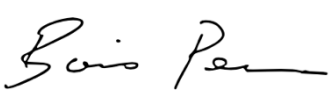
CARNATIONS

Center for Assured & Resilient Navigation in Advanced Transportation Systems

ILLINOIS INSTITUTE OF TECHNOLOGY · CHICAGO STATE UNIVERSITY · UC RIVERSIDE · Stanford · VIRGINIA TECH

USDOT Tier 1 University Transportation Center
Semi-Annual Progress Report – No. 3

Federal Agency:	US Department of Transportation Office of the Assistant Secretary for Research and Technology
Federal Grant Number:	69A3552348324
Project Title:	Center for Assured and Resilient Navigation in Advanced Transportation Systems: CARNATIONS
Center Director:	Boris Pervan, Ph.D. | pervan@iit.edu | (630) 853-6689 Professor of Mechanical and Aerospace Engineering Illinois Institute of Technology
Submission Date:	April 30, 2025
DUNS Number:	042084434
EIN Number:	362170136
Recipient Organization:	Illinois Institute of Technology 10 W 35th St, Chicago, IL 60616
Project/Grant Period:	06/01/2023 – 05/31/2029
Report Period Start Date:	09/30/2024
Report Period End Date:	03/31/2025
Report Term/Frequency:	Semi-annual
Signature:	

Acknowledgment of Report Authors and Contributors

This technical report represents the collective efforts of the entire CARNATIONS community—faculty, researchers, students, and partners—whose collaboration continues to drive progress in resilient transportation systems. The **Center Director (Boris Pervan)** extends special recognition to **Mathieu Joerger (Associate Director)** and **Aashish Narang (Program Manager)**, who co-authored this report. Their leadership, technical insights, and dedication to the mission of CARNATIONS have ensured that the content accurately reflects the scope and impact of the Center's work during this reporting period. Although authored by these three individuals, the report highlights contributions from **all research teams** across our consortium. Each project described herein results from close coordination and shared commitment from our broader team, and we are proud to showcase these collective accomplishments.

The following section outlines the core objectives and activities that guided our efforts during this reporting period, summarizing the Center's progress toward its mission of securing and advancing Resilient Positioning, Navigation, and Timing (R-PNT) technologies across multimodal transportation systems.

Introduction

The Center for Assured and Resilient Navigation in Advanced Transportation Systems (CARNATIONS), a Tier-1 University Transportation Center (UTC), was created to address one of the U.S. Department of Transportation's most pressing priorities: reducing cybersecurity risks in transportation systems. Our mission centers on advancing Resilient Positioning, Navigation, and Timing (R-PNT) technologies and secure Vehicle-to-Everything (V2X) communications, emphasizing PNT resilience across multimodal transportation networks. CARNATIONS operates three subcommittees—Research, Education and Workforce, and Technology Transfer—led by **Program Manager Aashish Narang,** and **Co-PI's Mark Psiaki, Matthew Spenko,** and **Samer Khanafseh, and.** These teams collaborate closely to advance research, education, workforce development, and the transfer of new technologies from academia to industry.

1 ACCOMPLISHMENTS

1.1. What are the major goals of the program?

CARNATIONS has established several objectives, aligned with the DOT strategic goals, to address the challenges of cybersecurity and PNT resilience in transportation systems. These goals are designed to guide research, enhance education, and facilitate technology transfer to industry. The core objective of the program is to identify and mitigate vulnerabilities in existing PNT systems, which are highly vulnerable to threats such as jamming, spoofing, and other forms of cyberattacks. Through the advancement of R-PNT technologies, CARNATIONS seeks to safeguard the integrity and resilience of

current and future transportation infrastructures, ensuring that they remain robust in the face of evolving cybersecurity challenges. In addition to its research efforts, CARNATIONS is dedicated to the development of a highly skilled workforce through education and outreach. CARNATIONS aims to equip the next generation with the expertise needed to address the complex issues surrounding transportation cybersecurity.

Additionally, CARNATIONS collaborates closely with industry partners to develop performance metrics for R-PNT systems, set industry standards, and establish open evaluation frameworks. These initiatives ensure that our research leads to practical, scalable solutions, facilitating the transition of novel technologies from the academic setting to real-world applications. Ultimately, CARNATIONS strives to advance secure, resilient navigation systems that will contribute to the development of safer, more reliable transportation systems, benefiting both public safety and the broader transportation ecosystem.

1.1.1. Research

In the past six months, CARNATIONS has made significant progress across its twelve core research projects through strong collaborations within our partner universities. This period saw advances in research, data analysis, student involvement, and knowledge sharing through conferences. Contributions from PIs and students have strengthened outcomes in resilient navigation, multimodal transportation, and vehicle technologies, aligning with U.S. DOT priorities. Below is a list of the projects and their respective Principal Investigators (PIs):

No.	Ongoing Projects	University Partners	Age	PIs	Status	Start Year	Duration	End Year
1	GNSS Anti-Jam & Anti-Spoof Antenna Technology for Multimodal Transportation	Stanford, VT	Old	Sherman Lo, Mark Psiaki	ACTIVE	October 01,2023	2023-2025	
2	Receiver Signal Processing to Resist GNSS Jamming and Spoofing Attacks	IIT	Old	Boris Pervan, Samer Khanafseh	ACTIVE	October 01,2023	2023-2025	
3	Defending Against GNSS Jamming and Spoofing by Multi-Sensor Integration	IIT	Old	Boris Pervan, Samer Khanafseh	ACTIVE	October 01,2023	2023-2025	
4	Radio-Frequency Signal Augmentation to Reduce PNT Jamming and Spoofing Risks	VT	Old	Mathieu Joerger, Mark Psiaki	ACTIVE	October 01,2023	2023-2025	
5	Towards Resilient V2X Communications over 5G/6G Networks	VT	Old	Walid Saad	ACTIVE	October 01,2023	2023-2025	
6	Multi-Vehicle/Infrastructure Jammer/Spoofer Detection and Localization	VT, UCR	Old	Jay Farrell, Matthew Barth, Mathieu Joerger	COMPLETED	October 01,2023	2023-2024	September 30, 2024
7	Threat Models and Use Cases for Multimodal Transportation	Stanford	Old	Todd Walter, Sherman Lo, Sam Pullen	ACTIVE	October 01,2023	2023-2029	

8	R-PNT Virtual Conflict Simulation	VT	Old	Hesham Rakha, Mark Psiaki	ACTIVE	October 01,2023	2023-2029	
9	Comprehensive Testing and Evaluation of Resilient PNT Systems	IIT, VT	Old	Mathieu Joerger, Matthew Spenko	ACTIVE	October 01,2023	2023-2029	
10	Improving GNSS Resiliency Using Edge AI Solutions	CSU	New	Moussa Ayyash	ACTIVE	October 01,2024	2024-2025	
11	Development of a Generalized Integrity Monitoring Framework	UCR	New	Matthew Barth	ACTIVE	October 01,2024	2024-2025	
12	Examining and Enhancing Vehicle Spoofing Detection Capabilities in CAV Applications Using BSM Information	UCR	New	Matthew Barth, Hang Qiu	ACTIVE	October 01,2024	2024-2025	
13	Resilient V2X Communication for Cooperative and Remote Driving	UCR	New	Hang Qiu	ACTIVE	October 01,2024	2024-2025	

This section summarizes each project's objectives, progress, accomplishments, anticipated deliverables, and potential impact as of March 2025.

(1) GNSS Anti-Jam & Anti-Spoof Antenna Technology for Multimodal Transportation

This project aims to enhance GNSS receiver resilience in transportation systems by developing detection and mitigation methods for GNSS jamming and spoofing using multi-element antennas. It explores antenna architectures such as Controlled Reception Pattern Antennas (CRPAs), Dual Polarization Antennas (DPAs), and cooperating patch antennas on multiple independent vehicles, while also evaluating blind signal processing techniques with both simulated and live data under jamming and spoofing conditions. Key progress includes successful field testing of DPA-based techniques during Jammertest 2024, which demonstrated the ability to differentiate between spoofed and genuine conditions and estimate spoofing source directions. Additionally, dual antenna receivers like the Novatel PwrPk7D and Trimble BX992 have been evaluated under nominal conditions, and blind signal processing algorithms were successfully applied to live-signal data from Jammertest 2024 and Prof. Psiaki's sabbatical data. Although blind null-steering recovery methods have had mixed results, efforts are ongoing to address challenges with spoofers and multipath interference.

The project will deliver commercially viable solutions, including DPA-based spoofing detection and algorithms for blind spoofing detection and recovery using loosely coupled antenna arrays. It will also provide analytical tools for predicting the performance of detection and recovery methods. These outcomes will significantly contribute to strengthening GNSS systems, enhancing cybersecurity in transportation applications, and supporting broader efforts to mitigate transportation cybersecurity risks.

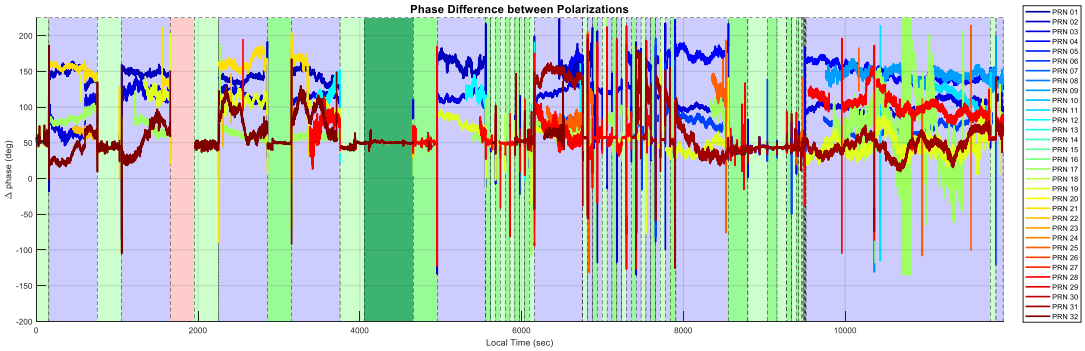


Figure 1. Phase differences over time during testing. Blue times (no spoofing), Red (jamming periods), Green (Different meaconing tests)

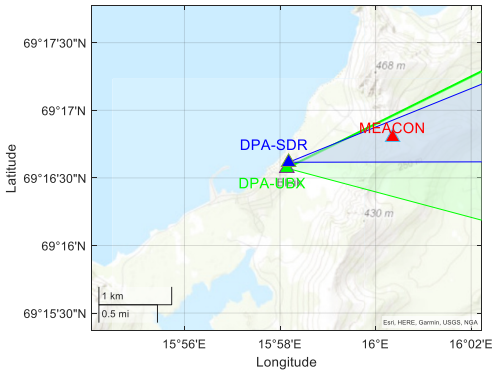


Figure 2. Estimated direction of arrival using DPA (phase differences)

