CENTER FOR CONNECTED AND AUTOMATED TRANSPORTATION

Report No. CCAT Project Number 16 March 10, 2021
Project Start Date: May 1, 2019
Project End Date: December 31, 2020

Reliable V2V Communication Networks: Applications in Fuel-Efficient Platooning

FINAL REPORT

by
Sridhar Lakshmanan (PI), Paul Richardson (co-PI), Paul Watta (co-PI)
Department of Electrical and Computer Engineering
University of Michigan - Dearborn

DISCLAIMER

Funding for this research was provided by the Center for Connected and Automated Transportation under Grant No. 69A3551747105 of the U.S. Department of Transportation, Office of the Assistant Secretary for Research and Technology (OST-R), University Transportation Centers Program. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the Department of Transportation, University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.

Suggested APA Format Citation:

Lakshmanan, Sridhar, & Richardson, Paul & Watta, Paul, (2021), "*Reliable V2V Communication Networks: Applications in Fuel-Efficient Platooning*". Report No. CCAT Project Number 16, Center for Connected and Automated Transportation, University of Michigan.

Identifier: http://hdl.handle.net/2027.42/166585
DOI: 10.7302/381

Contacts

For more information:

Sridhar Lakshmanan
Department of Electrical and Computer Eng
University of Michigan-Dearborn
2050 IAVS, 4901 Evergreen Rd
Dearborn, MI 48128-1491
Phone: 313-593-5516
Email: lakshman@umich.edu

CCAT
UMTRI, University of Michigan
2901 Baxter Road
Ann Arbor, MI 48152
uumtri-ccat@umich.edu
(734) 763-2498

CENTER FOR CONNECTED AND AUTOMATED TRANSPORTATION

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
CCAT Project Number 16	Leave blank – not used	Leave blank - not used

4. Title and Subtitle Reliable V2V Communication Networks: Applications in Fuel-Efficient Platooning Identifier: http://hdl.handle.net/2027.42/166585 DOI: 10.7302/381	**5. Report Date** March 10, 2021 **6. Performing Organization Code**
7. Author(s) Lakshmanan, Sridhar Ph.D., http://orcid.org/0000-0001-7387-3943	**8. Performing Organization Report No.** Enter any/all unique alphanumeric report numbers assigned by the performing organization, if applicable.
9. Performing Organization Name and Address Center for Connected and Automated Transportation University of Michigan Transportation Research Institute 2901 Baxter Road Ann Arbor, MI 48109 Department of Electrical and Computer Engineering University of Michigan-Dearborn 2050 IAVS, 4901 Evergreen Rd Dearborn, MI 48128-1491	**10. Work Unit No.** **11. Contract or Grant No.** Contract No. 69A3551747105
12. Sponsoring Agency Name and Address U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology 1200 New Jersey Avenue, SE Washington, DC 20590	**13. Type of Report and Period Covered** Final Report (May 2019 – December 2020) **14. Sponsoring Agency Code** OST-R

15. Supplementary Notes

Conducted under the U.S. DOT Office of the Assistant Secretary for Research and Technology's (OST-R) University Transportation Centers (UTC) program.

16. Abstract

This final report documents the project findings. The project investigated the ability of CV2X and DSRC communication systems to accurately send and receive data between vehicles which have lost their line-of-sight due to occluding obstacles. A propagation model to predict received radio power is developed using *WinProp*. The power prediction from the model is combined with packet reception data from actual radios to obtain a logistic distribution for packet reception rates as a function received power. We also offer a comparison of the relative performance of DSRC and CV2X systems using their respective logistic distributions and interpret our results to suit those planning vehicle-to-vehicle (V2V) communication systems.

17. Key Words	18. Distribution Statement
DSRC, CV2X, Radio Communications, Non-Line-Of-Sight, Modeling, Testing	No restrictions.

CENTER FOR CONNECTED AND AUTOMATED TRANSPORTATION

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	32	Leave blank – not used

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Table of Contents

List of Figures

Introduction

Singular Obstacle

Urban Canyon

Findings

Outputs, Outcomes, and Impacts

List of Tables

Introduction

Singular Obstacle

Urban Canyon

Introduction

With autonomy and active safety systems in vehicles becoming more and more prevalent, advanced communication systems between vehicles (vehicle-to-vehicle or V2V), and between the road infrastructure and vehicles (vehicle-to-infrastructure or V2I), considered together as vehicle-to-everything (V2X), become necessary. By establishing stable communication with other vehicles, autonomy and active safety systems can respond to problems that are not foreseeable with standard sensors, such as preventing a broadside collision around a blind corner by having each vehicle communicate its speed and position to the other ahead of time.

In our work, we consider the performance of V2X communication using both Cellular V2X (CV2X) and Dedicated Short-Range Communication (DSRC) radios. Here, performance is evaluated based on several Key Performance Indicators (KPIs) including Received Signal Strength Indicator (RSSI), received power, Packet Reception Rate (PRR), and its complement Packet Error Rate (PER). We consider primarily two scenarios for our testing: a singular metal obstacle such as a truck or trailer directly in front of a vehicle, cutting off its immediate line-of-sight (LOS), and an urban canyon such as a narrow street lined with building structure cutting off line-of-sight on both sides but offering inter-reflection and waveguiding possibilities. Motivation for focusing on NLOS comes from our parallel US Department of Energy project on fuel-efficient semi-truck platooning where we have observed power losses in excess of 15dB due to occlusion effects [1]. Our project partner Ford, reflecting the overall 5GAA community, is also very interested in the effects of NLOS on V2V.

Losing LOS makes predicting packet reception more difficult because it means relying on indirect paths from the transmitter to the receiver, which can result in path loss that depends dramatically on the specific scenario and can't be modeled by simply using the free-space path-loss equation. Depending on exactly what occluders are around to reflect off of and diffract around, the path loss caused by losing LOS could be anywhere from negligible to a full loss of all communication. Our goal here is to use testing and simulation to develop a method to better predict packet reception and loss in NLOS scenarios. Reference [2] is the scientific paper authored by project personnel and partner personnel.

We used pre-production Qualcomm Autotalks CV2X radios for the CV2X testing and Cohda Wireless MK5 OBU radios for the DSRC testing, with configuration parameters as specified in Table 1.

Configuration	DSRC	CV2X
HARQ Enabled	No	Yes
Data Rate	6MB/s	6MB/s
GPS Dependent	No	Yes
Packet Size	421B	421B
Channel Width	10 MHz	20MHz
Encoding	QPSK (MCS 10)	64-QAM (MCS 7)

Table 1: Radio Configuration, CV2X vs. DSRC.

For all our tests we used a 5.9 GHz channel and the omni-directional ECOM6-5900 from MobileMark for antennas. One such antenna was mounted to the rear roof of a test vehicle for far-field pattern measurement and the results were converted into the .apa format for viewing, as can be seen in Figure 1. We used a pair of antennas per-vehicle which were separated by about a meter and were configured with Maximal Ratio Combining (MRC) for reception, and the transmitters were sending packets at a rate of 10 Hz.

