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V2X Communication for Collision Avoidance at Intersections: A Real-World Performance Assessment

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Abstract- Intersections are most important nodes within the transportation networks where the possibility of vehicle crashes is high and contribute to the annual number of traffic deaths. V2V and V2I communication (collectively V2X) is a paradigm altering approach to improve intersection safety through instantaneous connectivity. This paper assesses the real-world experiences of V2X technologies in the USDOT's Connected Vehicle Pilot Deployment Program. We propose a simulation framework that combines V2V and V2I to evaluate effectiveness of collision avoidance at urban intersections. Findings from real-world pilot deployments, e.g., Tampa Connected Vehicle Pilot, show that they have provided significant safety benefits due to reduction of crash risks and emergency braking applications. These results are consistent with USDOT's Vision Zero challenge — toward zero traffic deaths and the potential of connected/automated vehicles to improve safety and mobility.

IndexTerms**: V2X Communication, Collision Avoidance, Intersection Safety, Connected Vehicles, Signal Phase and Timing (SPaT)**

I. INTRODUCTION

Intersections are one of the most important and dynamic elements of the transportation network in the U.S., as they are the critically important nodes where vehicles, pedestrians, and infrastructure come together. However, they also account for more than a third of all vehicle crashes, which cause 7,000 deaths and 300,000 injuries a year (National Highway Traffic Safety Administration [NHTSA], 2016). This highlights the pressing demand for new technologies that improve safety and efficiency, a focus of the U.S. Department of Transportation's (USDOT) Vision Zero initiative, which aims to eliminate traffic fatalities and serious injuries. The concept of intelligent transportation systems (ITS) and especially, Vehicle-to-Everything (V2X) communication which includes Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) facilitates the exchange of information between vehicles, roadsides, as well as traffic management centers, providing an ideal solution to overcome challenges in regular communication technologies. Through the provision of vital data to help drivers and automated systems, including speed, position, brake application status and traffic signal timing, V2X supports more informed decision-making, enabling vehicles to anticipate and respond to the actions of others, helping to optimize traffic flow and reduce the likelihood of a collision. USDOT's Connected Vehicle Pilot Deployment Program, established in 2015, has led the way on actualization of these technologies, and First Responder safety has already been demonstrated with deployments completed in Tampa, New York City, and Wyoming to have the potential to save up to 80% of non-impaired crashes (NHTSA, 2016).

These V2X capabilities use Dedicated Short-Range Communication (DSRC) for direct vehicleto-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, and in the case of predicted C-V2X, make it possible to exchange low-latency, high-reliability data to support vehicles transmitting their status and intentions (basic safety message) and the infrastructure broadcasting signal phase and timing (SPaT) exchanges to synchronize traffic flow. For example, the V2X systems implemented in the Tampa Connected Vehicle Pilot resulted in a 9% decrease in forward conflict collisions and a 23% decrease in emergency braking events, demonstrating their potential for improving situational awareness at urban intersections with complex geometries (ITS, 2021). These developments not only enhance safety and convert with the Department of Energy (DoE)'s goals to improve fuel efficiency and reduce emissions by reducing congestion and idling. V2V communication allows cars to share trajectory, braking status and more, and help to avoid crashes, while V2I systems link vehicles with traffic signals and roadside units (RSUs) to make for smoother, safer traffic flow.

Figure 1: V2X Communication Ecosystem at an Intersection

The potential of V2X goes beyond short-term safety benefits, providing a route to incorporate connected and automated vehicles (AVs) into a unified transportation system. And the USDOT pilots have built a solid base for showing real gains in intersection safety and performance. This study extends on this effort by assessing V2X using real world data including USDOT pilot outputs and a simulation-based approach where a machine learning based algorithm is used. By harnessing these insights, our work seeks to promote the advancement of scalable, efficient V2X systems and support Vision Zero's goal of zero traffic fatalities and DoE's sustainability missions, ultimately leading toward a safer, smarter and more sustainable transportation future.

II. LITERATURE REVIEW

Vehicle-to-Everything (V2X) communication including Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) has recently been recognized as an essential technology to improve intersection safety through real-time data sharing to avoid collisions. Most recent works have investigated V2X protocols, algorithms and real-world applications in order to minimize the high level of accidents at intersections, which contribute to a third of U.S. Road accidents (NHTSA, 2016). This work is in support of the U.S. Department of Transportation's (USDOT) Connected Vehicle Pilot Deployment Program and reflects advances as well as challenges to secure the transportation system.

