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NSTSCE

National Surface Transportation Safety Center for Excellence

# Fiber Sensing

## Real-time, Long-distance Traffic Monitoring

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Technology Impairment Mobility Infrastructure

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## EXECUTIVE SUMMARY

The report presents the pilot testing of NEC's distributed fiber optic sensing (DFOS) and artificial intelligence behavior detection technologies on the Virginia Smart Roads. The intent was to explore the viability of DFOS through existing fiber installations for traffic management and road safety, potentially superseding traditional methods like cameras or radar. Key use cases for DFOS include identifying wrong-way driving, traffic queues, emergency stops, and other non-standard driving behaviors, which are all critical for traffic management and safety.

NEC collaborated with the Virginia Tech Transportation Institute to install fiber optics along a highway section conforming to Virginia Department of Transportation (VDOT) standards and executed orchestrated driving scenarios to test detection capabilities under various traffic and weather conditions. The results of these tests demonstrated that DFOS could effectively detect wrong-way driving across different traffic densities. However, challenges remain with vehicle count and speed accuracy in high-traffic situations. In addition, the DFOS hardware solutions would need to be deployable in roadside cabinets with limited environmental control to be viable for deployment across VDOT's roadway system. The project underscores the strategic advantage of using existing network infrastructures for monitoring and suggests that while the NEC system shows promise in certain applications, further refinements are needed for handling complex traffic scenarios.

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# CHAPTER 1. INTRODUCTION

In the domain of traffic management and safety, distributed fiber optic sensing (DFOS) represents a potential pivotal technological advancement. The integration of existing, deployed fiber optic cable along roadways with fiber optic sensing equipment running specialized machine learning (ML) algorithms could transform traffic flow analysis in comparison to existing sensor solutions such as camera or radar systems.

DFOS technologies could be used to address a multitude of use cases relevant to traffic management and safety, as illustrated in Figure 1. These include the detection of wrong-way driving, traffic queues, and emergency stops, as well as the recognition of speeding and other non-standard driving behaviors. Additionally, DFOS systems can be utilized for continuous monitoring of highway traffic and road conditions. A primary benefit in the use of DFOS is the cost savings that can be achieved by deploying on existing fiber installations along roadways, thus contributing to a greater yield from the initial network installation investment. This strategic utilization of existing network infrastructure can be used to augment, and in some cases, replace traditional sensing technologies used to monitor roadway conditions.

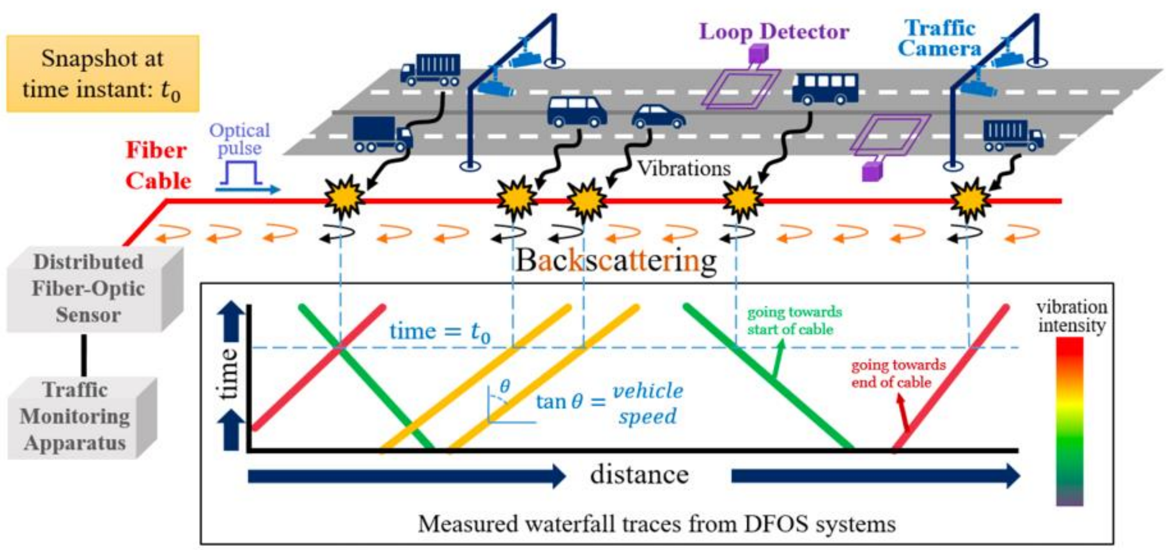
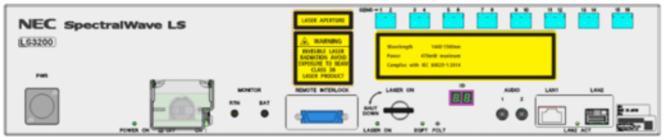



**Figure 1. Diagram. Distributed fiber optic sensing for transportation.**

This report details efforts undertaken to pilot test NEC's fiber sensing and artificial intelligence behavior detection technologies on the Virginia Smart Roads facility to evaluate its effectiveness and inform the Virginia Department of Transportation (VDOT) about its capabilities. Provided in Figure 2 are images showcasing the NEC DFOS equipment, operational specifications, and software interface. NEC North America provided the Virginia Tech Transportation Institute (VTTI) with the equipment and analytics labor to support these pilot tests.




| | Parameters | Item | Spec. | Note |
|---|---|---|---|---|
| 1 | Power specifications | Input voltage rage and frequency | 90V AC to 264V AC<br>47 to 63 Hz | |
| | | Power consumption | Typ. 60 W / Max 165 W | |
| 2 | Physical specifications | Dimensions (W x D x H) | 17.2 x 11 x 3.4 inches | Rack mount available |
| | | Weight | 26 Lbs./ 12 kg | |
| 3 | Sensing specifications | Optical wavelength | 1550 nm | |
| | | Support optical fiber | Single Mode Fiber | |
| 4 | Certifications | UL62368-1, FCC Class A, VCCI Class A | | |
| 5 | Environmental Specifications | Operation temperature | 0ºC~45ºC/ 32ºF~113ºF | Inside an air-conditioned environment is recommended |
| | | Operation humidity | 20~95% (Without condensation) | |

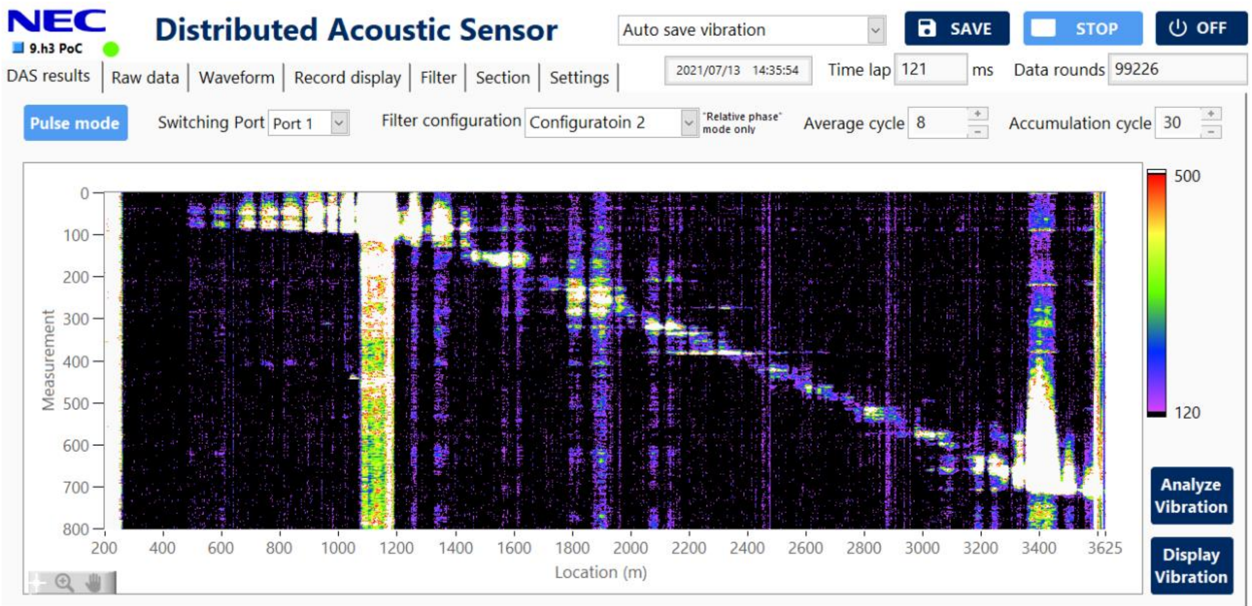



**Figure 2. Screen captures. NEC DFOS hardware and software systems.**

Specifically, this report details the installation effort to deploy fiber optics according to VDOT standards along the highway section of the Virginia Smart Roads (Chapter 2). The report then details the efforts performed by the research team to conduct a series of orchestrated driving scenarios to assess if wrong-way driving, stopped vehicles, and traffic queues can be detected NEC's equipment under varying conditions of low traffic, high traffic, and with and without rain, by (Chapter 3). An analysis performed by NEC on the performance of the system based on the orchestrated driving scenarios is presented in Chapter 4, followed by discussion and conclusions in Chapter 5.