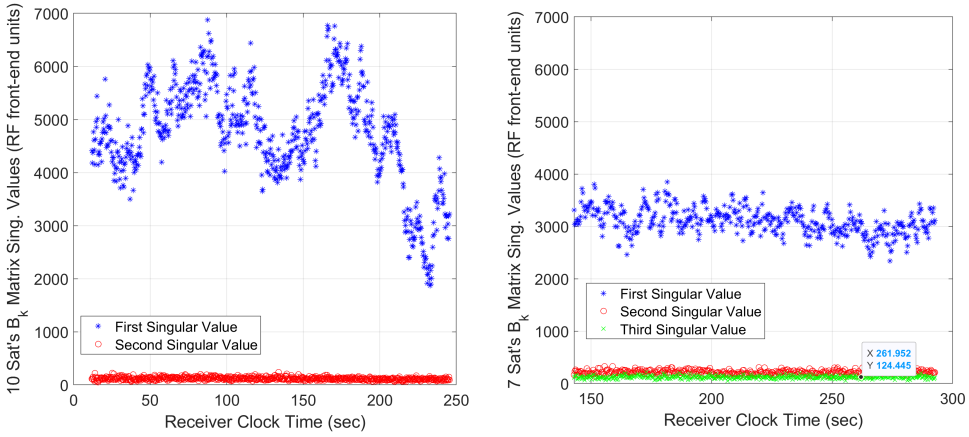


Figure 3. Confirmation of blind spoofing detection based on ratio of first to second singular values of the phasor matrix, applied to an Israeli live-spoofer data set involving 5 antennas and 2 spoofer directions of arrival. Left-hand panel: 2 singular values using Antenna A & B responses to one spoofer. Right-hand panel: 3 singular values using Antenna C, D, & E responses to the other spoofer.

(2) Receiver Signal Processing to Resist GNSS Jamming and Spoofing Attacks

This project explores two parallel approaches to enhance GNSS receiver signal processing for mitigating spoofing and jamming risks. The first approach focuses on

developing advanced signal autocorrelation monitoring techniques to detect spoofing attacks by decomposing the received signal into authentic, spoofed, and multipath components. This method allows for the detection of distinguishable correlation peaks, even when spoofed and true signals are closely aligned in code delay and Doppler frequency, overcoming the limitations of traditional magnitude-only analysis methods. The second approach addresses vulnerabilities in carrier tracking during jamming events by implementing Kalman filtering, which improves adaptability over traditional Phase Lock Loop (PLL) methods, successfully maintaining carrier locks during extended broadband interference.

Recent research has led to the development of a novel spoofing detection method using the Complex Cross Ambiguity Function (CCAF), which decomposes the GNSS signal into its authentic and counterfeit components. By utilizing complex-valued CCAF measurements, this technique exploits carrier phase differences between authentic and spoofed signals to significantly enhance detection sensitivity. A paper detailing this work has been submitted for peer review to *IEEE Transactions on Aerospace and Electronic Systems*. Prospective outcomes include advanced GNSS receivers with improved spoofing detection capabilities and enhanced carrier tracking resilience, offering more robust solutions for critical industries relying on GNSS technology. These advancements will contribute to the development of more secure and reliable positioning systems, addressing cybersecurity risks in transportation and other sectors.

(3) Defending Against GNSS Jamming and Spoofing by Multi-Sensor Integration

This project aims to enhance the resilience of GNSS systems by integrating multi-sensor technologies to address the challenges posed by GNSS jamming and spoofing. By augmenting GNSS with multiple sensors in advanced vehicles, we aim to ensure the continuous precision and reliability of PNT systems. Our research primarily focuses on three key areas: the development and testing of new methods to detect GNSS spoofing using Inertial Navigation Systems (INS), particularly in scenarios where the spoofer replicates the authentic GNSS signal with minimal errors. We derived an optimal monitoring technique to identify anomalies in the temporal structure of the spoofed measurements, which arise from the spoofer’s uncertainty in tracking the target's position.

Up to March 2025, significant progress has been made in this work. Birendra Kujur successfully defended his Ph.D. dissertation in November 2024, which forms the foundation of our current spoofing detection approach. In January 2025, we presented preliminary results at the ION International Technical Meeting, demonstrating the ability of our monitor to detect slow-onset spoofing using live test data. Additionally, a patent application for this method has been submitted, and further developments are expected to yield commercially viable solutions for GNSS spoofing detection. These advancements will contribute significantly to improving the robustness of GNSS systems, particularly in high-risk environments.

(4) Radio-Frequency Signal Augmentation to Reduce PNT Jamming and Spoofing Risks

This project focuses on the design and evaluation of complementary PNT algorithms using signals of opportunity (SoOP) from Low Earth Orbit (LEO) satellites not originally designed for navigation, with particular emphasis on their application to safety-critical transportation systems. Additionally, the project aims to evaluate the performance of a dedicated LEO satellite PNT system and strengthen collaboration between CARNATIONS and industrial partners, Xona Space Systems and Iridium. Our approach involves developing novel methods for vehicle position and velocity estimation based on time-sequenced Doppler measurements, incorporating Gauss-Markov models for vehicle motion and receiver clock dynamics. This method does not require prior knowledge of the vehicle's position, thus enhancing its applicability to dynamic environments.

As of March 2025, significant progress has been made. We are in the process of implementing and refining an analytical tool designed to predict key performance metrics—accuracy, integrity, continuity, and availability—of LEO satellite systems dedicated to PNT. This tool builds on aviation safety standards to quantify the reliability of LEO-based PNT systems, particularly for ground, rail, and maritime transportation. There have been ongoing discussions with Xona Space Systems to ensure the practicality of our performance predictions in alignment with their upcoming satellite constellation. Our team has also developed models for LEO satellite measurement errors, considering specific challenges presented by SoOP signals from constellations like Starlink and OneWeb. This work is crucial for enabling high-integrity positioning and minimizing risks in surface vehicle applications. Looking ahead, the project is poised to deliver several key outcomes, including error models for LEO satellite measurements, navigation filters that incorporate SoOPs, and risk-minimizing algorithms for utilizing LEO signals in surface vehicle applications. Furthermore, we will generate predicted performance maps that quantify the safety performance of LEO-based PNT, which will support the development of performance standards for transportation applications.

(5) Towards Resilient V2X Communications over 5G/6G Networks

This project advances the 5G/6G technologies to build secure, resilient, and low-latency vehicular networks. By enhancing V2X communications, the research aims to improve reliability, synchronization, and threat mitigation across connected transportation systems. Key outputs and achievements as of March 2025 include the introduction of a novel metric—Time-Critical Message Error (TCME)—to assess clock synchronization resilience, the development of a geodesic flow kernel-based domain adaptation technique for low-latency signal detection in 6G-V2X communications, and a hazard rate-based optimization framework for resilient resource allocation under imperfect channel state information.

Additionally, the team proposed analytical models for spoofing detection in integrated sensing and communication (ISAC) systems, focusing on phase-shift-based deception attacks using malicious reconfigurable intelligent surfaces (mRIS). Ongoing work includes the development of game-theoretic models to counter adversarial behavior in vehicular environments and cooperative data recovery strategies designed to assist vision-impaired vehicles through real-time V2X data sharing. The team is also modeling stochastic jitter in dynamic V2V links, helping shape communication protocols for low-latency, high-mobility scenarios. These innovations are set to enhance safety, trust, and efficiency in future mobility systems. A collaboration with UC Riverside is planned to support the transition and testing of these technologies.

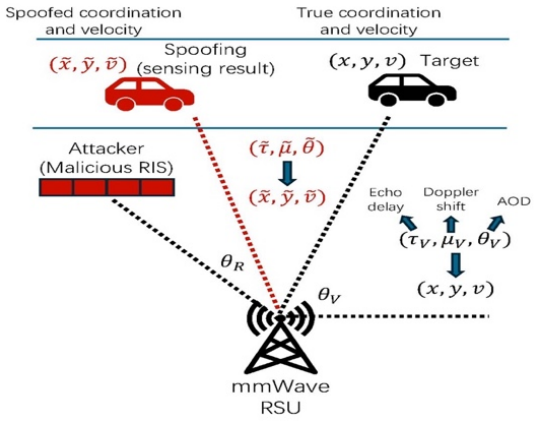


Figure 4. ISAC system model

(6) Multi-vehicle/Infrastructure Jammer/Spoofer Detection and Localization

Completed September 30, 2024.

(7) Threat Models and Use Cases for Multimodal Transportation

This project evaluates GNSS spoofing and jamming events and develops representative threat scenarios to test receiver resilience across transportation environments. Over the past six months, the team fielded both low-cost and high-end GNSS receivers in environments ranging from benign RF areas to locations with powerful spoofing signals. While high-end receivers provided superior diagnostic and spectral resolution, low-cost units also exhibited notable anti-spoofing capabilities. Receiver responses proved more complex than anticipated; devices already locked onto authentic signals often resisted spoofers with significantly offset intended locations, and partial spoofing enabled some signal rejection. Nonetheless, certain spoofing events led to inaccurate PVT outputs with large positional deviations. At a port in Israel, spoofing signals stronger than authentic ones were observed alongside deliberate jamming designed to trigger reacquisition, increasing spoofing susceptibility. Spoofed ephemeris data lagged authentic GPS by approximately 30 seconds, indicating real-time rebroadcasting. At Norway's Jammertest, low-cost receivers often retained lock on authentic signals despite low C/N_0, though brief jamming periods increased spoofing effectiveness. Raw RF data

collected from these tests is being analyzed using software-defined radios to investigate signal behavior, revealing transition-period partial captures and significant errors in position and clock domains. Concurrently, the team collaborates with RTCA SC-159 Working Group 2 to define spoofing scenarios for resilient aviation receivers. The group's objectives are to ensure: (1) recovery after spoofing exposure, (2) detection of spoofing presence, and (3) prevention of spoofed signal influence on PVT solutions. Scenarios cover spoofers ranging from simple repeaters to complex multi-antenna simulators. A critical conclusion is that a secure, independent time source is essential for effective recovery. This is difficult to implement in aviation but more practical in other transportation modes that use internet-based two-way communication.

By March 2025, the project has produced robust datasets, performance evaluations across receiver types, and key contributions to RTCA efforts. Future deliverables include a technical white paper on multimodal spoofing scenarios and peer-reviewed publications, including ION GNSS+ 2025 presentations. Aligned with USDOT priorities and CARNATIONS' mission, this work advances GNSS resilience through improved spoofing detection, resistance, and recovery capabilities.