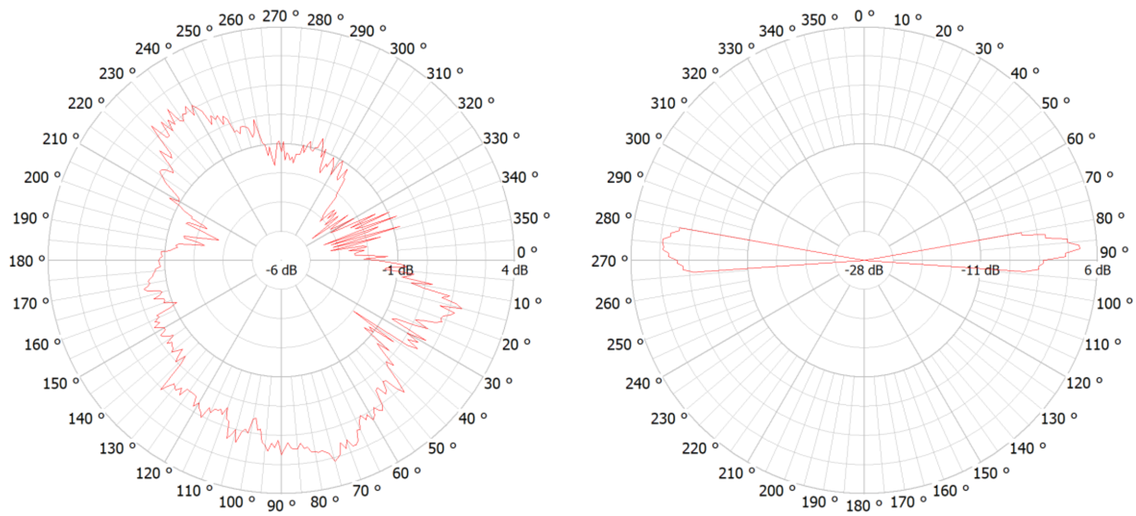

Fig. 1: ECOM6-5900 far-field antenna pattern. Left: azimuthal pattern at the horizon. Right: elevation profile for the measured angles, unmeasured at -∞ dBm.

We used a hybrid approach to analysis consisting of both real-world testing and data collection along with simulated field strength produced using Altair's *WinProp* suite of electromagnetic field propagation tools. We can then combine the metrics we capture from the real-world testing data with simulated received power to get a better picture of the entire scenario's performance and also develop a method for using simulated received power to predict PRR.

Singular Obstacle

Beginning with the simpler of the two scenarios, we examine the effects of a singular obstacle obstructing the direct LOS of a vehicle-mounted antenna. To test this, we situated a Lincoln *Nautilus* immediately behind a Ford F350 with a dump body, effectively a large block of flat metal to prevent any radiation passing through in the LOS direction. We then ran loops around the vehicle pair using a Ford *Taurus*, where both the stationary and moving vehicles were equipped with a radio and a pair of the antennas, plus some attenuation. The transmitters were configured to transmit at 5 dBm with 40dB of attenuators along the channel (20dB on each antenna). Figure 2 shows the path of the moving vehicle and the stationary vehicle location in the CV2X case, where the DSRC loop is approximately the same.

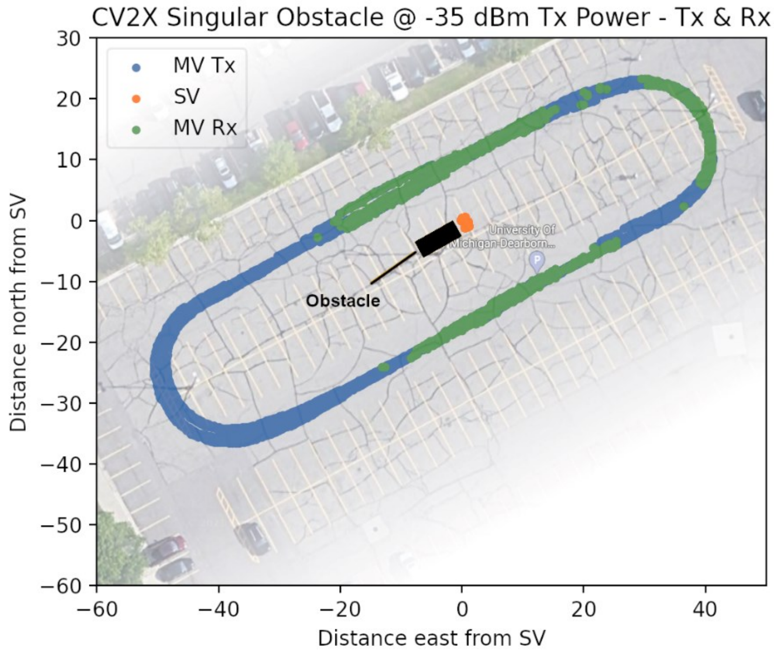

Fig. 2: The path of the moving vehicle MV as it made loops around the stationary vehicles, SV and obstacle.

We simulated the test setup using *WinProp*, producing the results shown in Figure 3. We used SRT with 2 reflections, 1 diffraction, simulated phase, and reflections off of the ground and box. We modeled the truck as a 9ft × 8.5ft × 18ft metal box and the ground as 30cm thick concrete. We will be able to use this simulation in conjunction with the CV2X and DSRC test results to form a more complete picture of the environment during testing.

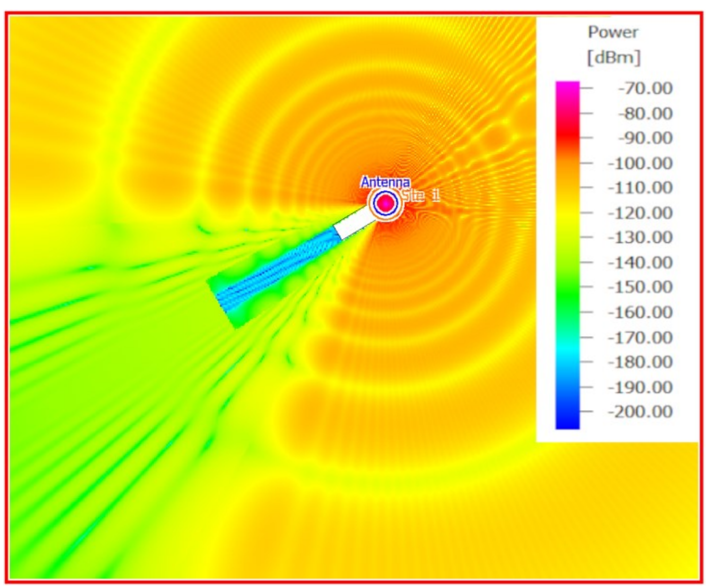

Fig. 3: Simulated field power from an omni-directional antenna mounted on a stationary vehicle next to an occluding obstacle, that is, the same setup as above.