# CHAPTER 2. FIBER INFRASTRUCTURE INSTALLATION

## PLANNING

The first step of the process involved determining if the existing fiber infrastructure on the Virginia Smart Roads could be utilized according to VDOT fiber burial standards. Review of engineering drawings, discussion with Virginia Smart Roads facility subject matter experts, and on-site assessment were performed to determine the feasibility of reusing existing fiber. Based on this assessment, however, it was determined that the existing fiber could not be utilized due to (1) non-conformance to typical VDOT burial depth standards and (2) the network design, which has the fiber connected and disconnected across multiple junction points, which would lead to significant signal degradation. Consequently, the VTTI team then began planning activities to trench and lay new fiber on the Smart Roads, as illustrated in Figure 3.

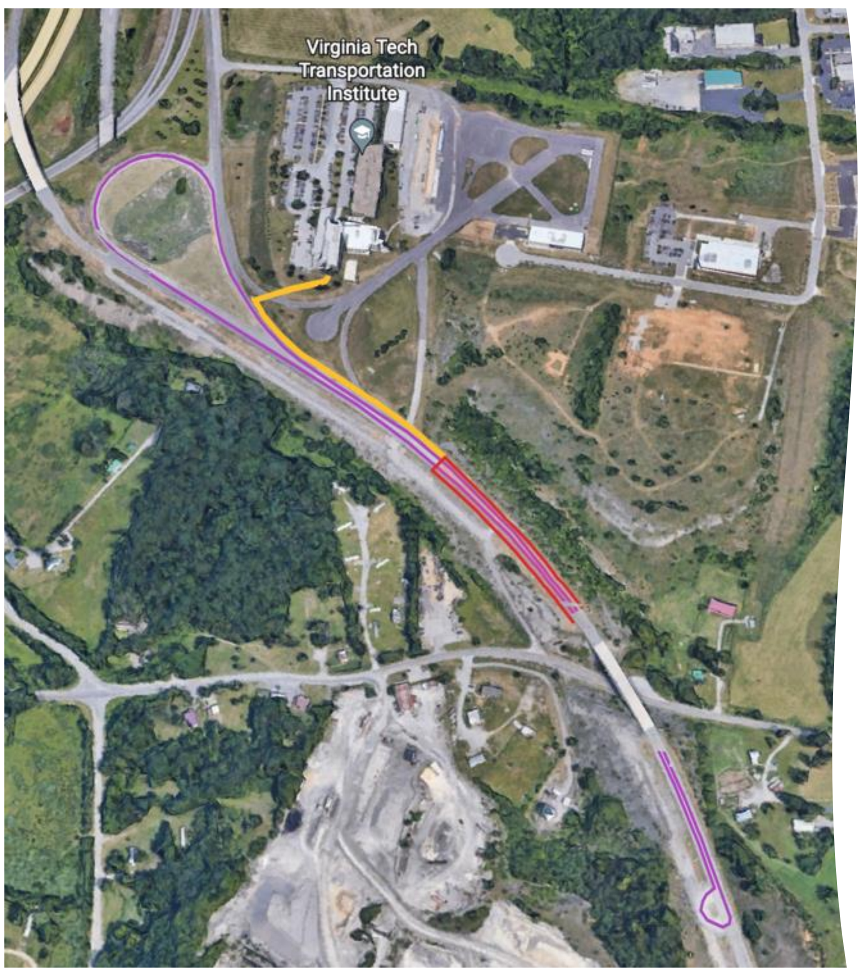



**Figure 3. Map. Virginia Smart Roads fiber installation plan.**

Along the orange line depicted in the figure, a new fiber line specific for this project was connected from the Virginia Smart Roads control room and pulled through existing buried conduit to the area highlighted by the red box. This red box area represents the primary location where vehicle use case test operations were to be performed and measured by the NEC equipment. In this red box area, a new fiber line was split once from the existing Yellow Line and junctioned to a Red Line, which was trenched according to VDOT standards on the soil adjacent to the roadway. The purple loop represents the vehicle driving path used to perform the test scenarios. Table 1 provides information related to the fiber, as well as the equipment used to terminate and junction the new line.

**Table 1. Virginia Smart Roads fiber optic installation equipment.**

| **Location** | **Fiber Connection** | **Fiber Equipment Information** |
|---|---|---|
| Smart Roads Control Room | SC/APC Bulkheads |  Orange Line terminates to SC/APC bulkhead in Smart Roads Control Room |
| Orange Line | TLC 24 @ 450 meters long | https://www.fiberinstrumentsales.com/tlc-24-fiber-sm-smf28-ultra-i-o-7-8mm-od-w-aia-plen-black.html |
| Orange – Red Line Junction | SC/APC Connectors | Orange Line TLC 24 fiber mates SC/APC connector with Red Line TLC 12 |
| Red Line | TLC 12 @ 600 meters long | https://www.fiberinstrumentsales.com/tlc-12-fiber-sm-smf28-ultra-indoor-outdoor-riser-black.html |

The Red Line section required trenching fiber and burial to a depth and lateral offset that matches the typical VDOT installation standard, as depicted in Figure 4. The intention behind burying to this standard was to provide an installation representative of typical VDOT fiber to evaluate performance based on the conditions that would be observed in field installations.

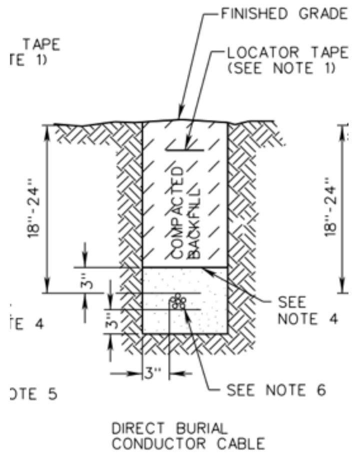



**Figure 4. Diagram. VDOT direct burial conductor cable standard.**

## TRENCHING

The Red Line section of fiber involved trenching the earth adjacent to the roadway based on the measurements and fill shown in Figure 5. The first step in the process was trenching the roadway to a depth between 23 and 29 inches using a Ditch-Witch (Figure 6). This depth was required to allow for a soft soil bed in which the fiber optics were laid, preventing direct contact with rock to minimize any potential damage. After trenching the entire Red Line area, the team then ran and laid the fiber on the soft soil bed (Figure 7). After laying all the fiber, the trenching team then backfilled with a soft soil layer of 8 inches, again to prevent direct contact with the top rocky soil backfill (Figure 8).