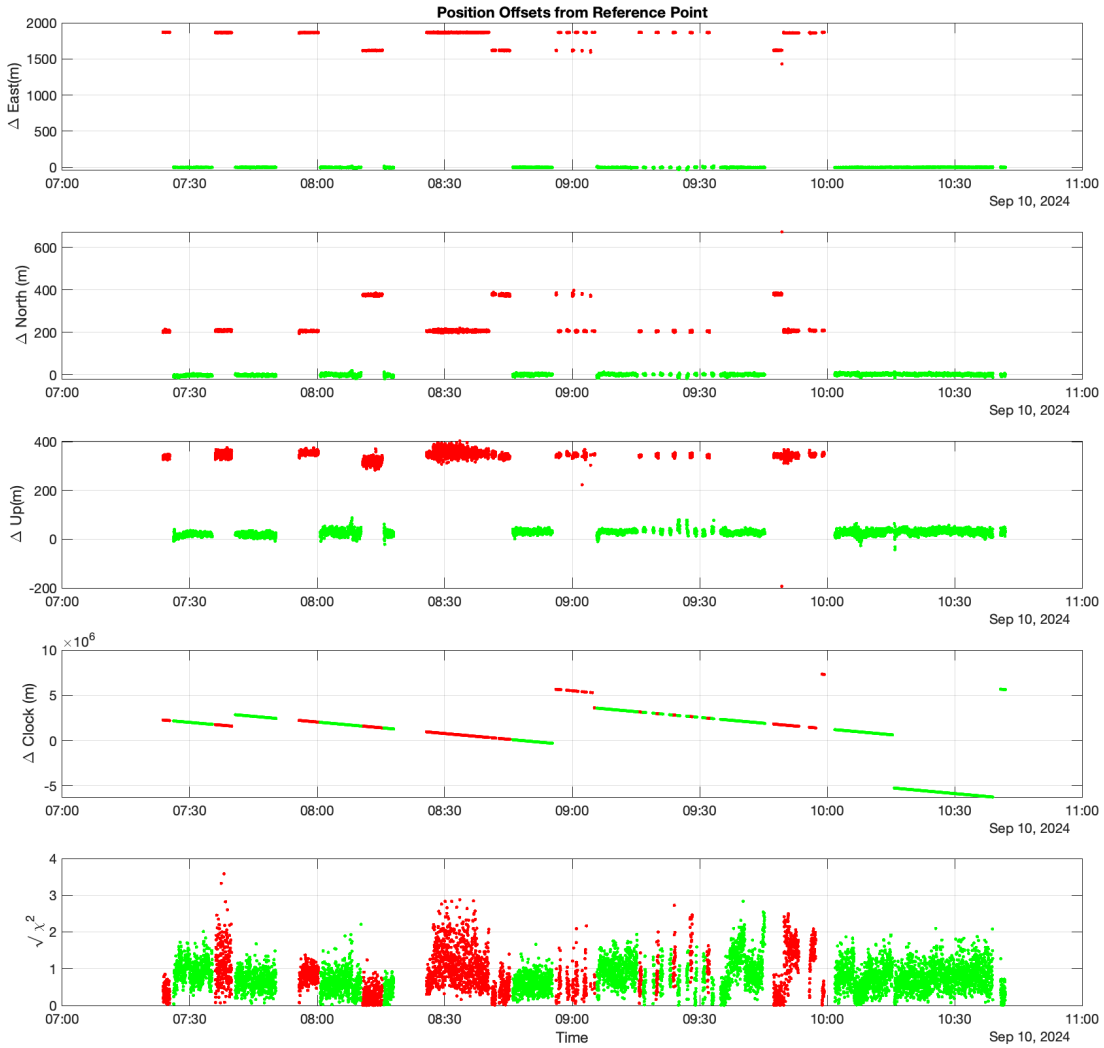
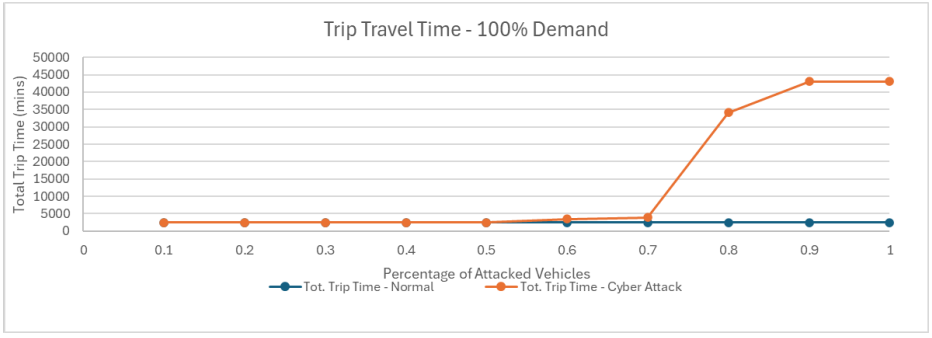


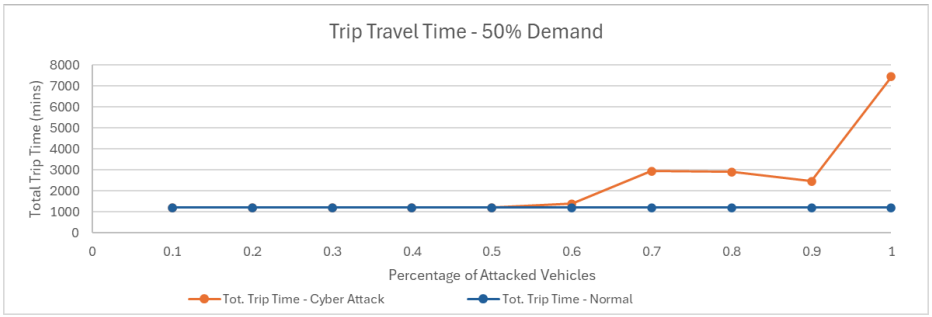
Figure 5. Collected spoofing data from JammerFest in Norway on September 10, 2024

(8) R-PNT Virtual Conflict Simulation

This project aims to simulate cyberattacks and assess their impact on the performance of transportation systems through “virtual conflict simulations” using a newly developed simulation environment. The study incorporates “red-team and blue-team” agents to introduce a range of attack and defense strategies. Over the past six months, extensive simulations have been conducted to analyze the effects of spoofing on a dynamic feedback routing application under varying traffic demand conditions. The results reveal that, as traffic demand increases (at 25%, 50%, and 100% of base traffic demand), the percentage of spoofed vehicles required to degrade system performance increases by 50%, 60%, and 70%, respectively. At the link level where spoofing occurs, we observed significant increases in both the number of vehicles and the total travel time on affected links as the percentage of attacked vehicles increased, highlighting the vulnerability of transportation systems to cyberattacks and the need for adaptive defense strategies.

In the upcoming months, we plan to extend our simulations by varying spoofing locations and the error factor of spoofed positions. We also intend to conduct simulations on larger, real-world road networks to evaluate the scalability of the dynamic routing application. Additionally, our mitigation strategy will focus on developing methods to identify suspicious data and enhance the strength of the system against cyberattacks. This research directly contributes to the U.S. DOT’s focus on reducing transportation cybersecurity risks and aligns with CARNATIONS’ goal to improve system integration and evaluation. The findings from this project provide valuable insights into the vulnerabilities of intelligent transportation systems, supporting the development of more resilient infrastructures and ensuring the security and reliability of modern transportation.





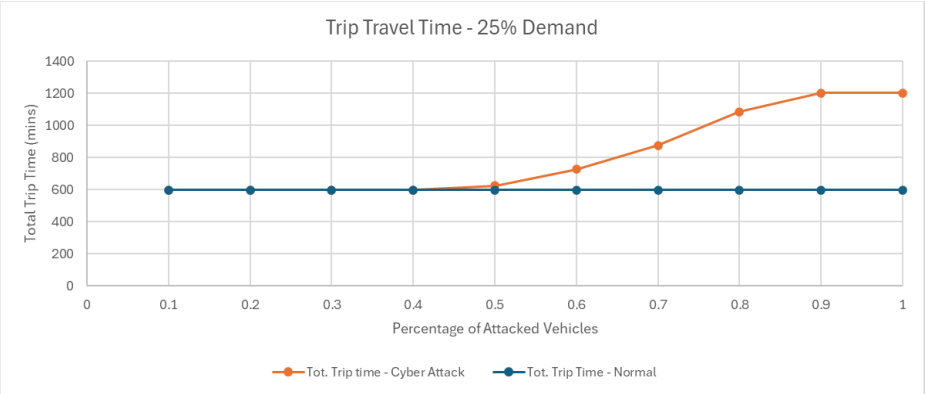


Figure 8. Trip-level travel time performance

		Total Link Travel Time			Number of Vehicles on Link		
		Traffic Demand			Traffic Demand		
		0.25	**0.50**	**1.00**	**0.25**	**0.50**	**1.00**
Percentage of Attacked Vehicles	**1.0**	75.14	75.22	72.26	75.20	75.17	72.15
	0.9	75.14	50.29	72.26	75.20	50.07	72.15
	0.8	73.73	54.78	61.15	73.61	54.55	60.91
	0.7	49.15	51.88	22.22	49.08	51.70	21.60
	0.6	27.40	20.14	14.52	27.18	19.67	14.13
	0.5	15.82	11.01	8.57	15.57	10.58	7.96
	0.4	8.47	8.84	6.39	8.18	8.41	5.90
	0.3	6.78	6.09	3.12	6.60	5.83	2.88
	0.2	4.80	4.20	2.54	4.49	3.93	2.40
	0.1	2.26	1.74	1.60	2.11	1.63	1.44

Table 1. Percentage of Performance Degradation compared to the normal scenario (without spoofing)

(9) Comprehensive Testing and Evaluation of Resilient PNT Systems

This project focuses on analyzing experimental data from radio frequency interference (RFI) events and evaluating the anti-jamming and anti-spoofing technologies developed by CARNATIONS. Given the legal constraints on open-sky broadcasting of radio-frequency signals at GNSS frequencies, testing has been limited to controlled environments such as anechoic chambers, which restricts the applicability to transportation systems. To address this, the project utilized crowd-sourced data from connected ground and aircraft receivers, as well as from cell phones, to monitor RFI both in the U.S. and internationally. New online tools were deployed to enable testing during jamming events, and non-GNSS sensor data was collected from multiple vehicles for future collaborative R-PNT research. The project also involved data collection during government-organized RFI experiments in the U.S., Norway, and Israel, areas affected by frequent spoofing incidents. Furthermore, a high-fidelity test setup was created in collaboration with Spirent to allow remote simulated spoofing experiments, thus enabling CARNATIONS researchers to conduct cost-effective testing. Plans for an anti-RFI testbed at VTTI are in progress, and the project is collaborating with UCR on a CAV

scenario test plan for the APEX 25 jamming/spoofing event at White Sands Missile Range in September 2025.