CV2X

We transmitted 5994 packets during the CV2X test and received 2305 of them back for an overall PRR of 38.46%, as detailed in Table 2.

	Transmitted	**Received**	**Lost**
MV	2997	1048	1949
SV	2997	1257	1715
Total	**5994**	**2305**	**3689**

Table 2: Breakdown of packet receptions and losses, CV2X singular obstacle.

We can plot the GPS positions of the received and lost packets relative to each other, as seen in Figure 4. Here, green packets were received, and blue packets were transmitted and lost.

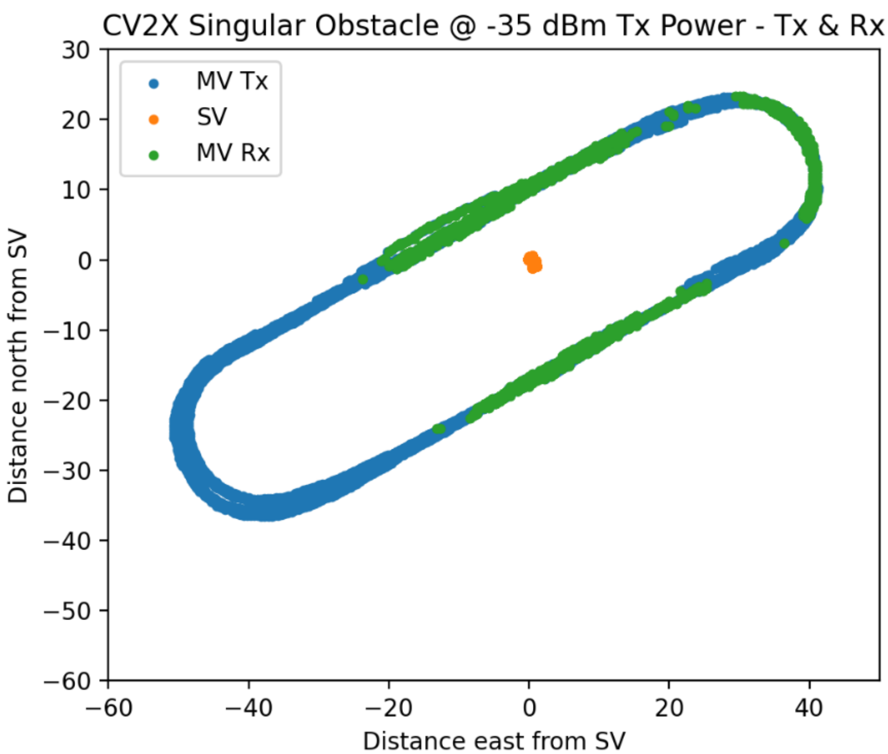

Fig. 4: GPS positions of received and lost packets, CV2X singular obstacle.

For those packets that were received, we can also plot their reception signal power alongside what the simulation predicts should be the received power at that location, as shown in Figure 5.

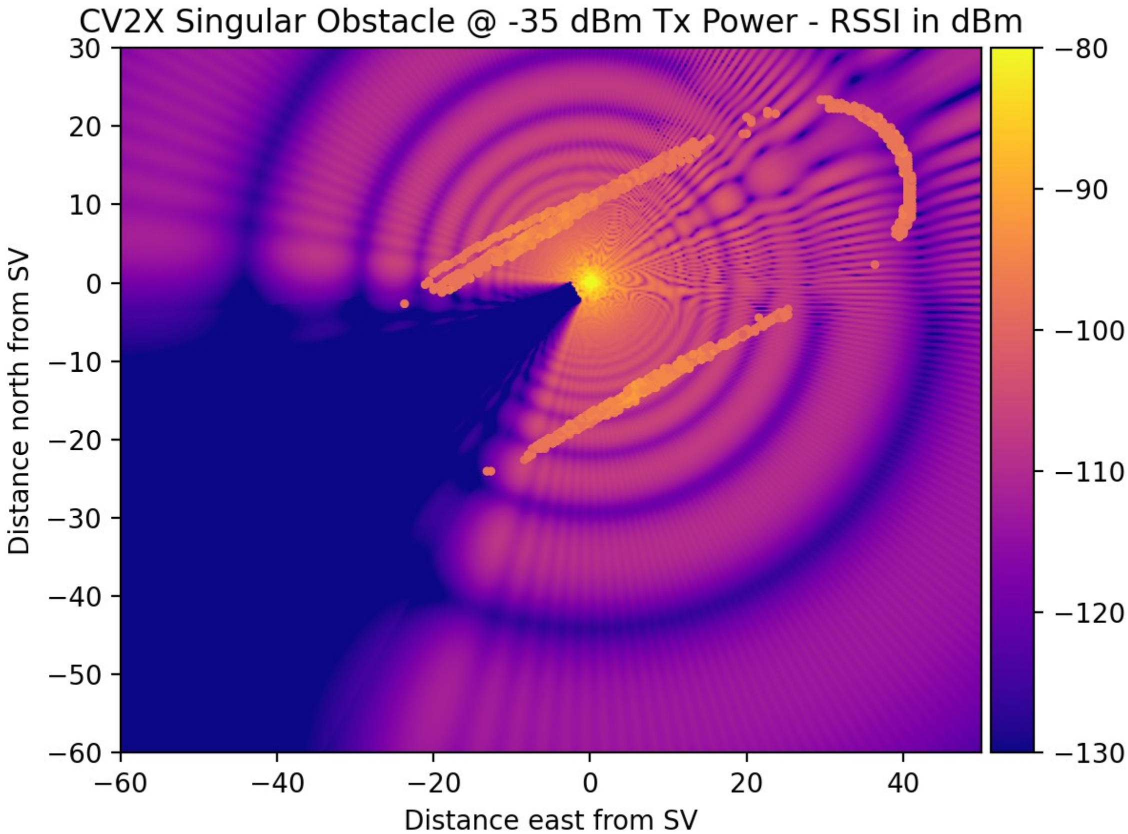

Fig. 5: Packet reception power overlaid with WinProp simulation results, CV2X singular obstacle.

We note that the actual reception power is similar to the simulation, but because the power level is at or below the edge of where reception becomes difficult, we really see only the packets which due to noise in the randomly fluctuating signal strength were able to be received at an abnormally high power relative to the average power at that position.

To better understand the implications of this, we binned this data into a histogram as shown in Figure 6. We have received packets in blue, lost packets in orange, frequency on the vertical axis, and simulated received power on the horizontal. This allows us to easily see the rate of packet reception and error for any given received power.