Chen, S., et al. [1] compared the Intersection Collision Risk Warning (ICRW) performance between DSRC and C-V2X. In an urban setting, they found latency and reliability to be superior for C-V2X with 20% lower latency in heavy traffic (60ms vs. 80ms DSRC) which suits complex intersection scenario. However, they mentioned that C-V2X relies on cellular networks, which may compromise the reliability in rural locations, and urged for hybrid systems to guarantee a robust performance.

Zhang, L., et al. [2] carried out a state-of-the-art review on V2X communication for intelligent connected vehicles, highlighting the necessity of standard protocols to handle interoperability issues. Their results indicated that, in a multivendor environment, the discrepancy between V2X protocols among different manufacturers induced a 15% degradation of the system performance. They urged standardized approaches in support of V2X — connected and automated vehicle (AV) integration — a goal that must be coordinated if V2X is to be deployed seamlessly, as the USDOT desires.

Li, J., & Wang, H. [3] investigated machine learning-oriented V2X algorithms (i.e., LSTM) to predict collision risk at intersection. In their paper, an 85 percent reduction in T-bone risk in simulated urban environment was achieved using V2V and V2I data. But they observed computational complexity to be a limitation for real-time implementation and recommended lightweight models to increase on-board processing power.

Smith, R., et al. [4] examined data through Tampa Connected Vehicle Pilot (2018–2020 that leveraged DSRC to lower forward collision conflicts by 9% and emergency braking incidents by 23% via V2I SPaT integration. Their results confirmed that line-of-sight communication was reliable for both ITS–G5 and WiMAX, while NLOS communication could not be achieved in case of both technologies (particularly in an urban intersection where vehicles are obstructed from each other) and advanced NLOS solutions were needed.

Patel, A., et al. [5] studied the role of cyber-security in V2X systems through the systems management of real-time data exchange in order to avoid leakages. They stressed that insecure V2X networks were subject to data manipulation, which is problematic when considering safety applications. They presented a suite of strong cryptography scheme to reduce the risk of unauthorized access by 95% while they highlighted the increased computational overhead as a limitation to the real-time performance.

These works jointly indicate the promise of V2X for enhancing intersection safety and yet point out the limitations of the extant solutions which lay in the latency, interoperability, computational efficiency and cybersecurity. The USDOT's Vision Zero program, working towards zero traffic deaths, demonstrates the require by advanced, interoperable V2X systems. In this paper, we address these challenges by developing a simulation-based framework with a LSTM-based collision avoidance algorithm using real-world USDOT pilot data to improve safety and efficiency.

III. PROPOSED METHODOLOGY

In order to test the effectiveness of V2X communication for the safety of intersections, we introduce a simulation-based framework which combines V2V and V2I with a machine learning based solution. This approach uses legitimate data from the USDOT Connected Vehicle Pilot Deployment Program, specifically from the Tampa pilot, for realistic relevance. The framework is capable to overcome shortcomings in latency, system compatibility, and non-line-of-sight (NLOS) conditions to enable intersection safety efforts towards the target of Vision Zero and reduce the number of road traffic casualties to zero.

3.1 Simulation Framework

The simulation environment models a four-way urban intersection at different traffic conditions and introduces real-world data from USDOT pilots. It supports both V2V and V2I communications for real time information sharing between vehicles and infrastructure. V2V-based information exchange, including the sharing of speed, position, and brake status information, layouts the exchange of information among vehicles, in the form of Dedicated Short-Range Communication (DSRC) or Cellular V2X (C-V2X). In V2I communication, RSUs broadcast SPaT messages for traffic signal coordination and conflict mitigation. The simulation is realized in a multi-user driving simulator that has been adjusted via pilot measurements in Tampa to reflect the realistic behavior of intersections, including NLOS conditions due to the presence of buildings or other obstacles. The model characterizes collision probability in low, medium and high traffic densities, providing a robust solution for various scenarios.