Key developments from this project include the implementation of a webpage to alert the PNT community and the general public about RFI to GNSS (https://rfi.stanford.edu/) and a second webpage that tracks RFI patterns from over 900 connected ground receivers (http://gnss-interference-lb-820701820.us-east-2.elb.amazonaws.com/state). A wideband GNSS dataset collected during interference tests in Norway is being assembled for future analysis. Additionally, efforts are being made to consolidate a multi-institutional testing facility, which will provide advanced testing capabilities utilizing both high-end simulators and hardware. These contributions directly support the U.S. DOT's strategic focus on reducing transportation cybersecurity risks. By strengthening collaborations with industry partners and participating in government-organized test events, this project is advancing the development of resilient and secure PNT systems, crucial for safeguarding transportation infrastructure.

(10) Improving GNSS Resiliency Using Edge AI Solutions

This project focuses on enhancing GNSS through the integration of Edge Artificial Intelligence (Edge AI) in environments where GNSS signals are disrupted or weak, such as urban canyons and indoor spaces. By leveraging low-power, compact edge devices, the project aims to process AI workloads locally, minimizing latency and improving real-time decision-making. Key research areas include the use of Machine Learning (ML) and Deep Learning (DL) models to enhance GNSS signals affected by multipath reflections, interference, and weak signals. Additionally, the project explores collaborative positioning, multi-sensor fusion, and hybrid positioning techniques that integrate technologies like Wi-Fi, Bluetooth, LiDAR, and 5G to improve positioning accuracy in challenging environments. Adaptive algorithms and the use of local maps will further improve GNSS resilience, enabling more reliable positioning in dynamic and obstructed environments.

As of March 2025, the project has made significant strides, including the proposal of an optical intelligent reflecting surface (OIRS)-aided vehicle-to-vehicle (V2V) system for enhancing Non-Line-of-Sight (NLoS) communication at road intersections, published in IEEE Transactions on Vehicular Technology. The team has also addressed mirror-element allocation in OIRS-aided UAV-based Free Space Optics (FSO) networks under proactive jamming, enhancing network resilience, with the work published in IEEE Transactions on Intelligent Vehicles. Furthermore, a deep neural network (DNN)-enabled resilient GNSS system was proposed to mitigate jamming and spoofing, with plans to extend this work using Tiny ML for Edge AI implementation. The outcomes of this project are expected to improve GNSS signal integrity and availability, reduce vulnerabilities to attacks, and enhance the accuracy of GNSS-based navigation in applications, offering scalable solutions for industries like autonomous vehicles, aviation, and maritime navigation.

(11) Development of a Generalized Integrity Monitoring Framework for CAV Applications

The objective of this project is to develop and evaluate a Generalized Integrity Monitoring Framework for Connected and Automated Vehicle (CAV) applications, focusing on assessing the integrity of vehicle positioning in various real-world scenarios. The project aims to design a SUMO-CARLA co-simulation platform integrating a digital twin model of a smart intersection in Riverside. (CARLA (Car Learning to Act) and SUMO (Simulation of Urban Mobility) are widely implemented simulators.), This platform will be used to test safety-critical scenarios, such as illegal pedestrian crossings and vehicle movements in occluded conditions. A unified metric will be proposed to assess the usability, reliability, and timeliness of shared information through Vehicle-to-Vehicle (V2V) or Vehicle-to-Infrastructure (V2I) communication. Furthermore, the project aims to analyze the effectiveness of this metric in optimizing sensor or information node selection for estimating road agent states and enhancing safety during critical maneuvers.

Through March 2025, significant progress has been made in the project's development. The SUMO-CARLA co-simulation environment for the Riverside smart intersection has been successfully designed, providing an advanced platform for simulating and testing practical CAV scenarios. Additionally, the team has presented a survey paper titled "The Role of Integrity Monitoring in CAVs: Current State-of-Practice and Future Directions," which has been submitted to the IEEE ITS Magazine and presented at the SAE World Congress 2025 in Detroit, Michigan. Looking ahead, the project will integrate additional landmarks and features into the virtual environment by utilizing sensor recordings from the smart intersection through AVL's Digital Ground Truth (DGT) platform. Furthermore, a preliminary safety dataset capturing human and automated driving behavior during safety-critical maneuvers will be developed. This work is expected to lay the groundwork for evaluating the feasibility and performance of CAV applications in mixed environments, offering critical insights into the capabilities of both ego vehicles and surrounding road agents.

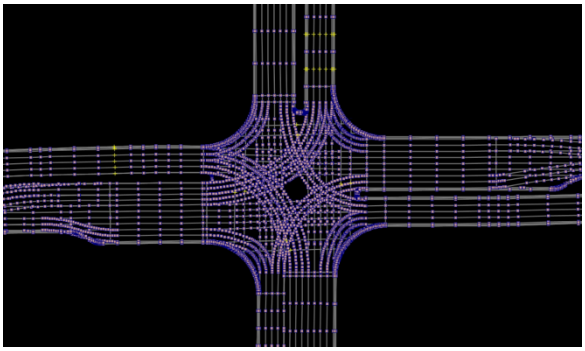


Figure 6. Intersection Layout

Figure 7. CARLA map of the smart intersection

(12) Examining and Enhancing Vehicle Spoofing Detection Capabilities in CAV Applications Using BSM Information

This project focuses on addressing the growing security vulnerabilities in CAV systems by examining the effects of GNSS spoofing and jamming attacks and proposing effective counter measures. The objective is to understand how such attacks impact not only the targeted autonomous vehicle but also nearby non-target vehicles, and to assess the degradation of CAV hardware components such as sensors and communication modules. In particular, the project aims to enhance vehicle positioning integrity and communication by leveraging Basic Safety Message (BSM) information for real-time spoofing detection and mitigation.

During the current reporting period, the team actively participated in the PNTAX24 event organized by the Department of Defense to collect practical GNSS jamming and spoofing datasets under controlled experimental conditions. On the first night, GNSS jamming was conducted on the L1/L2/L5 bands, and the resulting dataset is being used to analyze clock drift and behavioral degradation in commercial CAV hardware during jamming.

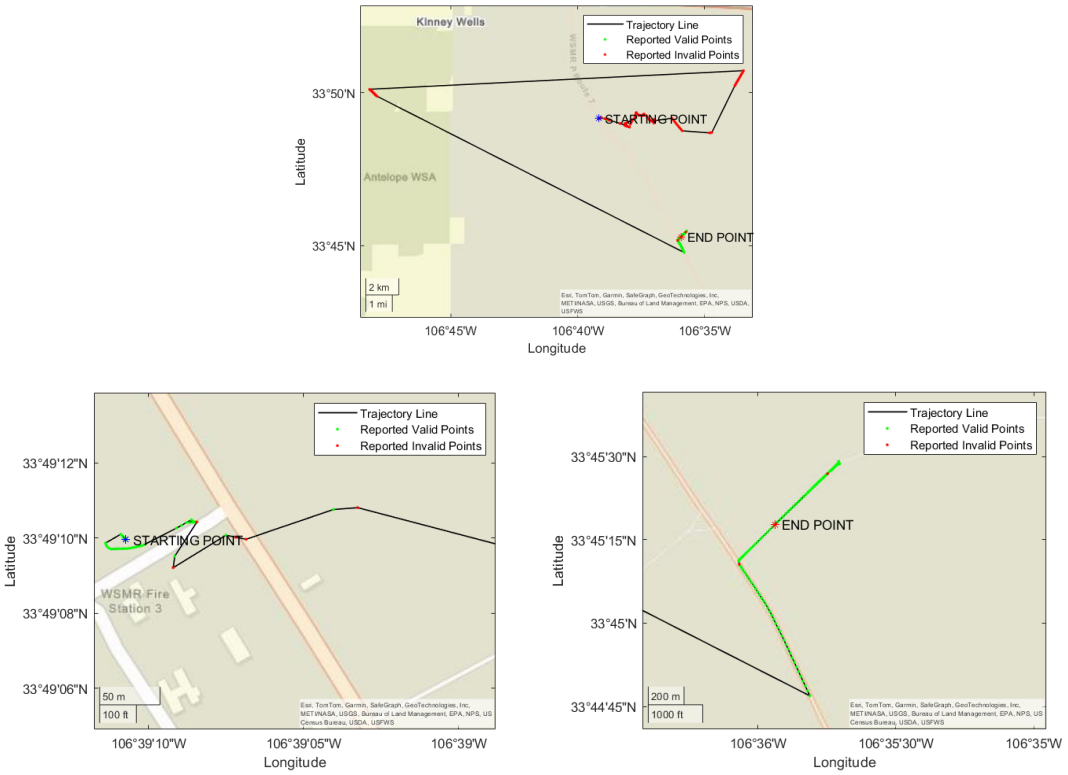


Figure 8. Full route with estimated trajectory

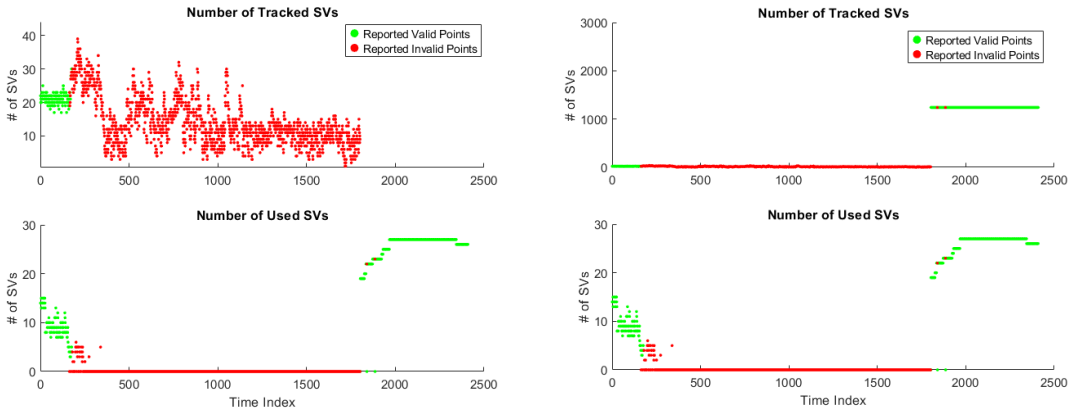


Figure 9: Tracked Satellite Vehicle Overflow to 1240 after jamming ends

A dual GPS jamming and spoofing operation was carried out on the second night. The second dataset is especially valuable, as it not only captures the hardware response to spoofing attacks but also includes LiDAR data that can be used to support localization efforts when GPS signals are compromised.