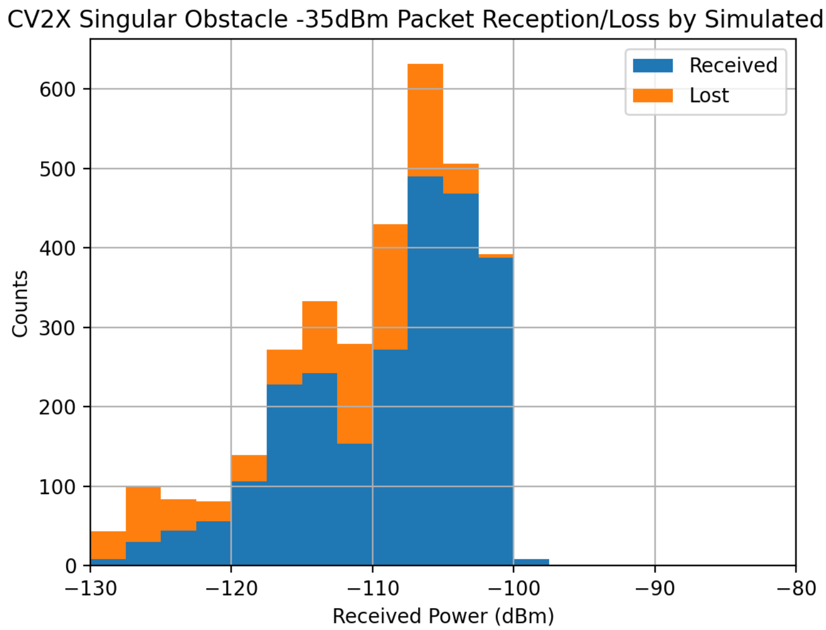

Fig. 6: Histogram of simulated received power vs. packet receptions/losses, CV2X singular obstacle.

We can make this even easier to read by plotting the ratio of packet receptions to overall packet transmissions for each point, as shown in Figure 7.

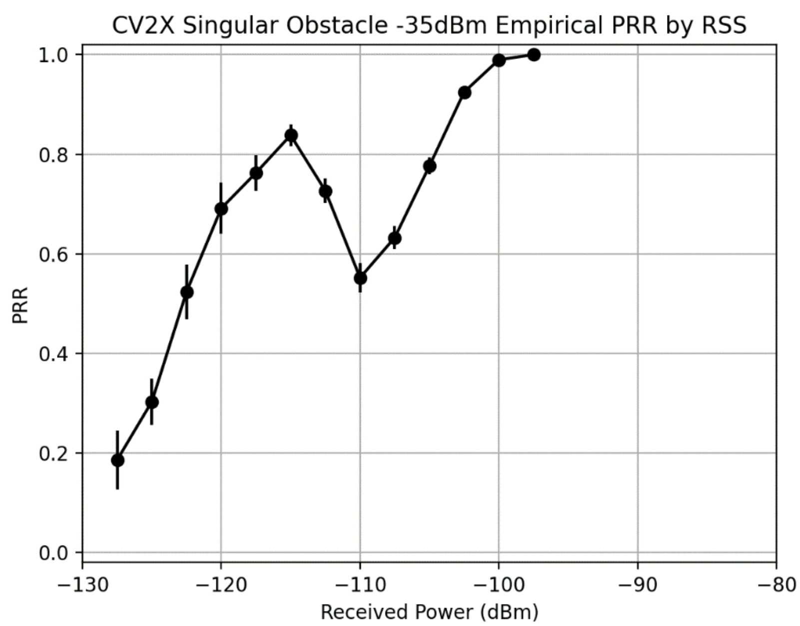

Fig. 7: Plot of PRR by simulated received power, CV2X singular obstacle.

We used Standard Error (SE) bars to indicate the uncertainty in measurement of some of these results. Finally, we can perform a logistic regression on the reception/loss of packets vs. the simulated expected received power to form a probabilistic model of expected PRR based on received power. The results of this regression are shown in Figure 8 below.

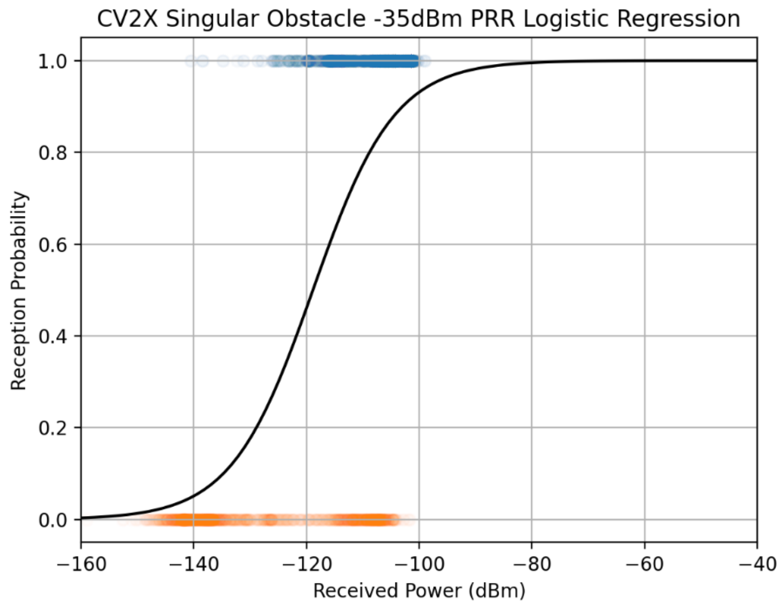

Fig. 8: Logistic regression of packet reception probability vs. simulated received power, CV2X singular obstacle.

DSRC

We transmitted 4640 packets during the DSRC test and received 740 of them back for an overall PRR of 15.95%, as detailed in Table 3.

	Transmitted	Received	Lost
MV	2325	346	1969
SV	2315	394	1931
Total	**4640**	**740**	**3900**

Table 3: Breakdown of packet receptions and losses, DSRC singular obstacle.

We can again plot the simulated power alongside packet GPS location, blue for transmitted and green for received, as seen in Figure 9.

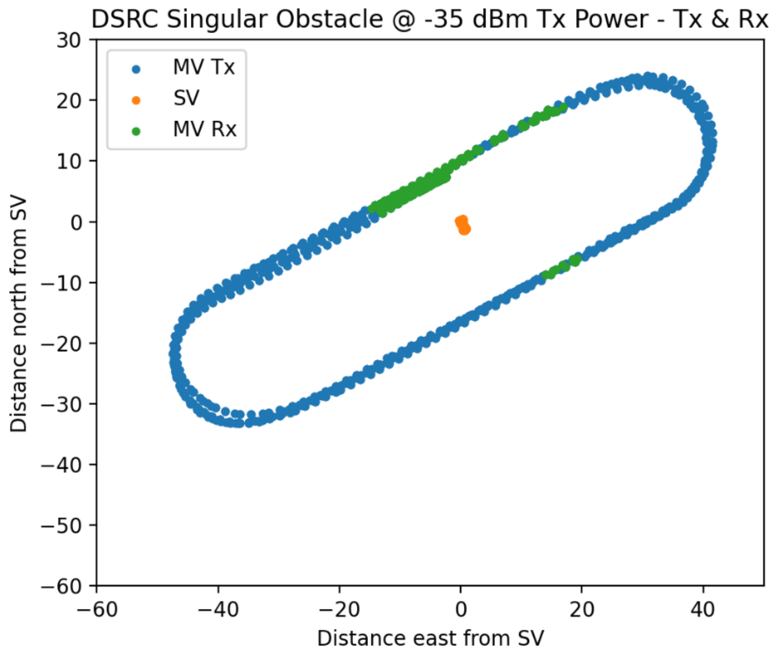

Fig. 9: GPS positions of received and lost packets, DSRC singular obstacle.