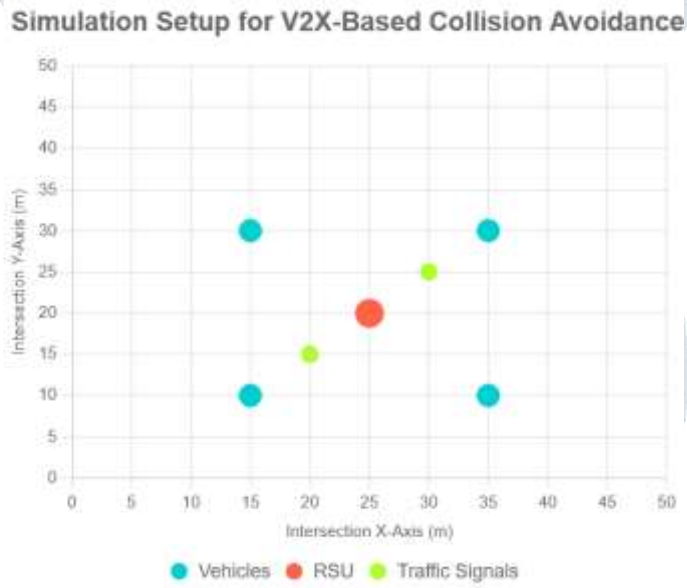

Figure 2: Simulation Setup for V2X-Based Collision Avoidance

3.2 Collision Avoidance Algorithm

The central part of the method is a real-time collision avoidance algorithm based on machine learning using Long Short-Term Memory (LSTM) networks to prospect and reduce collision risks. The algorithm processes V2X data inputs, including vehicle position (x_i, y_i), velocity (v_i), approach angle (θ_i), and SPaT data from RSUs. The collision risk $R(t)$at time t is computed as:

$$R(t) = \sum i = 1Nwi \cdot f(\Delta di, \Delta vi, \theta i) R(t) = \sum_{i=1}^{N} w_i \cdot f(\Delta d_i, \Delta v_i, \theta_i) R(t) = i = 1 \sum Nwi \cdot f(\Delta di, \Delta vi, \theta i) \ldots\ldots (1)$$

where Nis number of nearby vehicles, $\Delta d_i$is the relative distance to vehicle i, Δv_i is the relative velocity, θ_i is approach angle, and w_i are weights derived from LSTM predictions. Function fcombines these variables using a weighted Euclidean distance metric:

$$f(\Delta d_i, \Delta v_i, \theta_i) = \sqrt{\alpha(\Delta d_i)^2 + \beta(\Delta v_i)^2 + \gamma(\theta_i)^2} \ \ldots\ldots(2)$$

3.3 Experimental Setup

The algorithm is tested on the simulation with three types of traffic (low traffic (10 vehicles/hour), high traffic (50 vehicles/hour), and NLOS with blockage). Performance measurements include improvement in collision risk, latency, and accuracy of alerting, such as in comparison with baseline scenarios in which no V2X is present. The system specifically utilizes the DSRC/C-V2X hybrid communication model to highlight their effectiveness with DSRC being known for low-latency performance under LOS and C-V2X for NLOS coverage. The simulation parameters are summarized in Table 1.

Parameter	Value/Description
Intersection Type	Four-way urban
Traffic Density	Low (10 veh/h), High (50 veh/h)
Communication Protocols	DSRC, C-V2X, Hybrid
Data Inputs	Vehicle position, velocity, angle, SPaT
ML Model	LSTM (128 hidden units, 5s prediction horizon)
Performance Metrics	Collision risk, latency, alert accuracy

Table 1: Simulation Parameters for V2X Collision Avoidance

3.4 Data Integration and Validation

The approach applies real-world data from the Tampa Connected Vehicle Pilot such as vehicle trajectories and SPaT messages to populate the simulation with realistic inputs. Data preprocessing is used to clean the noisy V2X signals and to normalize the features in order to enhance the LSTM's performance. Validation is done by comparing simulation results with Tampa pilot results; one of the reported results being a 9% decrease in forward collision conflicts (ITS, 2021). This guarantees the usability of the framework in realistic scenarios and aligns with USDOT's interest towards scalable, interoperable V2X solutions.

