to broadcast detected stop signs and vehicle information via the WiFi network.
- **V2X Latency Modeling:** We employed a network model to simulate V2X communication latency, providing insights into the real-world performance of the system in transmitting critical safety and operational data between vehicles and infrastructure.
- **Cloud Integration Test:** The system's ability to update and synchronize with cloud infrastructure was also tested, ensuring that data could be stored and accessed remotely, which is crucial for scalability and data management.
- **Infrastructure to Cloud Testing:** This test evaluated the efficiency and reliability of data transmission from the infrastructure to the cloud, validating the system's capability to handle large-scale data processing and analysis, crucial for future real-time applications. The average latency between OpenIntersection and the cloud is 10 ms, enabling real-time monitoring and tele-operation.

VI. Conclusion and Future Works

The advancement of connected and autonomous vehicle (CAV) technologies presents significant challenges and opportunities for intersection design. OpenIntersection, through its innovative software-defined approach, aims to revolutionize intersection management by integrating these technologies into traffic systems. This approach not only enhances traffic efficiency and safety but also ensures scalability and adaptability to future technological advancements.

OpenIntersection has demonstrated substantial potential in indoor environments, where it successfully managed path-planning tasks and facilitated shared perception and V2X communication. Specifically, the offload tests showed that computational tasks could be effectively transferred from vehicles to the infrastructure, reducing vehicle computational loads and potentially enhancing traffic flow and safety. The integration of cloud services was tested, proving the system's capability to handle large-scale data processing, which is vital for future expansions.

The next phase of development involves implementing OpenIntersection in an outdoor environment at the University of Delaware STAR campus shown in Fig 3. This deployment

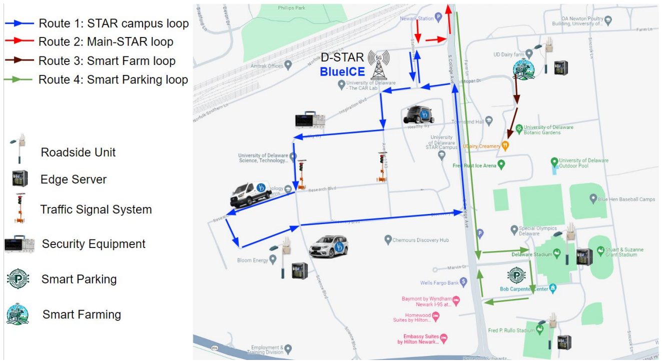

Fig. 3. Future work at the University of Delaware STAR campus. The D-STAR campus is an open-environment proving ground for connected and autonomous vehicles.

will allow us to conduct extensive real-world testing and integration with existing traffic systems, offering a more robust evaluation of the system's effectiveness in live conditions. These tests will focus on: *1) Real-World Integration: Evaluating how OpenIntersection interfaces with current traffic infrastructure to manage dynamic traffic conditions 2) User Feedback Collection: Engaging with real system users, including drivers, pedestrians, and city traffic managers, to gather actionable feedback for further system enhancements 3) Safety and Efficiency Metrics: Detailed tracking of safety improvements and traffic efficiency changes brought by OpenIntersection, focusing on reducing congestion and accidents.*

Looking beyond immediate future works, we are committed to expanding the scope of our software-defined intersections to broader applications, potentially leading to a paradigm shift towards software-defined cities. This vision includes developing more adaptive traffic management systems that can dynamically respond to varying traffic conditions and support the increasing autonomy of vehicles.

VII. Acknowledgement

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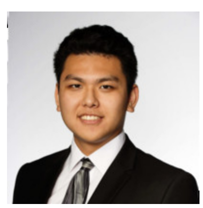

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