Once again, those packets that were received can also have their reception signal power plotted alongside what the simulation predicts should be the received power at that location, as shown in Figure 10.

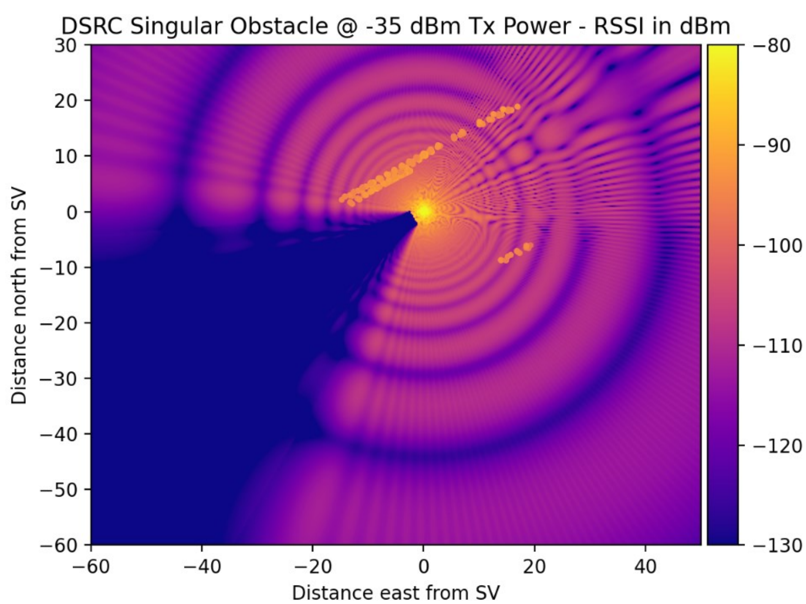

Fig. 10: Packet reception power overlayed with WinProp simulation results, DSRC singular obstacle.

Taking a histogram of this data yields Figure 11, which shows packet reception and loss counts by simulated power.

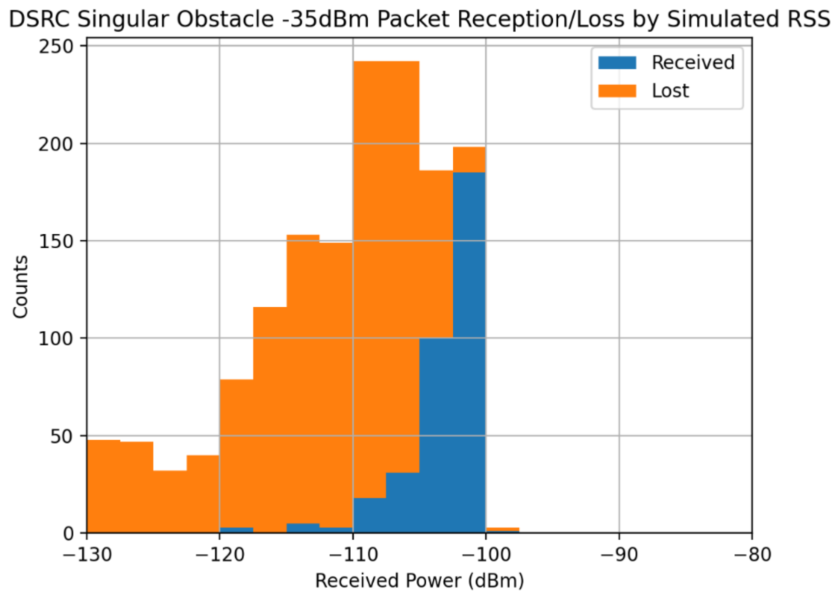

Fig. 11: Histogram of simulated received power vs. packet receptions/losses, DSRC singular obstacle.

Taking the ratio of received to total packets for each bin in the histogram yields Figure 12.

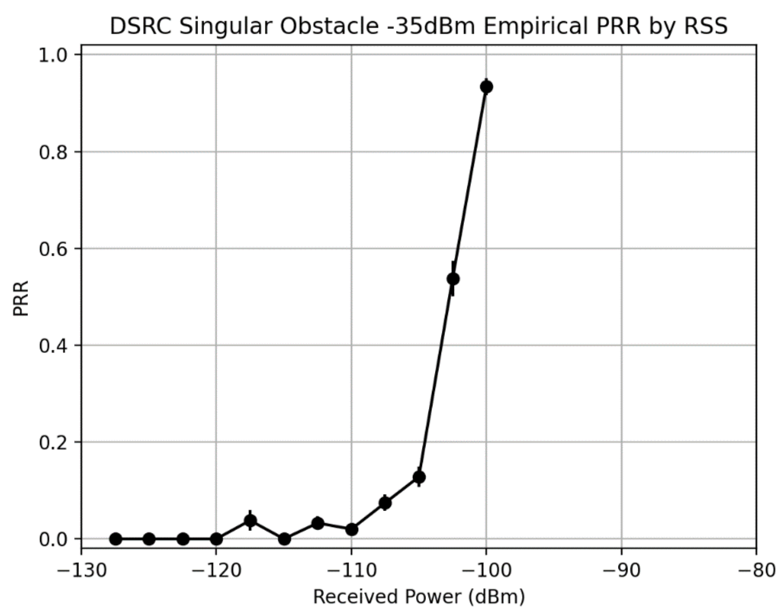

Fig. 12: Plot of PRR by simulated received power, DSRC singular obstacle.

Finally, we can take the logistic regression of packet reception probability vs. simulated reception power to get the plot in Figure 13. Compared to the CV2X case this shows a much sharper cutoff, which occurs at a higher power level, reducing performance.

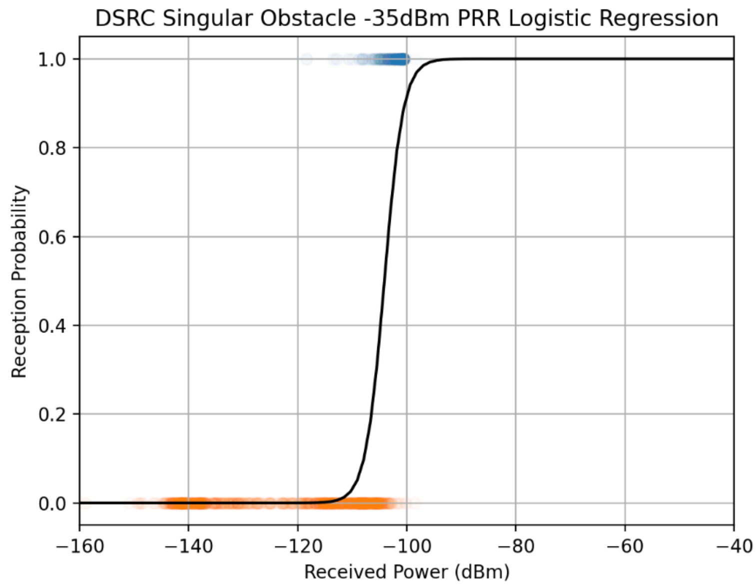

Fig. 13: Logistic regression of packet reception probability vs. simulated received power, DSRC singular obstacle.