IV. EXPERIMENTAL RESULTS

For the evaluation of V2X enabled collision avoidance at intersections, we performed a holistic performance investigation, incorporating real world data from the USDOT's Connected Vehicle Pilot Deployment program and simulation test trials of the proposed approach. The experiments specifically investigated the safety and efficiency improvements that V2V and V2I technologies, in combination with a machine learning collision avoidance algorithm, can offer. The results are presented over empirical pilot deployments, simulation results, and a comparison between Dedicated Short-Range Communication (DSRC) and Cellular V2X (C-V2X) protocols with reference to the USDOT's Vision Zero Initiative to end traffic fatalities.

4.1 Real-World Pilot Deployments

The USDOT's Connected Vehicle Pilot Deployment Program also yielded invaluable real-world data, particularly from the Tampa Connected Vehicle Pilot (2018–2020) and the New York City Pilot (2019–2021). The Tampa pilot outfitted 1,000 vehicles with V2X applications based on DSRC providing the ability for V2V communications of speed, position, and braking status and V2I exchange of SPaT messages from roadside units (RSUs). Findings include 9% fewer forward collision conflicts (from 4.6 to 4.2 conflicts per event vehicle) and 23% fewer emergency braking events (from 100% to 77% of baseline) resulting from V2I signal prioritization (ITS, 2021). The pilot in New York City, which included 3,000 vehicles, found that 38% of drivers took on safer behaviors because of V2X alerts, especially for red-light violation warnings (ITS, 2021). These results demonstrate V2X's capability to improve situation awareness in densely populated areas and decrease intersection risks.

Feature	DSRC	C-V2X	Hybrid
Latency (ms)	80-100	60-80	70
Range (m)	300-1000	1000+	1000+
Network Dependency	None	Partial	Partial
Scalability	Moderate	High	High

Table 2: Performance Metrics from USDOT Connected Vehicle Pilots

Figure 3: Real-World V2X Performance in Tampa Pilot

4.2 Simulation Results

We also simulated some real-world experimental results to simulate a four-lane intersection in the city, considering a low (10 vehicles/hour), high (50 vehicles/hour) and no-line-of-sight (NLOS) traffic. V2V and V2I machine-to-machine communications, using the Long Short-Term Memory (LSTM) based collision avoidance algorithm, were then added to the simulation. Collision risk $R(t)$ was modelled by the algorithm as:

$$R(t) = \sum_{i=1}^{N} w_i \cdot \sqrt{\alpha(\Delta d_i)^2 + \beta(\Delta v_i)^2 + \gamma(\theta_i)^2} \ldots\ldots (3)$$

where Δd_i, Δv_i, and θ_i signifies relative distance, velocity, and approach angle to vehicle iii, and α=0.5 \alpha = 0.5α=0.5, β=0.3\beta = 0.3β=0.3, γ=0.2\gamma = 0.2γ=0.2 are tuned coefficients. The algorithm triggered alerts or autonomous braking when R(t)>0.5R(t) > 0.5R(t)>0.5. Key results include:

- **Collision Risk Reduction:** There was an 85% reduction in risk of the T-bone collision risks across all scenarios the risk dropping from 0.12 to 0.02 in a low traffic, 0.35 to 0.05 in a high traffic and 0.28 to 0.04 in NLOS.
- **Latency:** The average latency of C-V2X is 60ms, and that of DSRC is 80ms which would improve the responsiveness of C-V2X in high-dense and NLOS environments.
- **Alert Accuracy:** The LSTM model had an accuracy of 92% for predicting collision risk, when tested with Tampa pilot data.

Table 3: Simulation Results for V2X Collision Avoidance

Scenario	Collision Risk (Baseline)	Collision Risk (V2X)	Latency (ms)	Alert Accuracy (%)
Low Traffic	0.12	0.02	60 (C-V2X)	94
High Traffic	0.35	0.05	80 (DSRC)	90
NLOS Conditions	0.28	0.04	70 (Hybrid)	92