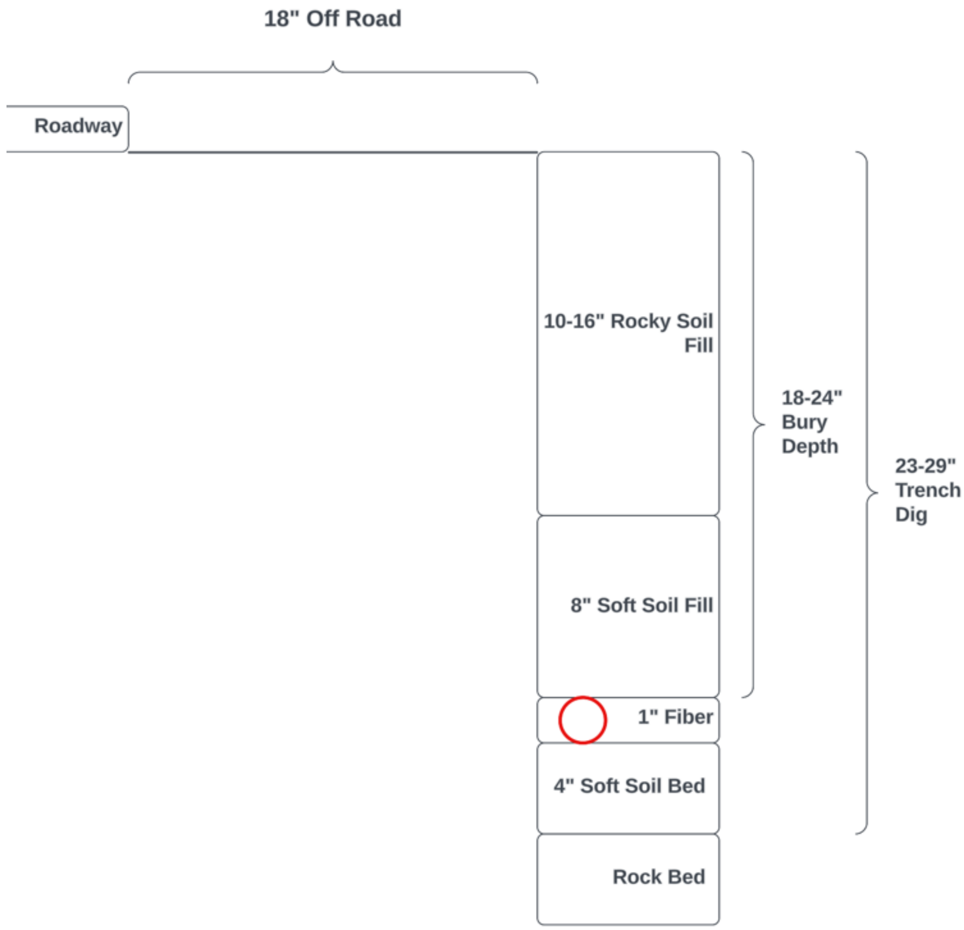



**Figure 5. Diagram. Virginia Smart Roads fiber optic trenching installation details.**

**Figure 6. Photos. Virginia Smart Roads fiber optic trenching activities.**

**Figure 7. Photo. Virginia Smart Roads fiber optic laying activities.**

**Figure 8. Photo. Virginia Smart Roads fiber optic backfilling activities.**

## FIBER CONNECTION

Termination of the new fiber line to Virginia Smart Roads control room (the Orange Line) was pulled to Bunker 2.5 for junction with the Red Line. The Orange Line has a total of 24 fiber strands for use, and the Red Line has a total of 12 fiber standards for use. A strand labeled “A” on the Orange Line was connected to the NEC DFOS fiber sensing equipment in the Virginia Smart Roads Control room, as displayed in Figure 9. That same strand, which runs to Bunker 2.5, is mated to the Red Line strand labeled “a” at Bunker 2.5. Starting at Bunker 2.5, the Red Line fiber runs across the roadway in a boxed loop, then comes back around to Bunker 2.5. Figure 10 provides the connectivity diagram.

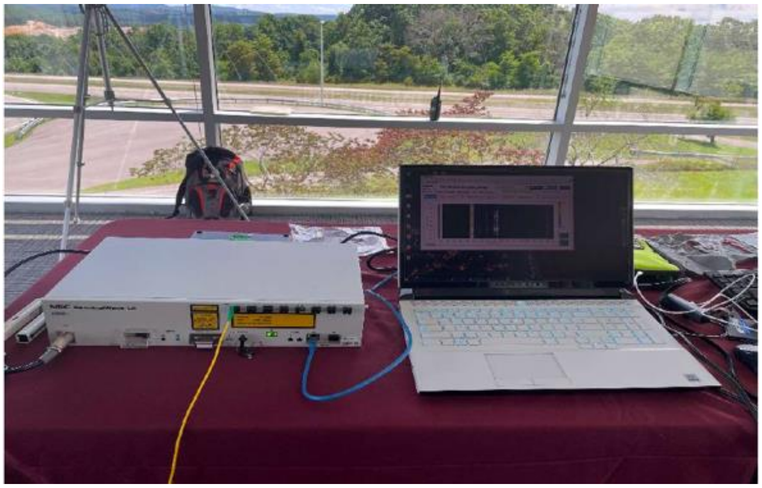


**Figure 9. Photo. Fiber connection to NEC equipment in Virginia Smart Roads control room.**

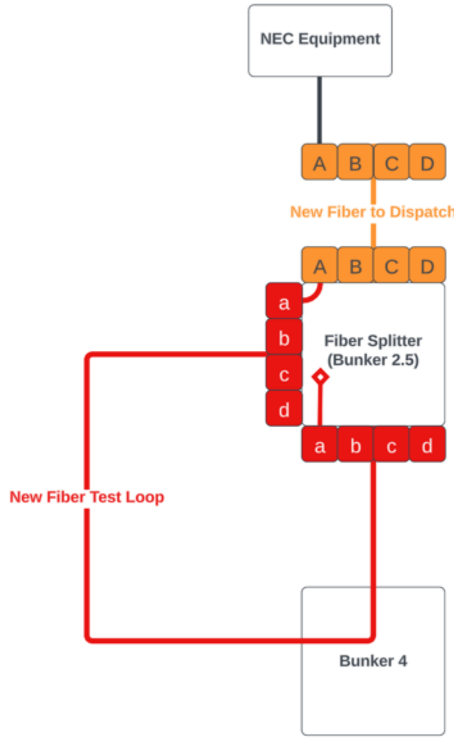



**Figure 10. Diagram. Fiber optic connection from the Virginia Smart Roads control room to roadway bunkers.**

## FIBER CONNECTION VALIDATION

Prior to performing on-road vehicle testing, the NEC and VTTI teams performed preliminary validation of the installation. Throughout the fiber pulling, trenching, laying, and backfill activities, the VTTI team ensured that there was connectivity between the Virginia Smart Roads control room Orange Line down to the end of the Red Line fiber at the bunker. Once fiber installation and connectivity validation assessments were completed, the NEC team arrived with their fiber sensing equipment. As depicted in Figure 11, the NEC team connected their equipment to the Orange Line within the Virginia Smart Roads control room. To calibrate their system, the NEC team went to four corners of the Red Line sensing area and hammered a flat placard, which provided an audio source that allowed the team to tune the parameters of the system for detection.

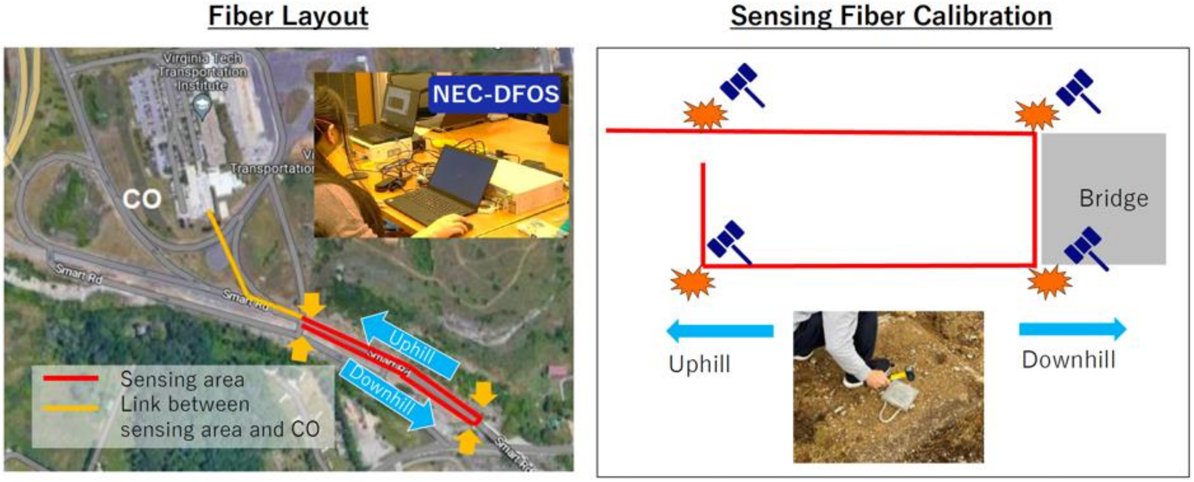



**Figure 11. Diagram. NEC fiber equipment calibration.**

After the calibration activities were completed, the team then utilized a single vehicle and drove through the detection zone to generate raw sensing waterfall trace data to validate the configuration, as depicted in Figure 12. The configuration activity verified details, such as the range locations of the uphill and downhill sides of the fiber run, lanes, and reference points, such as the bridge and gate.