Urban Canyon

Next, we moved on to the Urban Canyon scenario, which we modeled as a loop around a stationary vehicle that takes the moving vehicle through a narrow road with metal obstacles lining both sides, obstructing LOS. To test this, we situated the same Lincoln *Nautilus* in the center of a loop of test track with an urban canyon built up out of shipping containers for the moving vehicle to drive through. We then ran loops around the vehicle using the Ford *Taurus*, once again using the radio and a pair of the antennas per vehicle, this time with a transmit power of 15 dBm with the same 40dB of attenuation. Figure 14 shows the path of the moving vehicle and the stationary vehicle location in the CV2X case, where the DSRC loop is approximately the same.

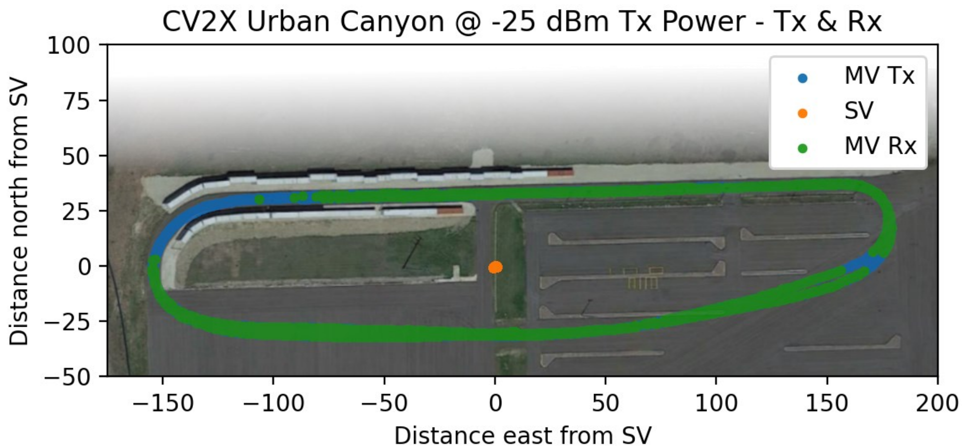

Fig. 14: The path of the moving vehicle MV as it made loops around the stationary vehicle SV and through the urban canyon.

We simulated the test setup using *WinProp*, producing the results shown in Figure 15. This time we opted for the Dominant Path Model (DPM) instead of SRT as the wave-guiding effects present in the canyon are important to simulate accurately.

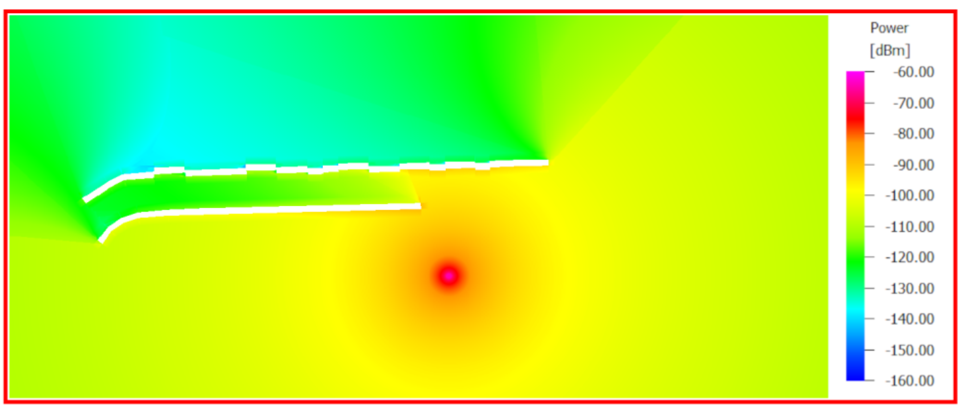

Fig. 15: Simulated field power from an omni-directional antenna mounted on a stationary vehicle in the center of the urban canyon loop.

CV2X

We transmitted 4060 packets during the CV2X test and received 3216 of them back for an overall PRR of 79.21%, as detailed in Table 4.

	Transmitted	Received	Lost
MV	2041	1579	440
SV	2019	1637	404
Total	**4060**	**3216**	**844**

Table 4: Breakdown of packet receptions and losses, CV2X urban canyon.

We can plot the GPS positions of the received and lost packets relative to each other, as seen in Figure 16. Once again, packets marked in green were received, and lost packets are marked in blue.

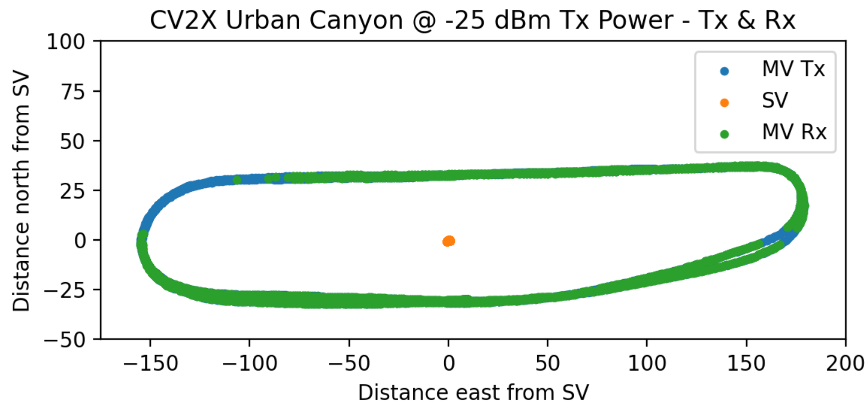

Fig. 16: GPS positions of received and lost packets, CV2X urban canyon.

Received packets with their power overlaid onto the WinProp simulated power are shown in Figure 17.

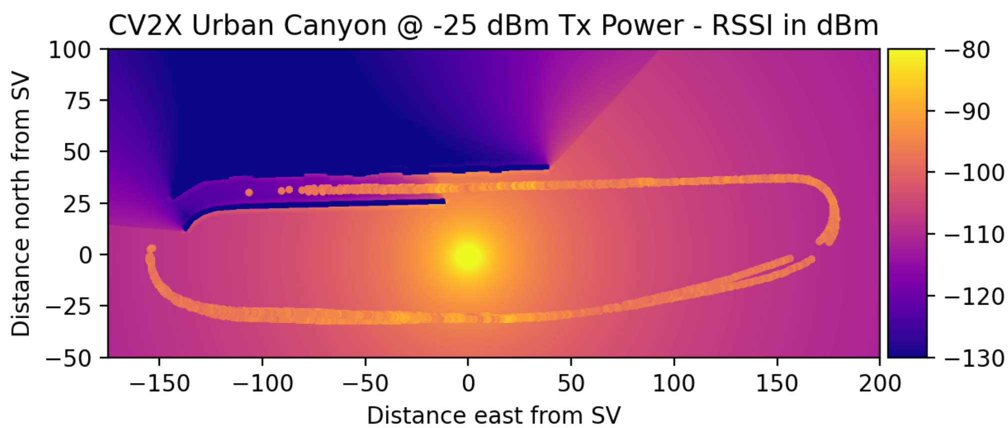

Fig. 17: Packet reception power overlaid with WinProp simulation results, CV2X urban canyon.