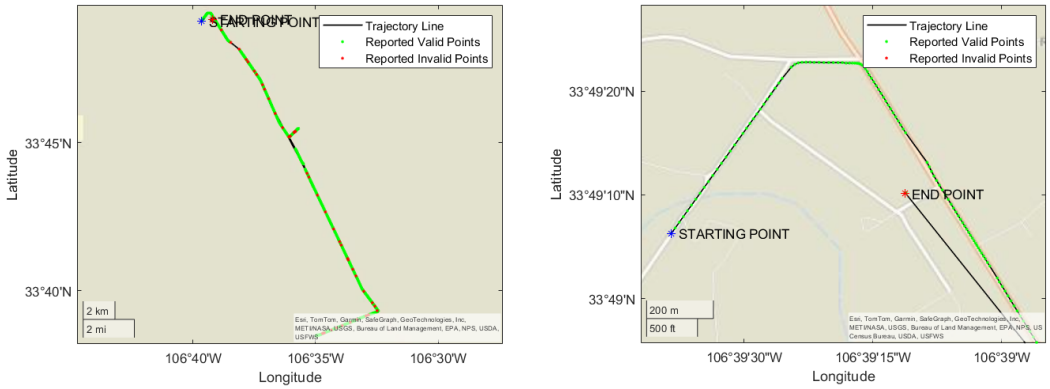


Figure 10: Full route with estimated trajectory. The actual starting position is in the same parking lot as the reported end point. (Data collection began while spoofed)

These comprehensive datasets enable a detailed understanding of hardware vulnerabilities and pave the way for resilient design solutions. Prospective outcomes of this work include the development of a customized Level 2 BSM capable of maintaining robust CAV functionality under GNSS-compromised conditions. The project is expected to significantly enhance the detection and mitigation of spoofing and jamming threats, contributing to improved safety and communication reliability in autonomous vehicle systems. The broader implications extend to industry-wide standards and protocols, promoting a more secure CAV ecosystem. A detailed experimental debrief summarizing the work conducted at PNTAX24 was presented to the Department of Defense in February 2025, emphasizing the relevance of this research to national transportation security efforts.

(13) Resilient V2X Communication for Cooperative and Remote Driving

This project focuses on addressing challenges in autonomous vehicle (AV) operation, particularly in handling corner cases caused by limited visibility or unexpected scenarios. It explores cooperative driving—sharing sensor data among vehicles—and remote driving—enabling human control of AVs when necessary. Both rely on secure, low-latency, high-bandwidth V2V and V2I communication through Cellular Vehicle-to-Everything (C-V2X). A major achievement this period is the acceptance of the paper *"SEE-V2X: C-V2X Direct Communication Dataset: An Application-Centric Approach"* at ACM SenSys 2025. The paper introduces the world's first publicly available dataset for C-V2X direct communication, collected using commercial off-the-shelf radios deployed on vehicles and infrastructure at real intersections. It evaluates real-world throughput, latency, and channel characteristics, highlighting critical cross-layer issues impacting performance and security.

The paper will be presented in May 2025, and the dataset will be publicly released and maintained for community use. Future work includes developing communication strategies to secure C-V2X links while optimizing performance. The dataset will also support the creation of network emulators, enabling reinforcement learning (RL) models to adapt system behavior in dynamic conditions. These outcomes pave the way for more realistic cooperative autonomy and contribute to cross-layer V2X design, enhancing network efficiency, security, and AV readiness for deployment.

CARNATIONS Collaborative Endeavors

During this reporting period, the team maintained close oversight of ongoing research activities while placing increased emphasis on achieving tangible outcomes and results. Collaboration remained a central focus across all levels of the Center, from Principal Investigators and the Program Manager to student researchers, supported by continuous engagement and feedback mechanisms. Efforts to enhance both internal and external collaboration were reflected through participation in conferences, exhibitions, group discussions, one-on-one meetings with the Advisory Board, and student poster competitions. CARNATIONS maintained a strong presence at key outreach events, including Stanford SCPNT 2024, ION ITM/PTTI, and the Illinois Tech Student Poster Competition, highlighting the center's active engagement and visibility within the broader scientific and technical community.

1.1.2. Leadership

CARNATIONS continues to demonstrate leadership in Resilient Positioning, Navigation, and Timing (R-PNT) through sustained contributions in research, technology transfer, education, and workforce development. Reinforcing its influence in the transportation research landscape, the Center actively participated in key conferences and meetings. In October 2024, CARNATIONS' students and the Associate Director presented their research, "*Uncovering Subtle GNSS Spoofing by Decomposing the Complex Cross Ambiguity Function*"—at the Stanford Annual SCPNT 2024. This work, coupled with a presentation on the Center's mission and initiatives as a USDOT Tier-1 University

Transportation Center, highlighted its role in advancing resilient and secure PNT technologies. CARNATIONS further strengthened its leadership position by organizing and hosting its second (yearly) symposium during the ION ITM/PTTI 2025 in Long Beach. This event brought together students, Principal Investigators, and members of the Advisory Board to assess research progress, share insights, and define strategic directions for upcoming initiatives. These engagements reflect CARNATIONS' ongoing commitment to shaping the future of resilient transportation systems through collaboration, innovation, and informed decision-making.

To strengthen operational efficiency and improve internal coordination, CARNATIONS undertook key organizational enhancements during the reporting period. These changes were informed by strategic input from the Executive Committee and valuable feedback from the CARNATIONS Advisory Board (CAB). Initially, subcommittees convened as full groups monthly. However, following the successful implementation of a more individualized engagement model by the Technology Transfer Subcommittee, the Center adopted a one-on-one meeting format across all subcommittees. In this revised structure, individual members meet directly with the subcommittee Co-Chair, who then consolidates insights and reports to the Program Manager. This transition has led to more focused discussions and improved decision-making processes and has now been applied to both the Education & Workforce Development and Research Subcommittees. Further, to simplify governance and enhance leadership accountability, CARNATIONS restructured its subcommittee leadership model. While each subcommittee was previously co-led by two Co-Chairs, starting in 2025, the Center transitioned to a single Chair (Lead) system. This adjustment was designed to eliminate role overlap, clarify responsibility, and enable more agile management of subcommittee functions, ultimately contributing to a more effective and responsive organizational framework.

1.1.3. Education and Workforce Development

Over the past six months, the Education and Workforce Development Subcommittee has made substantial progress in advancing the Center's academic mission. Under the leadership of Dr. Matthew Spenko, who was appointed as Subcommittee Lead in January 2025, several impactful initiatives have been launched. One of the most notable developments is the upcoming **Center-wide Student Competition on Precision Navigation**, proposed by Dr. Spenko and swiftly approved by the Executive Committee. Scheduled to launch in Fall 2025, the competition invites upper-level undergraduate and master's students to design GPS-based asset trackers equipped with spoofing detection capabilities. Through this challenge, participants will gain hands-on experience with Real-Time Kinematic (RTK) positioning, sensor fusion, and embedded systems, reinforcing essential concepts in resilient navigation and applied systems engineering. This initiative reflects the subcommittee's strong commitment to experiential learning and technical excellence.

The **Inter-University Teaching Model** has also continued to grow. In Spring 2025, two graduate-level courses were offered through Virginia Tech: *Advanced GPS Receiver Design* (instructed by Professor Mark Psiaki, with 23 students enrolled) and *Sensing and*

Perception for Autonomous Systems Navigation (instructed by Professor Mathieu Joerger, with 31 students enrolled). In the previous semester, Illinois Tech offered *Introduction to Navigation*, which had 11 students. In total, 65 students have participated in courses offered through the Inter-University Teaching Model in its first year of existence. These cross-institutional offerings enhance the curriculum by addressing advanced topics in GPS engineering and autonomous navigation, exemplifying the collaborative spirit of the Center's academic network. Additionally, the Subcommittee's **Webinar Series**—launched in September 2024—has maintained high levels of engagement. Four webinars were held during the reporting period: in September, November, February, and March. These events have provided valuable platforms for technical knowledge sharing and professional development. Together, these efforts demonstrate the Subcommittee's strategic vision and operational effectiveness in delivering impactful educational programs that align with the Center's long-term objectives.

1.1.4. Technology Transfer and Collaboration

The Technology Transfer Subcommittee has been instrumental in advancing CARNATIONS' research outcomes through targeted engagement with industry and government stakeholders. Since January 2025, under the leadership of Dr. Samer Khanafseh, the subcommittee has adopted a more agile, results-oriented approach. This includes quarterly one-on-one meetings with key stakeholders to translate research into actionable pathways for commercialization and real-world application. As a result, CARNATIONS' partnership base has expanded significantly, increasing from an initial nine collaborators to **41 active industry and government partners**. These partnerships have not only reinforced the research ecosystem but also accelerated the adoption and relevance of CARNATIONS' innovations.

In addition to establishing strategic partnerships, the Technology Transfer Subcommittee has launched several initiatives to support student career transitions and promote technology commercialization. A dedicated **job-posting platform** was introduced to streamline recruitment, enabling industry partners to share opportunities and students to submit resumes. This initiative has already facilitated the **successful placement of ten students in industry roles**.

Further strengthening commercialization efforts, the Technology Transfer Subcommittee facilitated the selection of CARNATIONS technologies by the Polsky Center for Entrepreneurship and Innovation at the University of Chicago to participate in the competitive Spring 2025 I-Corps Cohort, providing a structured opportunity to assess market readiness and refine go-to-market strategies. Moreover, the Technology Transfer Subcommittee participated in a National Science Foundation (NSF)-funded commercialization program, which enabled faculty members to pitch product concepts aimed at accelerating technology transfer. Through this initiative, the subcommittee advanced to the finalist stage of the competition. The finalist team, comprising students and led by faculty in coordination with Kaplan and the Polsky Center, focused on refining the commercialization strategy and securing potential follow-on funding to push the technology toward market readiness.

Complementing these efforts, the Technology Transfer Subcommittee has also established a **quarterly newsletter** to disseminate updates on research publications, intellectual property filings, and experimental results. This initiative has received positive feedback for enhancing transparency and strengthening stakeholder engagement. Additionally, the subcommittee has contributed significantly to academic dissemination through peer-reviewed journal articles and conference presentations, particularly in the areas of V2X, V2V, and transportation system resilience—further positioning CARNATIONS as a leader in advancing innovation through collaborative and translational research efforts.