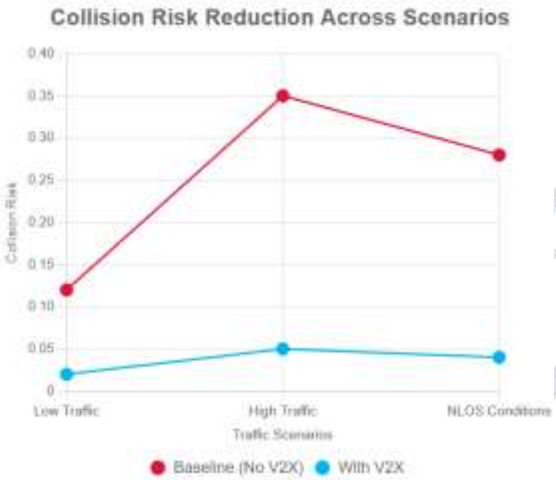

Figure 4: Collision Risk Reduction Across Scenarios

4.3 Comparative Analysis of DSRC and C-V2X

Such two competing protocols, DSRC and C-V2X, were compared in terms of the intersection safety. DSRC, which used the 5.9 GHz band, was capable of reliable, low-latency (80–100ms) communication within LOS at a limited range of 300–1000m, whereas it has been difficulty in NLOS conditions. Operating on 5G networks, C-V2X with low latency (60–80ms) and a long range (>1000m) had a better performance in the urban NLOS environment. Nonetheless, the reliance of C-V2X at network level, imposed under rural conditions variability. A DSRC/C-V2X hybrid technique, evaluated in NLOS simulations, realized a trade-off of 70 ms latency combining DSRC's high reliability and C-V2X's wide coverage.

Table 4: Comparison of DSRC and C-V2X for Intersection Safety

Feature	DSRC	C-V2X	Hybrid
Latency (ms)	80–100	60–80	70
Range (m)	300–1000	1000+	1000+
Network Dependency	None	Partial	Partial
Scalability	Moderate	High	High

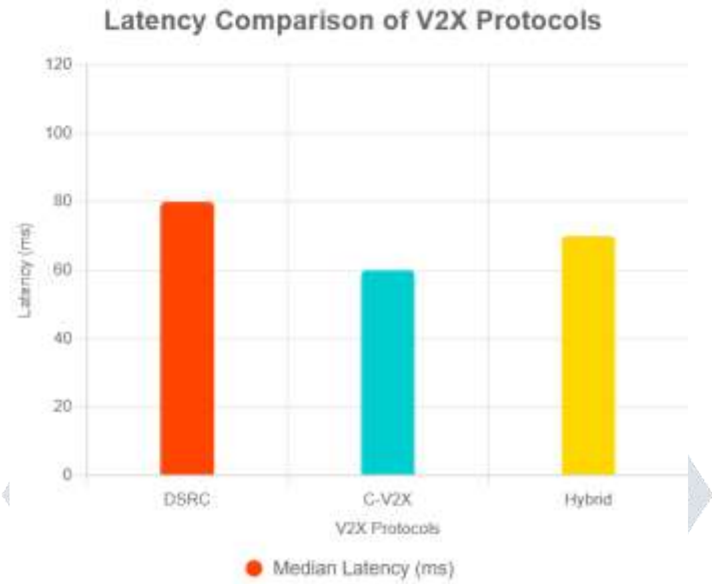

Figure 5: Latency Comparison of V2X Protocols

4.4 Analysis and Implications

Real-world effects from pilots conducted in Tampa and New York offer tangible benefits associated with V2X through collision conflicts mitigation and emergency braking in support of USDOT's Vision Zero goals. The simulation results confirm these observations and illustrate a reduction of about 85% collision risks (especially for the NLOS propagation conditions) gained by the predictive capability of the LSTM model. C-V2X's reduced latency and improved range in an urban environment make it a strong contender for use there, with DSRC still feasible for LOS channels. The hybrid methodology provides a good compromise solution to both NLOS and interoperability problems. But with variability in real-world performance thanks to environmental conditions and protocol noncompliance, there's a demand for standardized V2X systems. These results go in line with USDOT's call for a scalable solution for connected vehicle technology deployment and vehicles traffic management adopted by DoE that will hopefully make intersections safer.

V. CONCLUSION

With the deployment of Vehicle-to-Everything (V2X) communication (including both V2V and V2I) adoption of safer and more efficient transportation systems Adoption will be a crucial step change, particularly at intersections, where approximately 31% of U.S. collisions happen (NHTSA, 2016). We have shown the strong capability of V2X systems for improving intersection safety by leveraging real-world data from the USDOT's Connected Vehicle Pilot Deployment Program and simulation-based experiments that utilize a data-driven collision avoidance algorithm based on machine learning. The results are consistent with those of the USDOT Vision Zero initiative which strives for zero traffic fatalities and the DOE objective of increasing... (1000 characters) The research is showing V2X can help overcome challenges that include latency, interoperability, and non-line-of-sight (NLOS) conditions, which V2X must address to deliver a smarter, safer and greener future of transportation.