To better understand the implications of this, we binned this data into a histogram as shown in Figure 18. We have received packets in blue, lost packets in orange, frequency on the vertical axis, and simulated received power on the horizontal. This allows us to easily see the rate of packet reception and error for any given received power.

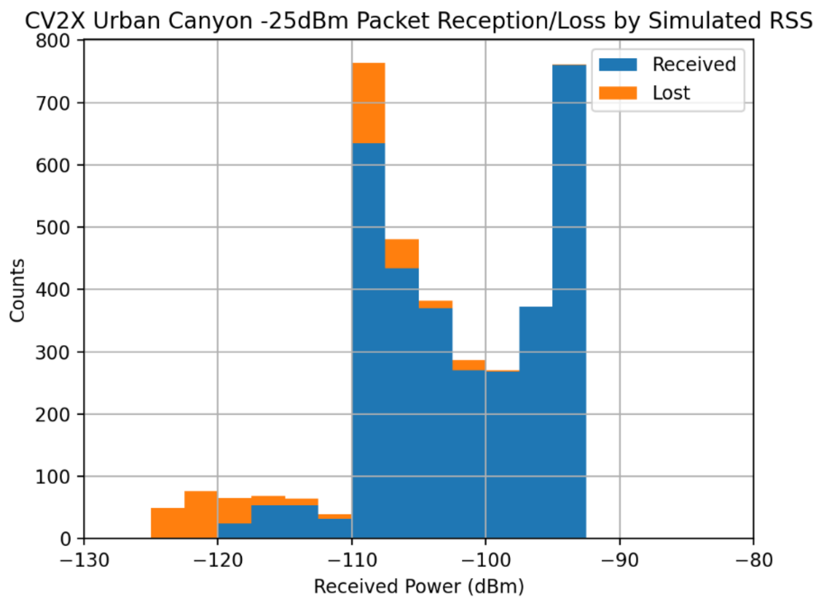

Fig. 18: Histogram of simulated received power vs. packet receptions/losses, CV2X urban canyon.

We can make this easier to read by plotting the ratio of packet receptions to overall packet transmissions for each point, as shown in Figure 19.

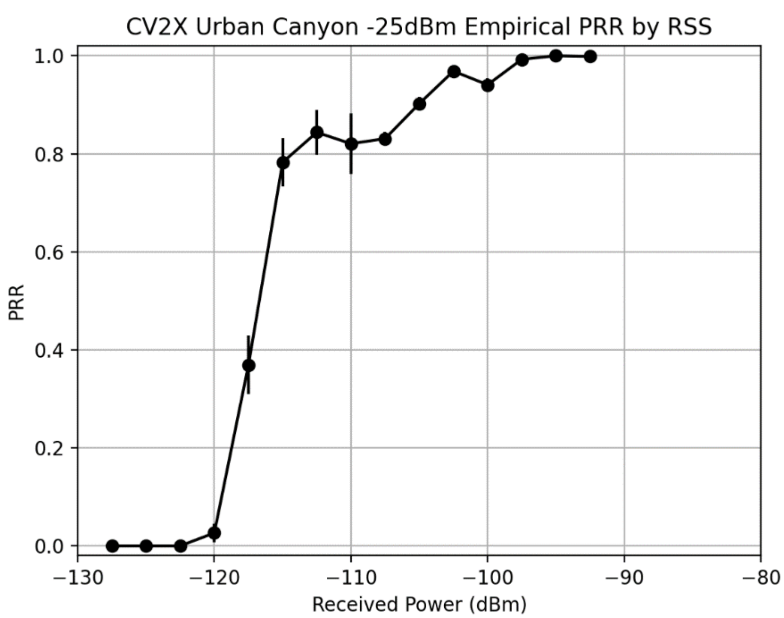

Fig. 19: Plot of PRR by simulated received power, CV2X urban canyon.

We used Standard Error (SE) bars to indicate the uncertainty in measurement of some of these results. Finally, we can perform a logistic regression on the reception/loss of packets vs. the simulated expected received power to form a probabilistic model of expected PRR based on received power. The results of this regression are shown in Figure 20 below.

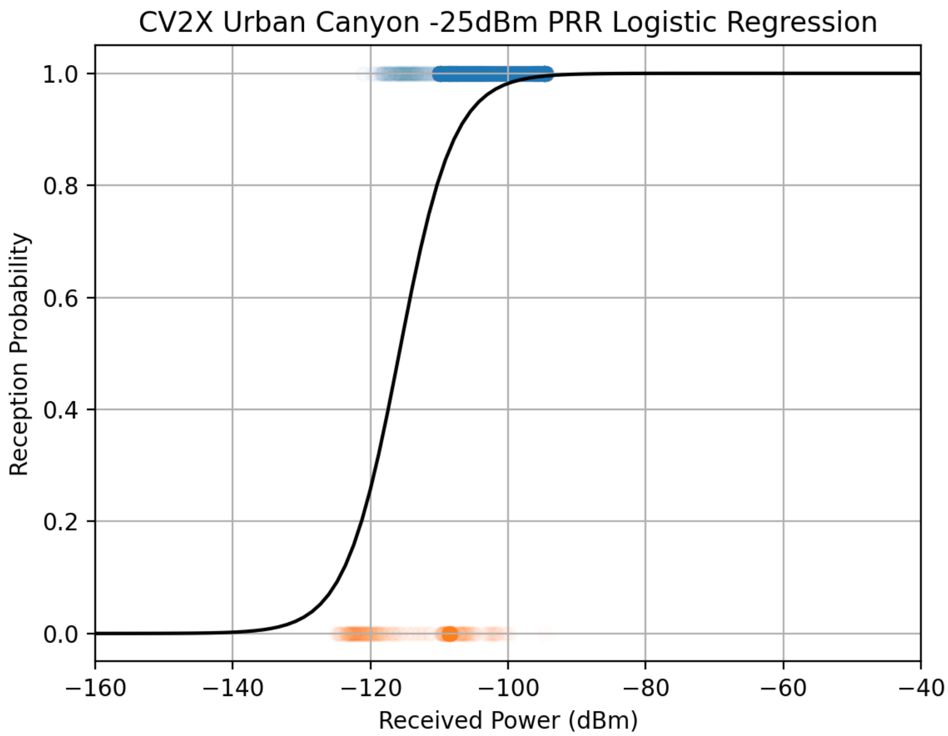

Fig. 20: Logistic regression of packet reception probability vs. simulated received power, CV2X urban canyon.