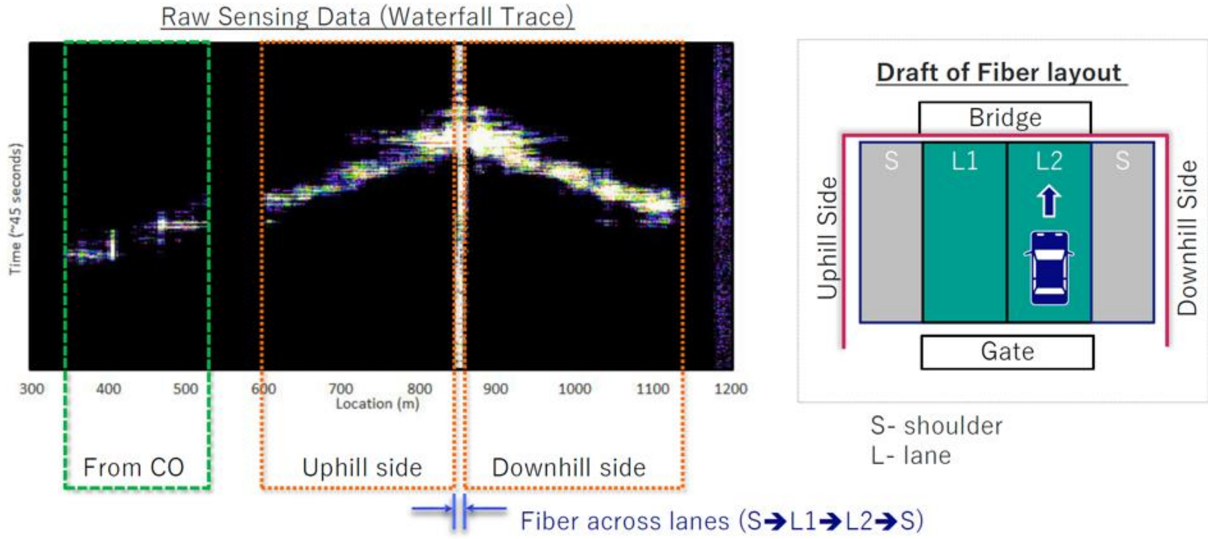



**Figure 12. Diagram. NEC fiber equipment calibration.**

# CHAPTER 3. USE CASE DRIVING SCENARIOS

After planning, trenching, installation, and validation of the fiber equipment placed on the Virginia Smart Roads, the team executed a series of use case driving scenarios. The primary objective of this effort was to verify the detection performance of the NEC fiber sensing equipment by collecting data from vehicles traversing the test section across a range of vehicle numbers, lane use, speeds, and actions. The following use cases scenarios were tested:

- Free flow
- Stop-and-go traffic
- Vehicle pull-over
- Wrong-way driving

## USE CASE SCENARIO DRIVER PROTOCOLS

The project team developed driver protocol scripts orchestrating how to position and drive vehicles to support the different scenarios. The scripts were shared with VTTI staff volunteer drivers, and a safety briefing was conducted to assure safe testing practices. The following sections detail each of the use case scenarios. Figure 13 provides a reference to key locations on the Smart Roads for the scenarios.


**Figure 13. Map. Key locations for use case scenarios on the Virginia Smart Roads.**

**Use Case Scenario 1 – Free Flow**

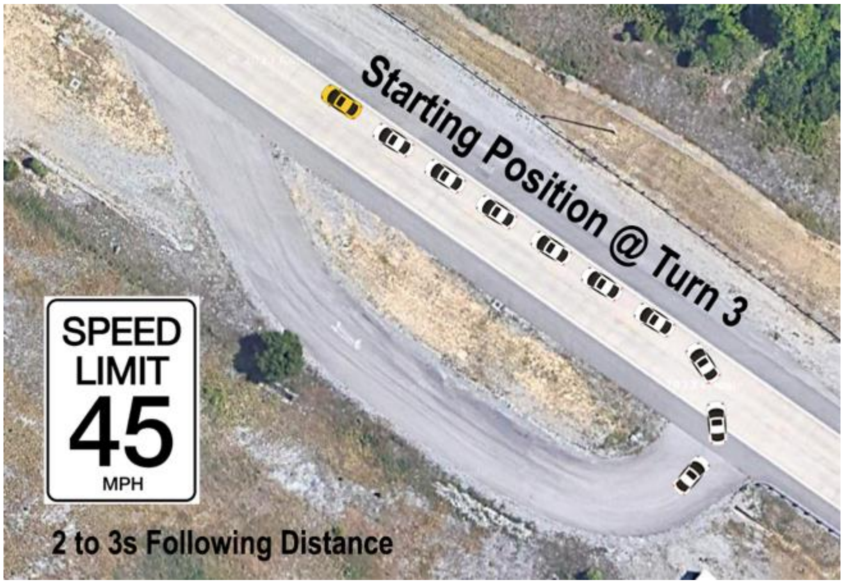



**Figure 14. Diagram. Use Case Scenario 1: Free-flow vehicle configuration.**

- Lead vehicle stops at the entrance to T3, facing uphill (see Figure 14).
- When all vehicles are in position, the lead vehicle will verify with NEC that they are ready to record data.
- Lead vehicle will then proceed at 45 mph.
  - Lead vehicle radios: "*All vehicles - uphill -* ***Free-Flow*** *Lap 1*."
- Following vehicles proceed behind the lead vehicle, maintaining a 2- to 3-second following distance.
- All vehicles proceed to T1, continue around the loop, and continue downhill.
  - Lead vehicle radios: "*All vehicles - downhill -* ***Free-Flow*** *Lap 1*."
- All vehicles return to T3, completing Lap 1.
- Lead vehicle returns to starting position.
- Once the last vehicle reaches T3, it begins Lap 2, repeating the previous steps.
- Complete a total of 10 laps (~50 minutes).