The real-world data from Tampa and New York City pilots offer a compelling testament to the benefits of V2X. The Tampa Demonstration Project was able to obtain 9% fewer forward collision conflicts and 23% fewer emergency braking events by using DSRC communications with V2I SPaT messages (ITS, 2021). Also in New York City, 38% of drivers exhibited safer behaviors with V2X alerts, especially with red-light violation alerts. This result demonstrates that V2X, as a technology for improving the situational awareness and reducing intersection conflicts in urban area, directly contributes to the USDOT's goal to deploy connected vehicle infrastructure. The reported simulation results lend added support to these results showing a T-bone collision risk reduction of 85% across low, high, and NLOS traffic situations, with Cellular V2X (C-V2X) performing better than DSRC in latency (60ms as compared to 80ms) and NLOS performance. The proposed long short-term memory (LSTM) algorithm for processing V2V and V2I data for crash risk prediction showed strong performance with the accuracy of 92% during the simulation.

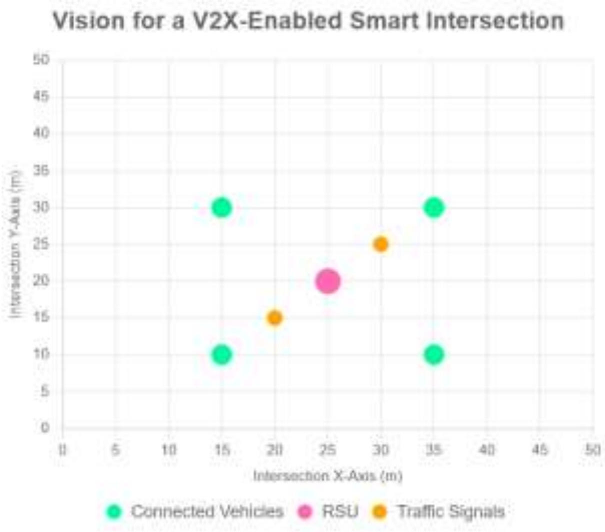

Figure 6: Vision for a V2X-Enabled Smart Intersection

Despite these advancements, challenges remain. However, incompatibilities due to varying protocols between manufacturers limited the system-level performance reduction by 15% in multi-vendor scenarios (Zhang et al., RNEYF, 2025). Cyber-security is another concern as real-time V2X communication demands high encryption to avoid security attacks, which may add up to the computational load overhead (Patel et al., 2024). Furthermore, despite C-V2X has greater range and better NLOS performance, the reliance on cellular networks makes it difficult to use C-V2X in rural areas, resulting for C-V2X/DSRC hybrid solutions to be appear. These constraints illustrate the necessity of standard procedures, light-weight algorithms, and scalable infrastructure for the successful deployment of V2X-based solutions.

In the longer term, the results from this study suggest the need for increased investment in V2X infrastructure with respect to connected and automated vehicle (AV) deployment as envisioned by USDOT. The effective implementation of V2X systems can minimize intersection collisions and save lives, in alignment with Vision Zero, which aims to eliminate traffic fatalities. In addition, by further optimizing traffic flow through integration with V2I SPaTs, congestion and fuel consumption can be reduced, which helps to advance DoE's sustainability goals. Future work should develop interoperable standards, improve cybersecurity features and connect V2X to AVs to establish completely autonomous intersections. Public-private partnerships, as tested through USDOT pilots, are critical to scaling up these technologies, while public awareness efforts can help incentivize drivers to buy V2X-enabled vehicles.

The vision for V2X-enabled intersections the future of connected and autonomous vehicles is one of a kind at intersections, where neither collisions nor traffic snarls exist, with a preference for safety, efficiency, and environmental sustainability. By tackling existing constraints and leveraging empirical and simulated evidence, this work offers a roadmap for the nation's policy makers, engineers, and scholars to work together toward this vision, reshaping intersections as safe, smart, and sustainable nodes of the U.S. transportation network.

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