1.2. What was accomplished under these goals?

1.2.1 Research

Research Performance Metrics	Output April 2024	Output April 2025
Number of new technologies, procedures/policies, and standards/design practices influenced by the research and adopted by organizations.	1	4
Number of research projects funded by sources other than UTC and matching fund sources	2	3
Number of research articles presented in conferences and published in peer-reviewed journals.	3	35

1.2.2 Leadership

Leadership Performance Metrics	Output April 2024	Output April 2025
Number of keynote speeches/invited presentations at academic and professional conferences.	0	7
Number of leadership positions in local, national, and international organizations.	11	34
Number of CARNATIONS-affiliated students in scholar and professional leadership positions.	0	6

1.2.3 Education and Workforce Development

Education/Workforce Development Performance Metrics	Output April 2024	Output April 2025
Student enrollment numbers and grades in CARNATIONS courses.	0	65
Number of Webinars Organized	0	5
Number of Courses taught by CARNATIONS	0	3

1.2.4 Technology Transfer and Collaboration

Technology Transfer and Collaboration Performance Metrics	Output April 2024	Output April 2025
Number of CARNATIONS research efforts successfully transferred to partners and stakeholders.	0	0
Number of new collaborative efforts between institutions formed because of CARNATIONS.	9	23
Number of CARNATIONS-affiliated patents.	0	1
Number of CARNATIONS-related students joining partners or collaborators.	0	10

1.3 How have the results been disseminated?

CARNATIONS has prioritized the broad and effective dissemination of research outcomes through a multi-channel strategy that encompasses academic, technical, and stakeholder-focused avenues. These efforts ensure that research findings reach the appropriate audiences and contribute to ongoing developments in the Resilient Positioning, Navigation, and Timing (R-PNT) domain.

Conference Presentations and Recognition

Research results have been shared at several high-profile, peer-reviewed venues. These include the Institute of Navigation's International Technical Meeting (ION ITM) 2025, the 2024 Symposium on Cognitive and PNT Technologies (SCPNT), IEEE-affiliated events, and the CARNATIONS Semi-Annual Symposium 2025 hosted in Long Beach, CA. These platforms served as critical opportunities for knowledge exchange, peer validation, and thought leadership in resilient navigation and transportation innovation. In a notable recognition of CARNATIONS' student engagement and research excellence, **Dawson Beatty was awarded the Student of the Year in January 2025 at the Transportation Research Board (TRB) Annual Meeting**. On Tuesday, January 7, Mr. Beatty presented findings from his data collection experiment conducted during **JAMMERTEST 2024** in Norway, showcasing the program's commitment to fostering student-led innovation in GNSS resilience.

Internal Engagement and Knowledge Sharing

In addition to public dissemination, CARNATIONS sustains a strong internal knowledge-sharing culture. Regular bi-weekly research meetings are held among principal investigators, graduate students, and staff to present project updates, coordinate collaborative work, and ensure alignment with strategic goals. These sessions serve both as checkpoints and incubators for emerging research ideas.

Educational Outreach and Webinars

The CARNATIONS Educational Webinar Series, launched in September 2024, has proven effective for technical outreach and community engagement. Four webinars were conducted during the reporting period (September, November, February, and March), each featuring expert speakers and interactive discussions with academic and industry participants. These webinars expand the reach of research insights beyond formal academic settings.

Stakeholder and Industry Engagement

CARNATIONS also maintains direct outreach through one-on-one meetings with industry partners, enabling targeted discussions around technology transition, commercial viability, and collaborative opportunities. These engagements help align ongoing research with practical application needs and industry standards.

Quarterly Newsletter and Media Communications

To further amplify visibility and stakeholder outreach, CARNATIONS publishes a professionally designed Quarterly Newsletter that highlights recent publications, intellectual property disclosures, field test results, student milestones, and institutional news. To date, two issues have been published—**Issue 1** and **Issue 2**—each serving as a vital communication tool for federal partners, academic institutions, and private-sector stakeholders. These coordinated distribution efforts ensure that the Center's work remains transparent, impactful, and aligned with national priorities in transportation innovation and resilience.

Through this integrated dissemination strategy, CARNATIONS continues to contribute substantively to national conversations on transportation cybersecurity, resilient navigation systems, and workforce development in PNT and autonomous mobility.

1.3.1 What do you plan to do during the next reporting period to accomplish the goals?

During the next reporting period, substantial efforts will be dedicated to expanding the breadth and impact of ongoing research initiatives. A cross-institutional student competition will be launched in Fall 2025 to establish greater collaboration across partner universities, stimulate interdisciplinary innovation, and address key challenges in the resilient PNT. Additionally, a team from Stanford University will participate in **JAMMERTEST 2025** in Norway, gathering critical data on GNSS interference resilience, thereby contributing to advancing the field of signal protection and positioning accuracy under challenging conditions. The dissemination of research findings will be strategically leveraged through participation in several high-profile events. These include the **CARNATIONS Days 2025 Conference**, which will provide a platform for evaluating current progress and refining future research priorities. Furthermore, CARNATIONS will be exhibiting at and sponsoring the **2025 IEEE World Forum on Public Safety**

Technology, thereby increasing visibility and engagement with leading industry and academic stakeholders.

A major highlight of the upcoming cycle is CARNATIONS' strong presence at **ION GNSS+ 2025** in Baltimore this September, where approximately a **dozen CARNATIONS-affiliated research papers** will be presented. ION GNSS+ is the **largest annual international conference in the Positioning, Navigation, and Timing (PNT) domain**, attracting top researchers, federal agencies, and industry leaders from around the world. This event represents a key opportunity to share our innovations, benchmark against global research, and reinforce our leadership in resilient PNT systems. CARNATIONS researchers will also present at the **Council of University Transportation Centers (CUTC) Summer Meeting 2025**, reaffirming the program's dedication to transportation innovation at the national level. To complement these efforts, a **center-level magazine** will be developed to highlight the outcomes of collaborative research, student contributions, and the technological advancements stemming from the project. These activities reflect a deliberate and sustained effort to expand the reach, influence, and relevance of the research endeavors in the coming months.

2 PARTICIPANTS & COLLABORATING ORGANIZATIONS

2.1 What organizations have been involved as partners?

CARNATIONS has built strong partnerships with leading industry organizations. These collaborations provide essential expertise and resources, advancing research in resilient Positioning, Navigation, and Timing technologies. These alliances are key to achieving our goals and ensuring practical application of our findings.

Below is the list of CARNATIONS' university and industry partners:

Partner Institutes

No.	Institute	Principal Investigator
1	Illinois Tech	Boris Pervan, Samer Khanafseh, Matthew Spenko
2	Virginia Tech	Mathieu Joerger, Mark Psiaki, Hesham Rakha, Walid Saad
3	UC-Riverside	Matthew Barth, Hang Qiu
4	Chicago State	Mousa Ayyash
5	Stanford	Todd Walter, Sherman Lo, Sam Pullen

Industry Partners

No.	Industry	Person of Contact (POC)
1	TuSimple	Zhendong Yu
2	UrsaNav	C. Schue
3	TORC	Andrew Culhane
4	DOT	Andrew Hansen
5	Xona Space	Brian Manning

6	Xona Space	Tyler Reid
7	Spirent	Ajay Vemuru
8	Bosch	Boubeker Belabbas
9	Trimble	David De Lorenzo
10	MITRE	Christopher Hegarty
11	SAE	Tim Weisenberger
12	DOT	Karen Van Dyke
13	Hexagon	Sandy Kennedy
14	Spirent	Jeremy Bennington
15	Satelles	Michael O'Connor
16	VIT	M. Higgins
17	Aeva	Fisher Shi
18	Is4s	John Raquet
19	VOLPE (DOT)	Hadi Wassaf
20	CA DOT	Asfand Siddiqui
21	CA DOT	Dean Campbell
22	Port of Long Beach	Noel Hacegaba
23	Qualcomm	Guttorm Opshaug
24	The Aerospace Corporation	Steven W. Lewis
25	ILAV Association	J. Quandt
26	Motional	Karl Iagnemma
27	FAA	James Aviles
28	MITRE	Steve Langel
29	Qunav	Andrey Soloviev
30	IS4S	Matthew Zeiger
31	Oroliads	Tim Erbes
32	Seoul National University	Changdon Kee
33	Illinois Institute of Technology	Seebany Datta-Barua
34	DLR	Michael Meurer
35	Aero	John Janeski
36	StarNav	Joshua Morales
37	Collins Aerospace - RTX	Phillip Izdebski
38	Vector Nav	Jermey Davis
39	Corvus Labs	Spencer Leamy
40	TruNav	Samer Khanafseh (also PI)
41	International Telecommunication Union	Russell Shields

2.2 Have other collaborators or contacts been involved?

CARNATIONS members and collaborators join periodically throughout the year, contributing to various meetings and symposia. Our most recently added partners

include Simon Baksh from JAVAD, Jeremy Davis from VectorNav, and Russell Shields from the International Telecommunication Union. Below is the list of participants from the most recent CARNATIONS Symposium and meetup.

CARNATIONS-ION/ITM Symposium 2025			
PRINCIPAL INVESTIGATORS			
No.	**Name**	**Role**	**Mode**
1	Boris Pervan	Director	In-Person
2	Mathieu Joerger	Assoc. Director	Virtual
3	Aashish Narang	Program Manager	Virtual
4	Moussa Ayyash	PI	-
5	Matthew Barth	PI	In-Person
6	Hang Qiu	PI	Virtual
8	Samer Khanafseh	PI	In-Person
9	Sherman Lo	PI	In-Person
10	Sam Pullen	PI	Virtual
11	Hesham Rakha	PI	-
12	Walid Saad	PI	Virtual
13	Todd Walter	PI	In-Person
STUDENTS			
1	Sara Hemati	VT	Virtual
2	Semih Karadogan	VT	Virtual
3	Tingyu Shui	VT	Virtual
4	Pratiti Paul	VT	Virtual
5	Alqasem Hindi	VT	Virtual
6	Wang, Shizhuang	VT	Virtual
7	Malani, Shorya	VT	Virtual
8	Mohamed Farag	VT	Virtual
9	Dawson Beatty	VT	Virtual
10	Kana Nagai	IIT	In-Person
11	Sahil Ahmed	IIT	In-Person
12	Aru Nayak	VT	In-Person
13	Mihir Nemana	IIT	In-Person
14	Birendera Kujur	IIT	In-Person
15	Saswat P. Nayak	UCR	In-Person
16	Liam Carey	VT	In-Person
17	Shinsaku Kuwada	IIT	In-Person
Partners			
18	KarenVan Dyke	DOT	In-Person
19	Andrew Hansen	DOT	Virtual
20	Haddi Wassaf	Volpe	In-Person
21	Christian Ardito	StarNav	Virtual

22	Joshua Morales	StarNav	In-Person
23	Steve Langel	MITRE	Virtual
24	David DeLorenzo	Trimble	Virtual
25	Cagatay Tanil	Amazon Air	Virtual
26	Chuck Schue	UrsaNav	Virtual
27	Stewen W Lewis	Aero	In-Person
28	John Janeski	Aero	Virtual
29	Michael Meurer	DLR	Virtual
30	Matthew Zeiger	IS4S	Virtual

3 OUTPUTS

3.1 Publications, Conferences, and Presentations

Journal Papers, ***Conference Papers, Presentations, and Submissions***

(1) Ahmed, S., Khanafseh, S., & Pervan, B. GNSS spoofing detection and exclusion by decomposition of the complex cross ambiguity function with INS aiding. In Proceedings of ION GNSS+, Denver, CO. September 2023. Federal support acknowledged.