**Use Case Scenario 2 – Lead Vehicle Pull-Over**

***Uphill Runs***

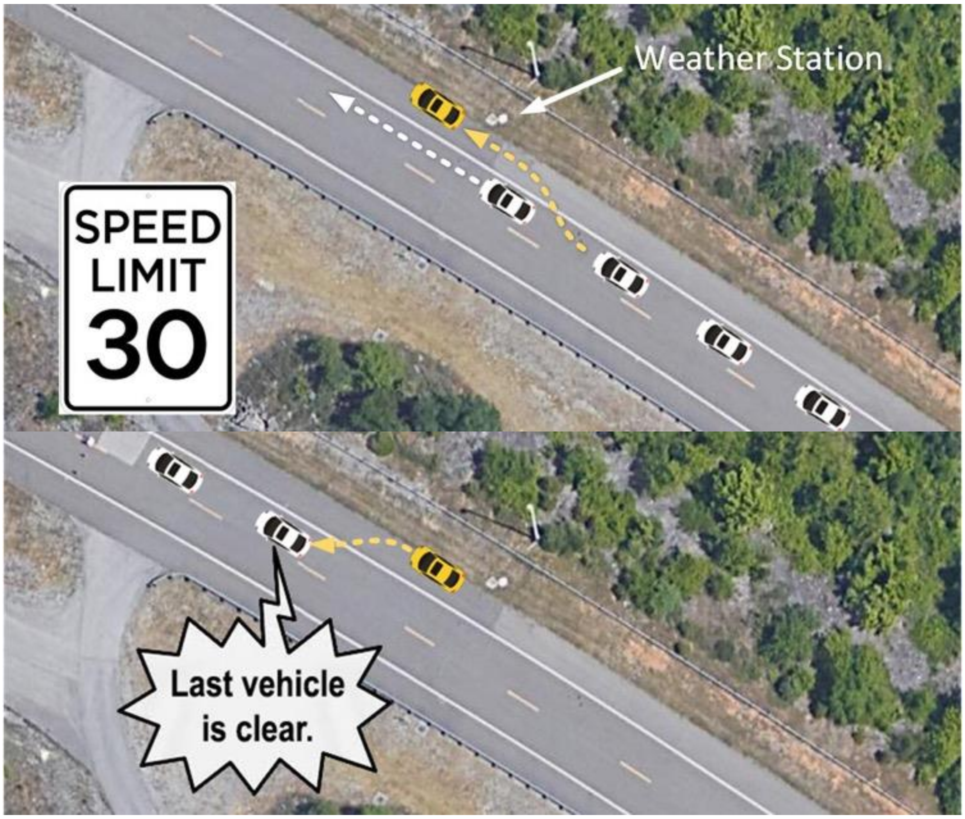



**Figure 15. Diagram. Use Case Scenario 2: Lead vehicle pull-over vehicle configuration (uphill).**

- All vehicles start at T3 starting position.
- The lead vehicle verifies that NEC is ready to collect data.
  - Lead vehicle radios: "*All vehicles – uphill – **Pull-Over** Lap 1*."
- All vehicles proceed at 30 mph with a 2- to 3-second following distance.
- As the lead vehicle approaches the test area, it will slow and pull over by the weather station (see Figure 15).
- Following vehicles should slow down as necessary to allow the lead vehicle to safely pull over, then continue past the lead vehicle at 30 mph.
- The second vehicle will then become the lead vehicle for the downhill run and leads the convoy through T1.
- As the last vehicle passes the pulled-over vehicle, it will indicate it is clear for the pulled-over vehicle to rejoin the convoy.
  - Last vehicle radios: "*The last vehicle is clear*."

***Downhill Runs***

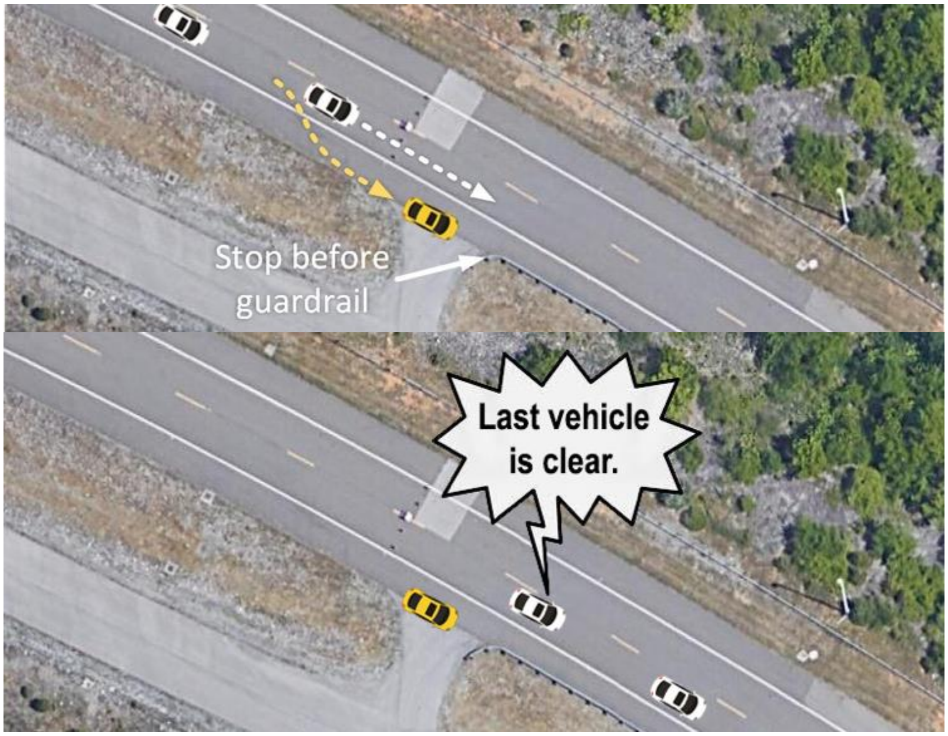



**Figure 16. Diagram. Use Case Scenario 2: Lead vehicle pull-over configuration (downhill).**

- All vehicles continue around T1 and begin the downhill run.
  - The new lead vehicle radios: "*All vehicles – downhill – **Pull-Over** Lap 1*."
- Lead vehicle slows down and pulls over before the start of the guardrail in the test area (see Figure 16).
- Following vehicles should slow down as necessary to allow the lead vehicle to safely pull over, then continue past the lead vehicle at 30 mph.
- As the last vehicle passes the pulled-over vehicle, it will indicate it is clear for the pulled-over vehicle to rejoin the convoy.
  - Last vehicle radios: "*The last vehicle is clear*."
- All vehicles return to the starting position in T3.
- Complete a total of 10 laps (~1 hr).

**Use Case Scenario 3 – Wrong Way**

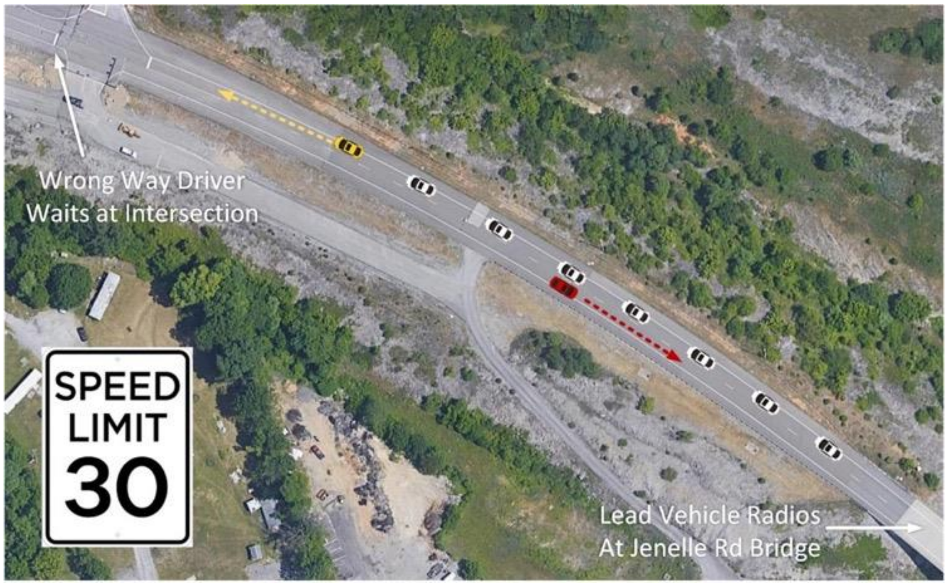



**Figure 17. Diagram. Use Case Scenario 3: Wrong-way vehicle configuration.**

***Uphill Runs***

- Wrong-way vehicle (WWV) waits at the intersection, facing downhill.
- All other vehicles go to starting position at T2.
- When NEC and all vehicles are ready, lead vehicle begins the lap.
  - Lead vehicle radios: "*All vehicles – uphill –* ***Wrong Way*** *Lap 1*."
- When the lead vehicle reaches the Jennelle Road Bridge, it will release the WWV.
  - Lead vehicle radios: "*Wrong Way Vehicle, go*."
- The WWV begins its downhill run.
  - WWV radios: "*Wrong Way Vehicle – heading downhill*."
- The WWV continues to T2, turns around, and stops at the Jennelle Road Bridge. All other vehicles continue around T1 and start downhill run.

***Downhill Runs***

- The WWV waits at the Jennelle Road Bridge.
  - WWV radios: "*Wrong-way vehicle in position*."
- The lead vehicle begins the downhill run.
  - Lead vehicle radios: "*All vehicles – downhill –* ***Wrong Way*** *Lap 1*."
- When the lead vehicle reaches the intersection, it will release the WWV.
  - Lead vehicle radios: "*Wrong Way Vehicle, go*."
- The WWV begins its uphill run.
  - WWV radios: "*Wrong Way Vehicle – heading uphill*."
- The WWV continues around T1 and returns to the intersection.
- All other vehicles return to starting position at T2.
- Complete a total of 10 laps (~1 hr).

**Use Case Scenario 4 – Stop and Go**

***Uphill Runs***


**Figure 18. Diagram. Use Case Scenario 4: Stop and go vehicle configuration (uphill).**

- Lead vehicle begins at the starting position on Jennelle Road Bridge.
- Following vehicles line up behind the lead vehicle.
- Lead vehicle verifies that NEC is ready to collect data.
- When all vehicles are ready, the lead vehicle begins the uphill run.
  - Lead vehicle radios: "*All vehicles – uphill –* ***Stop & Go*** *Lap 1*."
- Lead vehicle will accelerate to 10 mph, and then come to a stop approximately every 40 ft.
  - Use the skip lines as a guide – there is a 40 ft gap between the start of each skip line.
  - After coming to a stop, the lead vehicle will wait approximately 2 seconds before accelerating again.
- Following vehicles should follow close behind one another, being prepared to stop whenever the vehicle in front of them stops.
- AVOID SUDDEN OR HARD BRAKES.
- Once a vehicle reaches the intersection, it may accelerate back to normal speeds and continue around T1.

***Downhill Runs***

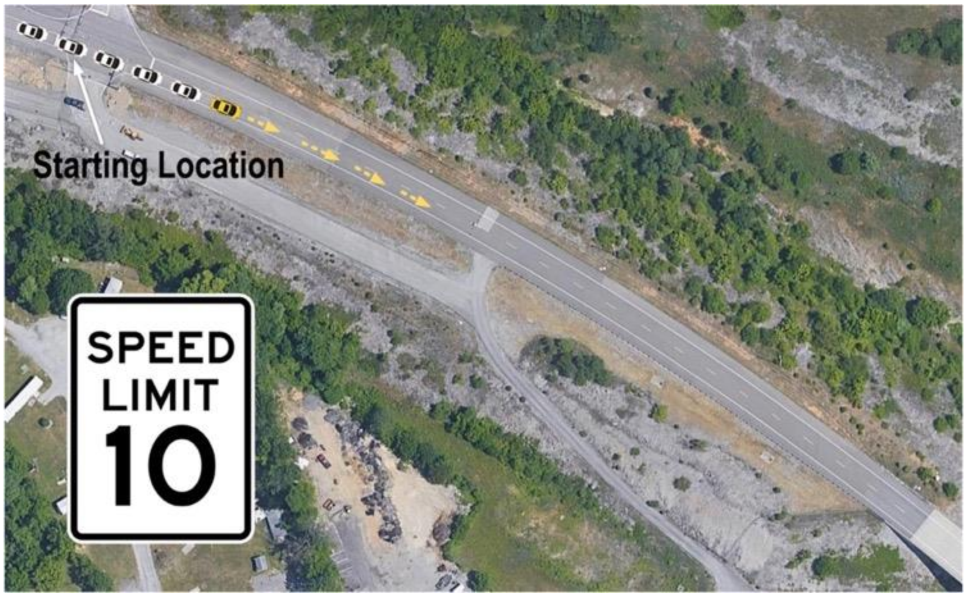



**Figure 19. Diagram. Use Case Scenario 4: Stop & Go vehicle configuration (downhill).**

- Lead vehicle will stop at the starting position at the intersection.
- Once all vehicles have finished their uphill run and lined up behind the lead vehicle, they will begin the downhill run.
  - Lead vehicle radios: "*All vehicles – downhill – Stop & Go Lap 1*."
- All vehicles will repeat the same steps, stopping and starting approximately every 40 ft, with the lead vehicle waiting 2 seconds after each stop.
- Once a vehicle reaches the Jennelle Road Bridge, it may accelerate back to a normal speed, return to T2, turn around, and return to Jennelle Road Bridge to set up for the next lap.
- Complete a total of 10 laps (~1.5 hrs).

## USE CASE SCENARIO COLLECTED DATA

The VTTI team coordinated with NEC to run the use cases scenarios according to the orchestration plan. The outcome of those efforts resulted in approximately 10.5 total hours of collected data for the various use cases and vehicle densities (detailed in Table 2). During these runs, NEC collected the backscatter waterfall data from the interrogator hardware units and coded the various scenarios. NEC then applied their artificial intelligence analytics to identify vehicle trajectory information while also evaluating each scenario to determine whether or not they were successful at identifying the behavior or desired operational metrics, as shown from Figure 20 to Figure 27.

**Table 2. Use case scenario data collection event log.**

| Date | Time Range | Vehicle Count | Use Case Scenario | Laps |
|---|---|---|---|---|
| Tuesday 02/28/203 | 10:00 a.m.–12:00 p.m. | 8 | Free Flow | 5 |
| Tuesday 02/28/203 | 10:00 a.m.–12:00 p.m. | 8 | Pull Over | 5 |
| Tuesday 02/28/203 | 10:00 a.m.–12:00 p.m. | 8 | Wrong Way | 5 |
| Tuesday 02/28/203 | 10:00 a.m.–12:00 p.m. | 8 | Stop & Go | 5 |
| Tuesday 02/28/203 | 12:00 p.m.–2:00 p.m. | 5 | Free Flow | 5 |
| Tuesday 02/28/203 | 12:00 p.m.–2:00 p.m. | 5 | Pull Over | 5 |
| Tuesday 02/28/203 | 12:00 p.m.–2:00 p.m. | 5 | Wrong Way | 5 |
| Tuesday 02/28/203 | 12:00 p.m.–2:00 p.m. | 5 | Stop & Go | 4.5 |
| Wednesday 03/01/2023 | 2:30 p.m.–4:00 p.m. | 2 | Wrong Way | 10 |
| Wednesday 03/01/2023 | 2:30 p.m.–4:00 p.m. | 2 | Wrong Way Drift | 10 |
| Wednesday 03/01/2023 | 2:30 p.m.–4:00 p.m. | 2 | Hard Brake | 10 |
| Thursday 03/02/2023 | 1:00 p.m.–4:00 p.m. | 4 | Free Flow | 10 |
| Thursday 03/02/2023 | 1:00 p.m.–4:00 p.m. | 4 | Wrong Way | 10 |
| Thursday 03/02/2023 | 1:00 p.m.–4:00 p.m. | 4 | Pull Over | 10 |
| Thursday 03/02/2023 | 1:00 p.m.–4:00 p.m. | 4 | Stop & Go | 10 |
| Friday 03/03/2024 | 10:00 a.m.–12:00 p.m. | 6 | Wrong Way | 10 |
| Friday 03/03/2024 | 10:00 a.m.–12:00 p.m. | 6 | Pull Over | 10 |
| Friday 03/03/2024 | 10:00 a.m.–12:00 p.m. | 6 | Stop & Go | 5 |
| Friday 03/03/2024 | 10:00 a.m.–12:00 p.m. | 6 | Free Flow | 2 |