(2) Joerger, M., Jada, S., Yan, C., Psiaki, M., & Bowman, J. Resilient PNT for safe transportation. AUVSI Symposium, Blacksburg, VA. October 2023. Federal support acknowledged.

(3) Hu, W., Uwineza, J.-B., & Farrell, J. A. Outlier accommodation for multi-GNSS precise point positioning using risk-averse performance-specified approach. Accepted to American Control Conference (ACC), January 2024.

(4) Nagai, K., Ahmed, S., & Pervan, B. Integrity with LiDAR incorrect extraction faults in adverse weather conditions. In Proceedings of the 2024 International Technical Meeting of the Institute of Navigation, Long Beach, CA. January 2024. Federal support acknowledged.

(5) Saswat, P. Infrastructure-assisted cooperative state estimation via augmentation of asynchronous kinematic measurements. ION ITM, Long Beach, CA. January 2024.

(6) Saswat, P. Feasibility studies on CAV applications with state uncertainties: A survey. IEEE FISTS. February 2024.

(7) Nagai, K., Spenko, M., Henderson, R., & Pervan, B. Fault-free integrity and continuity for driverless urban vehicle navigation with multi-sensor integration: A case study in downtown Chicago. NAVIGATION, 71(1), March 2024. Federal support acknowledged.

(8) Kujur, B., Khanafseh, S., & Pervan, B. Optimal INS monitor for GNSS spoofer tracking error detection. NAVIGATION, 71(1), March 2024. Federal support acknowledged.

(9) Ayyash, M. Jamming-resilient mirror element allocation scheme for OIRS-aided UAV-based FS networks. IEEE Transactions on Intelligent Vehicles. https://doi.org/10.1109/TIV.2024.3450191, March 2024.

(10) Joerger, M., & Jada, S. Impacts of GNSS interference on CAVs. ERASMO, UTC France. Federal support acknowledged. March 2024.
(11) Hu, W., Mohsenian-Rad, H., & Farrell, J. A. Optimization-based outlier accommodation for CAV state estimation. Submitted to IEEE Transactions on Vehicular Technology. March 2024.
(12) Hu, W., Jiang, Z., Mohsenian-Rad, H., & Farrell, J. A. Convex reformulation of risk-averse state estimation with binary variables. Submitted to the CDC. March 2024.
(13) Andrei, V., Djuhera, A., Li, X., Monich, U., Boche, H., & Saad, W. Resilient, federated large language models over wireless networks: Why the PHY matters. Submitted to IEEE GLOBECOM. April 2024.
(14) Nagai, K. Fault-free integrity of urban driverless vehicle navigation with multi-sensor integration: A case study in downtown Chicago. ION Webinar. Federal support acknowledged. April 2024.
(15) Zixi, L. An automated pipeline for detection and localization of GNSS interference sources. Aerospace UPP Conference. April 2024.
(16) Anargyros, K. Low-cost GNSS monitors for RFI detection. Aerospace UPP Conference. April 2024.
(17) Ayyash, M. Jamming attacks on FSO networks: Challenges, opportunities, and a public safety use-case. IEEE WF-PST. May 2024.
(18) Andrei, V. C., Djuhera, A., Li, X., Monich, U. J., Boche, H., & Saad, W. Resilient, federated large language models over wireless networks: Why the PHY matters. In Proceedings of IEEE ICC Workshop, Denver, CO. June 2024.
(19) Rife, J., Wassaf, H., Khanafseh, S., & Pervan, B. Fundamental architectures for high-integrity georeferenced LiDAR positioning. In Proceedings of ION GNSS+, Baltimore, MD. Federal support acknowledged. September 2024.
(20) Stas, M. Optimization-based outlier accommodation for tightly coupled RTK-aided inertial navigation systems in urban environments. Presented at IEEE ITSC, Edmonton, Canada. September 2024.
(21) Becker, J., & Joerger, M. Uncertainty quantification for radar/inertial pose estimation in GNSS-denied areas. ION GNSS+, Baltimore, MD. Federal support acknowledged. September 2024.
(22) Joerger, M., & Hassani, A. Wrong association risk bounding using innovation-projections for landmark-based LiDAR localization. ION GNSS+, Baltimore, MD. September 2024.
(23) Nagai, K., & Pervan, B. Integrity with LiDAR positioning: Case studies in automatic feature extraction. ION GNSS+, Baltimore, MD. Federal support acknowledged. September 2024.
(24) Nagai, K., & Pervan, B. Enhanced integrity of LiDAR localization: A study on feature extraction techniques. ION GNSS+, Baltimore, MD. Federal support acknowledged. September 2024.
(25) Moore, M. O., Psiaki, M. L., & Buehrer, R. M. Time-diverse Doppler-only LEO PNT: Initial solution. ION GNSS+, Baltimore, MD. September 2024.
(26) Shui, T., & Saad, W. Design and analysis of resilient vehicular platoon systems over wireless networks. In Proceedings of IEEE GLOBECOM. December 2024.

(27) Shelim, R., Saad, W., & Ramakrishnan, N. Fast geometric learning of MIMO signal detection over Grassmannian manifolds. In Proceedings of IEEE GLOBECOM. December 2024.
(28) Andrei, V. C., Djuhera, A., Li, X., Monich, U. J., Saad, W., & Boche, H. Resilient, federated large language models over wireless networks: Why the PHY matters. In Proceedings of IEEE GLOBECOM. December 2024.
(29) Ahmed, S., Khanafseh, S., & Pervan, B. Uncovering subtle GNSS spoofing via cross ambiguity decomposition. IEEE Transactions on AES. Revised version. Federal support acknowledged. December 2024.
(30) Chen, Y. H., Liu, Z., Kriezis, A., Lo, S., & Walter, T. Combining ADS-B, LCM, and DPA for GNSS jammer detection. ION ITM. January 2025.
(31) Kujur, B., Khanafseh, S., & Pervan, B. Performance of optimal INS monitor against live spoofing. ION ITM, Long Beach, CA. Federal support acknowledged. January 2025.
(32) Chen, Y. H., Liu, Z., Kriezis, A., Lo, S., & Walter, T. Interference detection in massive GNSS jammer test. ION ITM, Long Beach, CA. January 2025.
(33) Lo, S., Liu, Z., Ibrahim, L., Chen, Y. H., & Walter, T. Observations of GNSS spoofing in Russia, 2023–2024. ION ITM, Long Beach, CA. January 2025.
(34) Kriezis, A., Chen, Y. H., Akos, D., Lo, S., & Walter, T. Real-world spoofing detection with low-cost receivers. ION ITM, Long Beach, CA. January 2025.
(35) Kriezis, A., Chen, Y. H., Lo, S., Walter, T., Pullen, S., & Akos, D. Low-cost receiver RF interference analysis. Inside GNSS. March 2025.

3.2 Website(s) or other Internet site(s)

CARNATIONS maintains an active digital presence, with weekly updates to its website to ensure timely distribution of research outcomes, event information, and program milestones, in alignment with established guidelines. Annual feedback is also collected through the website to enhance user experience. Our presence on LinkedIn, Instagram, and YouTube has expanded significantly, with analytics showing increased reach and engagement across platforms. The YouTube channel hosts recordings of webinars, conference highlights, and educational content, all of which are also accessible via the website.

In November 2024, CARNATIONS launched a quarterly newsletter to further support outreach and information sharing. Two editions have been published and distributed to subscribers, with archived issues available on the website. These efforts collectively strengthen stakeholder engagement and knowledge transfer.

3.3 Technologies or techniques

Nothing to report.

3.4 Inventions, patent applications, and/or licenses

As reported earlier, CARNATIONS has submitted a patent application titled "*Optimal Detector for GNSS Spoofing Using Auxiliary Sensors.*" The filing, facilitated through Illinois Tech legal counsel, remains in process, with final approval expected by Fall 2025.

Inventors: Birendra Kujur, Samer Khanafseh, Boris Pervan

4 OUTCOMES

Over the past six months, CARNATIONS has made significant progress across research, education, outreach, and technology transfer. A total of thirteen research projects are currently active, and one successfully completed, through contributions from all member institutions. These projects underscore CARNATIONS' commitment to advancing modern Positioning, Navigation, and Timing (PNT) technologies.

The Education and Workforce Subcommittee has expanded academic offerings, increasing the number of shared courses from one to three, alongside a continued rise in educational webinars. The subcommittee also facilitated the placement of the Engineering Research Toolkit (ERT) and played a key role in enhancing student-industry engagement. Regular research discussion calls—now held twice a month due to increased demand—have strengthened collaboration among principal investigators and students. Additionally, a growing number of outreach events, including the CARNATIONS Annual Symposium, poster competitions, and student-led presentations, have deepened engagement with the academic and professional communities.

In technology transfer, CARNATIONS has expanded its network to 41 industry and government partners, including the FAA, Volpe Center, SAE, and numerous leading PNT technology firms. A major milestone was the launch of a job-posting portal, facilitating successful transitions of CARNATIONS' students into industry roles. Our patent on GNSS spoofing detection was selected by the University of Chicago's Polsky Center for the exclusive Spring 2025 I-Corps Cohort, marking a pivotal step toward commercialization.

Complementing these efforts, a quarterly newsletter continues to disseminate research updates, publications, and partner highlights. Looking ahead, CARNATIONS remains committed to delivering high-impact research, strengthening cross-sector partnerships, and advancing innovation in resilient transportation technologies.

5 IMPACTS

5.1 What is the impact on the effectiveness of the transportation system?

The research and outreach activities conducted by CARNATIONS during the reporting period (October 2024 to March 2025) have made significant contributions to the effectiveness of the transportation system. The development of Resilient Positioning, Navigation, and Timing (R-PNT) technologies is crucial for improving the safety, reliability, and efficiency of transportation systems, especially with the increasing integration of autonomous and connected vehicles. Key outputs, including multiple high-impact journal publications and conference presentations, demonstrate CARNATIONS' leadership in resilient transportation technologies. Notably, research on GNSS spoofing detection and multi-sensor integration, including projects on fault-free integrity for driverless vehicle navigation and jamming-resilient communication networks, directly contribute to the robustness of transportation systems. These innovations enhance the

reliability of positioning systems, which are essential for safe navigation in complex and potentially hazardous environments, such as urban canyons or areas with GPS interference.