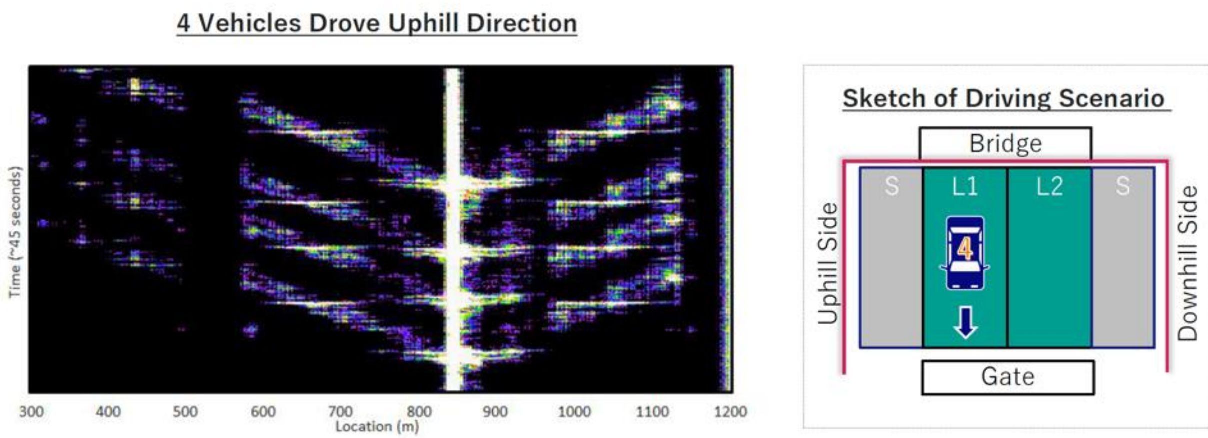



**Figure 20. Diagrams. Use Case Scenario 1: Free flow uphill waterfall plot and sketch of driving scenario.**

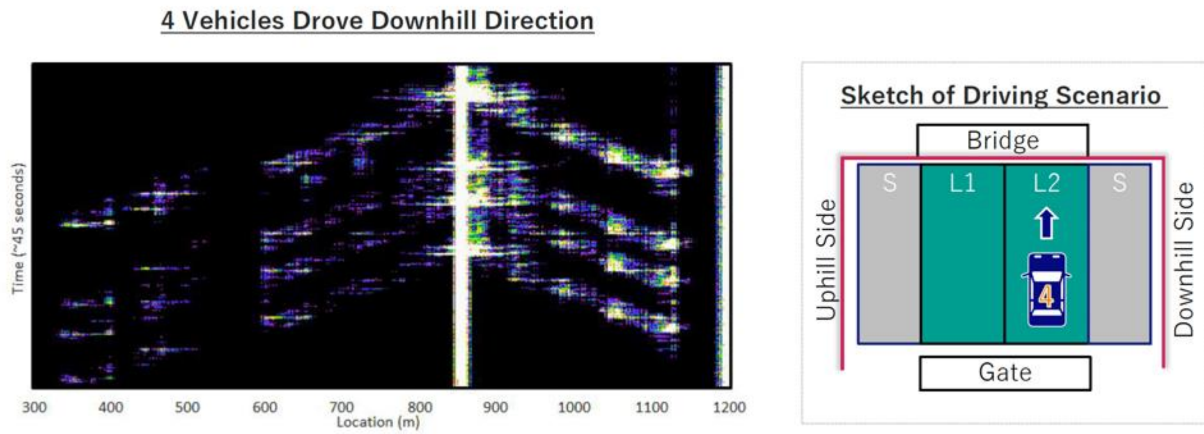



**Figure 21. Diagrams. Use Case Scenario 1: Free flow downhill waterfall plot and sketch of scenario.**

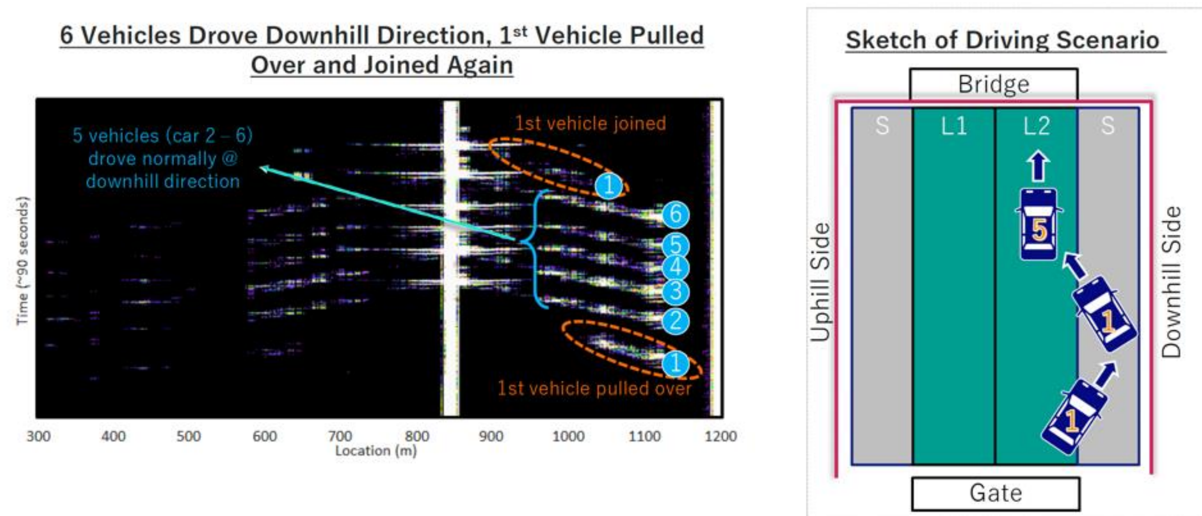



**Figure 22. Diagrams. Use Case Scenario 2: Lead vehicle pull-over downhill waterfall plot and sketch of scenario.**

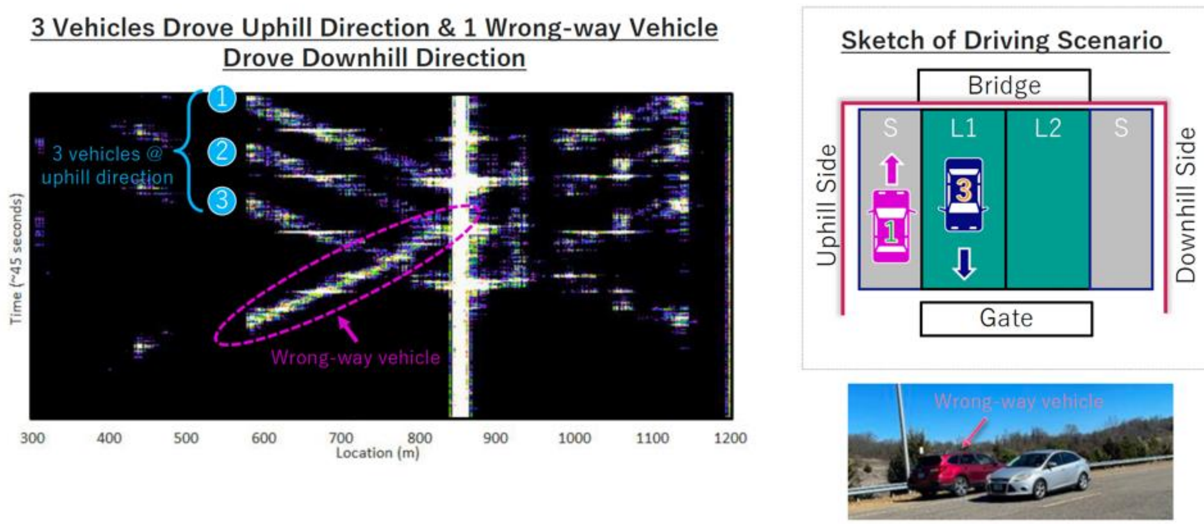



**Figure 23. Diagrams. Use Case Scenario 3: Wrong-way (adjacent) waterfall plot and sketch of scenario, with photo.**

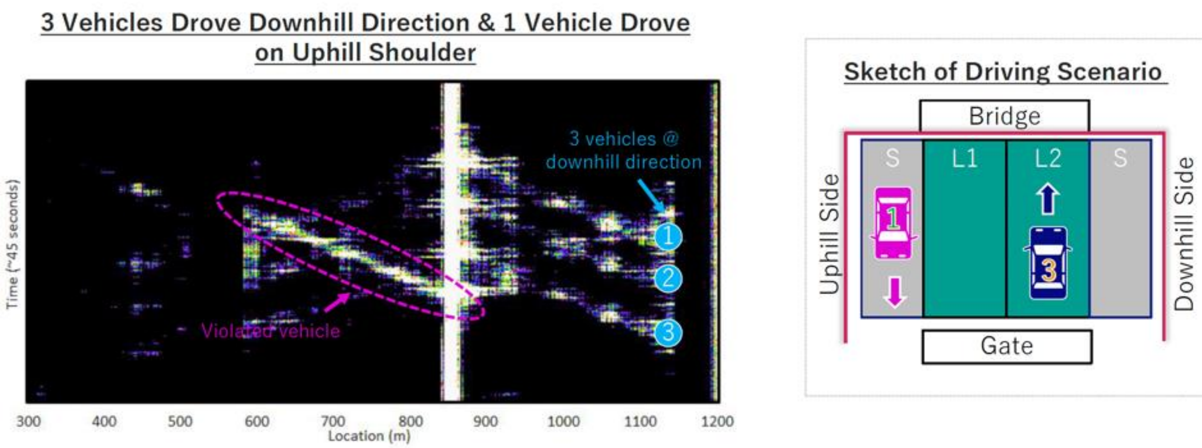



**Figure 24. Diagrams. Use Case Scenario 3: Wrong-way (1 lane gap) waterfall plot and sketch of scenario.**

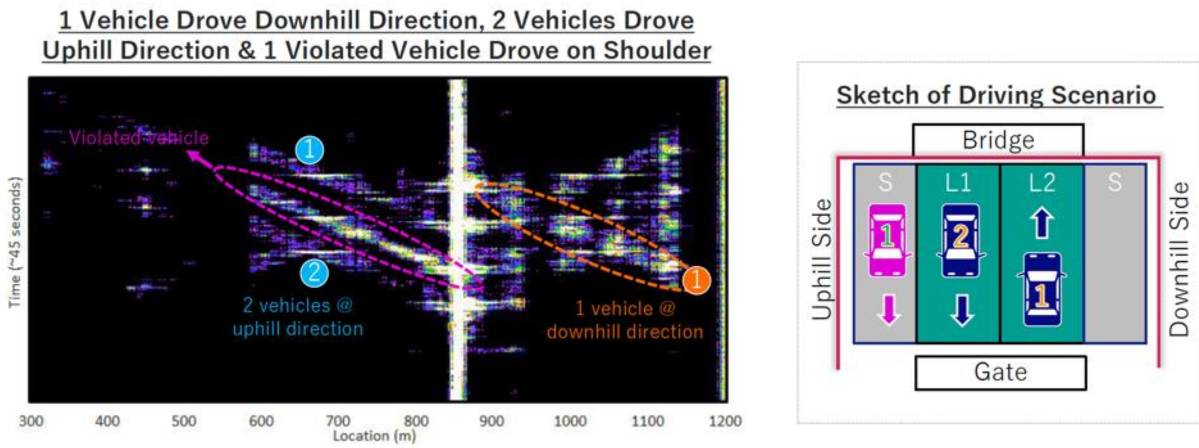



**Figure 25. Use Case Scenario 3: Wrong-way (3 lane) waterfall plot and sketch of scenario.**

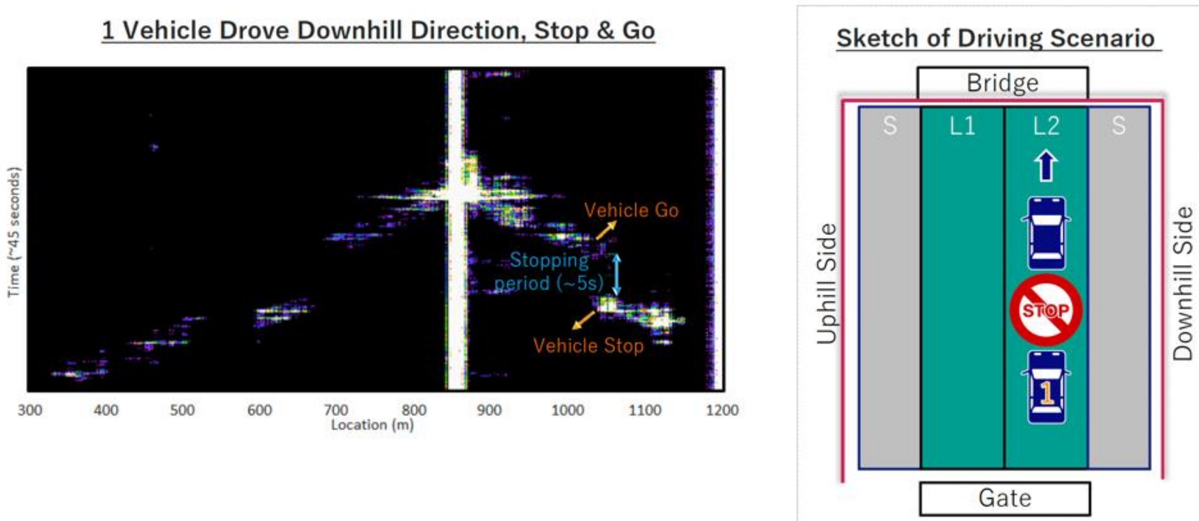



**Figure 26. Diagrams. Use Case Scenario 4: Stop & Go (1 vehicle) waterfall plot and sketch of scenario.**

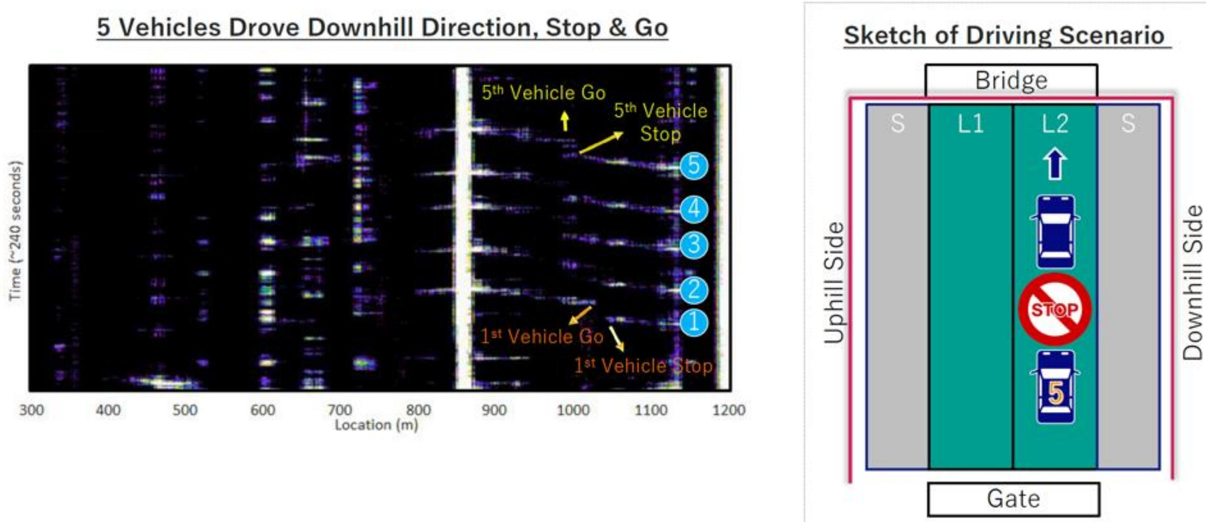



**Figure 27. Diagrams. Use Case Scenario 4: Stop & Go (5 vehicles) waterfall plot and sketch of scenario.**

# CHAPTER 4. RESULTS

As discussed, NEC carried out a performance analysis of their system per the relevant test scenarios. The results suggest that the fiber sensing technology is effective at identifying wrong-way driving with interfering traffic existing. However, the system began to lose accuracy in traffic counts and speeds when many vehicles were present, as indicated in Table 3 below.

**Table 3. NEC-analyzed results for use case scenarios.**

## Detection Rate

| Test Scenario | Total Vehicles in Lane 1 (Green Annotations) | Detected Vehicles in Lane 1 (Green Annotations) | Detection Rate* in Lane 1 (Green Annotations) % | Total Vehicles in Lane 2 (Red Annotations) | Detected Vehicles in Lane 2 (Red Annotations) | Detection Rate in Lane 2 (Red Annotations) % | Detected Vehicle(s) in WRONG Direction | WRONG Way Detection (WVD)** Rate for % | Combined Lane 1 and Lane 2 Detection Rate % |
|---|---|---|---|---|---|---|---|---|---|
| freerun_8Vehicle | 8 | 2 | 25% | 8 | 2 | 25% | NA | NA | 25% |
| freerun_4Vehicles | 4 | 4 | 100% | 4 | 4 | 100% | NA | NA | 100% |
| Wrongway_4Vehicle | 6 | 6 | NA | 2 | 2 | NA | YES | 100% | NA |
| Wrongway_6Vehicle | 6 | 6 | NA | 6 | 6 | NA | YES | 100% | NA |
| Wrongway_8vehicle | 7 | 2 | NA | 1 | 1 | NA | YES | 100% | NA |
| ALL SCENARIOS | | | | | | | | 100% | 75% |

Note:
*For free run cases "detection Rate" is attributed to the number detected vehicles as a percentage of the actual number of vehicles present during the tests.
** Wrong Way Detection is successful when the system has detected all the vehicles driving in the wrong direction (number of detected vehicles in the main direction is not accounted for in calculating WWV regardless of its accuracy)

# CHAPTER 5. CONCLUSION

The efforts undertaken in this project establish the Virginia Smart Roads as an environment able to test and improve fiber sensing equipment for transportation-related applications. The establishment of this test environment allows for controlled and scripted test scenarios to be executed, enabling system developers to improve upon their existing systems. This is evident in the work described in this report and the deployment of the NEC system. Based on the use case scenario data collected and analyzed, the NEC system can detect vehicles driving the wrong way across a range of vehicle traffic densities. On the other hand, in its current iteration, the system has trouble accurately counting the total number of vehicles when vehicle traffic densities are higher. In addition, the technology is not yet offered in a product form that could be broadly deployed on VDOT roadways.