Moreover, CARNATIONS' active participation in conferences and symposia, along with its growing network of industry and government partners, fosters collaboration that translates research into practical solutions for transportation challenges. The partnership with organizations such as the FAA, Volpe Center, and SAE further ensures that the developed technologies can be integrated into existing infrastructure, thereby improving system resilience and performance. Additionally, the deployment of the ERT toolkit and the expansion of educational webinars contribute to workforce development, ensuring that industry professionals are equipped with the latest tools and knowledge to implement these technologies effectively. The job portal launched during this period is instrumental in connecting graduates with industry opportunities, promoting the transfer of research into operational systems.

CARNATIONS' ongoing efforts to circulate research findings through its website, social media platforms, and quarterly newsletter ensure that stakeholders are informed and engaged. This outreach enhances public and industry awareness of the importance of PNT systems, laying the foundation for broader adoption and continued innovation in transportation systems. Overall, the advancements made by CARNATIONS in PNT technologies and its strong focus on collaboration with industry partners are directly contributing to the enhancement of transportation system effectiveness, safety, and efficiency, paving the way for secure future transportation networks.

5.2 What is the impact of technology transfer on industry and government entities, on the adoption of new practices, or on research outcomes that have led to initiating a start-up company?

The impact of technology transfer on industry, government entities, and the adoption of new practices has been significant during this period. Through expert guidance from the Technology Transfer Subcommittee and CARNATIONS Advisory Board (CAB), key advancements include:

(1) **Advocating Open Standards**: Promoting open standards ensures alignment with industry practices, fostering interoperability, and broader adoption of technologies.

(2) **Standardization Through Collaboration**: Developing harmonized threat models strengthens international partnerships and enhances cross-border cooperation in R-PNT technologies.

(3) **Practical Testing of Spoofing Solutions**: Testing of GNSS spoofing detection techniques ensures the robustness and reliability of our solutions for operational deployment.

(4) **Commercialization Efforts**: Through an NSF-funded program, faculty refined commercialization strategies, advancing our research toward market readiness and attracting potential follow-on funding.

(5) **Strengthening Partnerships**: Close collaboration with the DOT and industry partners accelerates the implementation of research outcomes, ensuring practical impact.

5.3 What is the impact on the body of scientific knowledge?

The recent contributions in the areas of navigation, positioning, and intelligent vehicle systems have significantly advanced the existing body of scientific knowledge. This impact can be summarized through key themes drawn from the various journal papers, conference papers, presentations, and submissions listed below.

5.3.1. Enhancing Safety and Integrity in Navigation Systems

Journal articles published:

- Nagai, K., Spenko, M., Henderson, R., & Pervan, B. (2024). Fault-Free Integrity and Continuity for Driverless Urban Vehicle Navigation with Multi-Sensor Integration: A Case Study in Downtown Chicago. NAVIGATION, 71(1), Spring 2024.
- Kujur, B., Khanafseh, S., & Pervan, B. (2024). Optimal INS Monitor for GNSS Spoofer Tracking Error Detection. NAVIGATION, 71(1), Spring 2024.

These studies contribute to improving safety protocols in autonomous vehicles by presenting methodologies for ensuring system integrity in complex urban environments. By integrating multiple sensors, they provide a framework for fault detection and continuity assurance, vital for developing reliable navigation systems.

5.3.2. Innovative Detection and Resilience Techniques

New methodologies have been introduced to address challenges in navigation systems, particularly in detecting jamming and spoofing while improving real-time system resilience. Key contributions include:

- Ayyash, M. (2024). Jamming-Resilient Mirror Element Allocation Scheme for OIRS-Aided UAV-Based FS Networks. IEEE Transactions on Intelligent Vehicles. doi:10.1109/TIV.2024.3450191.
- Ahmed, S., Khanafseh, S., & Pervan, B. (2023). GNSS Spoofing Detection and Exclusion by Decomposition of the Complex Cross Ambiguity Function with INS Aiding. Proceedings of ION GNSS+ 2023, Denver, CO, September 2023. Federal support acknowledged.
- Becker, J., & Joerger, M. (2024). Uncertainty Quantification for Radar/Inertial Pose Estimation in GNSS-Denied Areas. Proceedings of the 37th International

Technical Meeting of The Satellite Division of The Institute of Navigation (ION GNSS+ 2024), Baltimore, MD.

- Ayyash, M. (2024). Jamming Attacks on FSO Networks: Challenges, Opportunities, and a Public Safety Use-Case. 2024 IEEE World Forum on Public Safety Technology (WF-PST), May 2024.

Additionally, CARNATIONS is pleased to acknowledge the following paper, which received a best-of-session presentation award at ION GNSS+ 2024 Baltimore, MD:

- Joerger, M., & Hassani, A. (2024). Wrong Association Risk Bounding Using Innovation-Projections for Landmark-Based LiDAR Localization. Proceedings of the 37th International Technical Meeting of The Satellite Division of The Institute of Navigation (ION GNSS+ 2024), Baltimore, MD.

These contributions represent significant advancements in improving the resilience of navigation systems against jamming and spoofing threats, offering novel strategies for real-time detection and mitigation.

5.3.3. Real-World Applications and Case Studies

Theoretical findings are applied in practical case studies, demonstrating the effectiveness of navigation technologies in real-world scenarios, particularly for autonomous vehicles and transportation safety. Important case studies include:

- Nagai, K. (2024). Fault-Free Integrity of Urban Driverless Vehicle Navigation with Multi-Sensor Integration: A Case Study in Downtown Chicago. ION Webinar, April 3, 2024.
- Joerger, M., Jada, S., Yan, C., Psiaki, M., & Bowman, J. (2023). Resilient Positioning, Navigation, and Timing for Safe Transportation. AUVSI Ridge and Valley Chapter Symposium: Partnerships for Autonomy.
- Joerger, M. and S. Jada. "Impacts of GNSS Interference on Connected and Automated Vehicles." Presentation at Enhanced Receiver for Autonomous Mobility (ERASMO). University of Technology of Compiègne – Alliance Sorbonne Université, France (2024).

5.3.4. Cross-Disciplinary Research and Collaboration

Research combining telecommunications, machine learning, and navigation technologies has promoted cross-disciplinary collaboration and knowledge sharing. Notable papers include:

- Andrei, V., Djuhera, A., Li, X., Monich, U., Boche, H., & Saad, W. (2024). Resilient, Federated Large Language Models over Wireless Networks: Why the PHY Matters. Submitted to IEEE Global Communications Conference (GLOBECOM), 2024.

- Andrei, V. C., Djuhera, A., Li, X., Monich, U. J., Boche, H., & Saad, W. (2024). Resilient-By-Design Framework for MIMO-OFDM Communications under Smart Jamming. In Proc. of the IEEE International Conference on Communications, Second Workshop on Enabling Security, Trust, and Privacy in 6G Wireless Systems, Denver, CO, USA, June 2024.
- Shui, T., & Saad, W. (2024). Design and Analysis of Resilient Vehicular Platoon Systems over Wireless Networks. In Proc. of IEEE Global Communications Conference (GLOBECOM), December 2024.

5.3.5. Informing Policy and Standards

Studies have provided valuable insights for policymakers, contributing to the development of standards that enhance the security and reliability of navigation technologies. One such paper includes:

- Ayyash, M. (2024). Jamming Attacks on FSO Networks: Challenges, Opportunities, and a Public Safety Use-Case. 2024 IEEE World Forum on Public Safety Technology (WF-PST).

5.3.6. Foundation for Future Research

Ongoing research continues to lay the groundwork for further exploration of innovative technologies, especially in the context of connected autonomous vehicles (CAVs). Recent submissions include:

- Hu, W., Mohsenian-Rad, H., & Farrell, J. A. (2024). Optimization-Based Outlier Accommodation using Linear Performance Constraints for CAV State Estimation in Urban Environments. Submitted to IEEE Transactions on Vehicular Technology, March 1, 2024.
- Hu, W., Jiang, Z., Mohsenian-Rad, H., & Farrell, J. A. (2024). Convex Reformulation of Risk-Averse Linear State Estimation with Mixed-Binary Variables for Outlier Accommodation.

5.4 What is the impact on transportation workforce development?

The initiatives guided by the Education and Workforce Development Subcommittee have a significant impact on the transportation workforce by actively shaping a skilled, and adaptable workforce for Positioning, Navigation, and Timing technologies. The key contributions include:

- **Internships and Employment Opportunities:** By establishing a job portal, we directly connect students with industry employment opportunities, bridging the gap between education and practical experience.
- **Joint Workshops and Seminars:** Collaborative events with industry partners foster knowledge exchange, ensuring students and professionals stay informed on emerging technologies and innovative solutions to industry challenges.

- **Industry-Driven ERT Projects:** Incorporating industry challenges into educational projects allows students to gain hands-on experience while addressing current industry needs. This ensures that students are not only learning theory but also tackling everyday problems, making them industry ready.

- **Expanded Course Offerings:** The inclusion of additional specialized courses in Positioning, Navigation, and Timing technologies ensures that the workforce is well-equipped with the latest knowledge and skills aligned with the demands of the industry.

- **Strengthened Industry Collaboration:** By enhancing collaboration with diverse industry partners, we promote technology transfer and create research opportunities that benefit both academia and industry, fostering a dynamic workforce that can drive innovation.

- **Establishment of CARNATIONS Newsletter:** The newsletter serves as a tool for continuous engagement with the transportation community, sharing updates, opportunities, and advancements that keep the workforce informed and prepared for ongoing developments in the field.

- **Designing and Creation of Center-Level Competitions for Students:** Creating center-level competitions encourages students to apply their knowledge in practical scenarios, fostering innovation and problem-solving skills while motivating them to pursue excellence in their fields.

These efforts collectively enhance the workforce's ability to meet current and future challenges, ensuring that the transportation sector is supported by a highly skilled and capable talent pool.

6 CHANGES/PROBLEMS

The subcommittees have streamlined their structure for better collaboration and efficiency by transitioning from two co-chairs to a single chair and shifting from group meetings to one-on-one sessions with members. These changes improve decision-making, coordination, and targeted outcomes.

6.1 Changes in approach and reasons for change

Nothing to report.

6.2 Actual or anticipated problems or delays and actions or plans to resolve them.

Nothing to report.

6.3 Changes that have a significant impact on expenditures

Nothing to report.

6.4 Significant changes in use or care of human subjects, vertebrate animals, and/or biohazards

Nothing to report.

6.5 Change of primary performance site location from that originally proposed

Nothing to report.

7 SPECIAL REPORTING REQUIREMENTS

Nothing to Report.