While the drop-off here is slightly harsher, this plot gives a very similar result to that which was obtained in the singular obstacle case, indicating more generality for the model.

DSRC

We transmitted 3814 packets during the DSRC test and received 687 of them back for an overall PRR of 18.01%, as detailed in Table 5.

	Transmitted	**Received**	**Lost**
MV	1911	360	1543
SV	1903	327	1584
Total	**3814**	**687**	**3127**

Table 5: Breakdown of packet receptions and losses, DSRC singular obstacle.

One last time we plot the GPS locations of received (green) and lost (blue) packets, as shown in Figure 21.

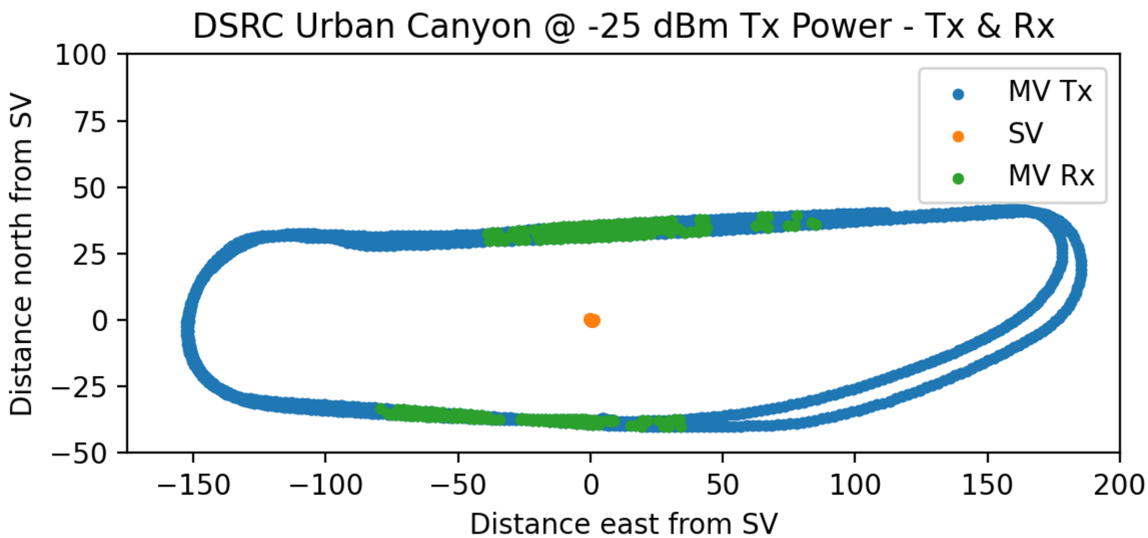

Fig. 21: GPS positions of received and lost packets, DSRC urban canyon.

Received packets with their power overlaid onto the WinProp simulated power are shown in Figure 22.

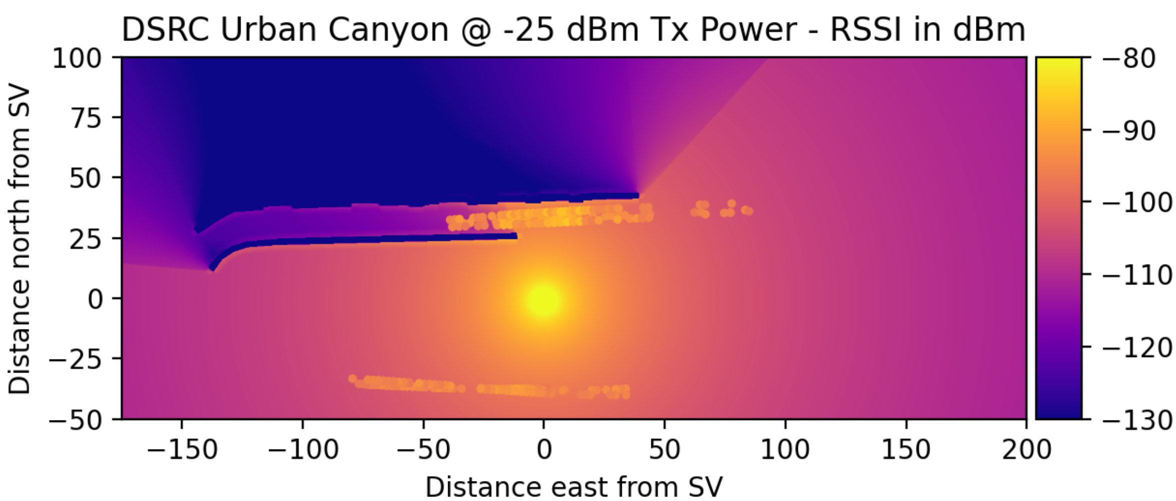

Fig. 22: Packet reception power overlaid with WinProp simulation results, DSRC urban canyon.

We analyze this again in the context of a power vs. reception histogram in Figure 23.

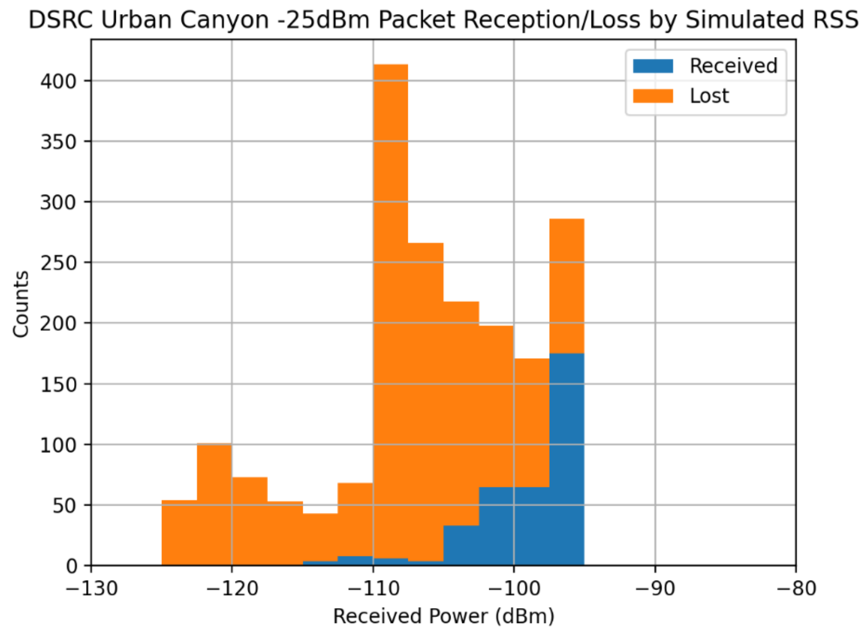

Fig. 23: Histogram of simulated received power vs. packet receptions/losses, DSRC urban canyon.

Plotting the ratio between received and all packets gives us the PRR vs. received power plot in Figure 24.

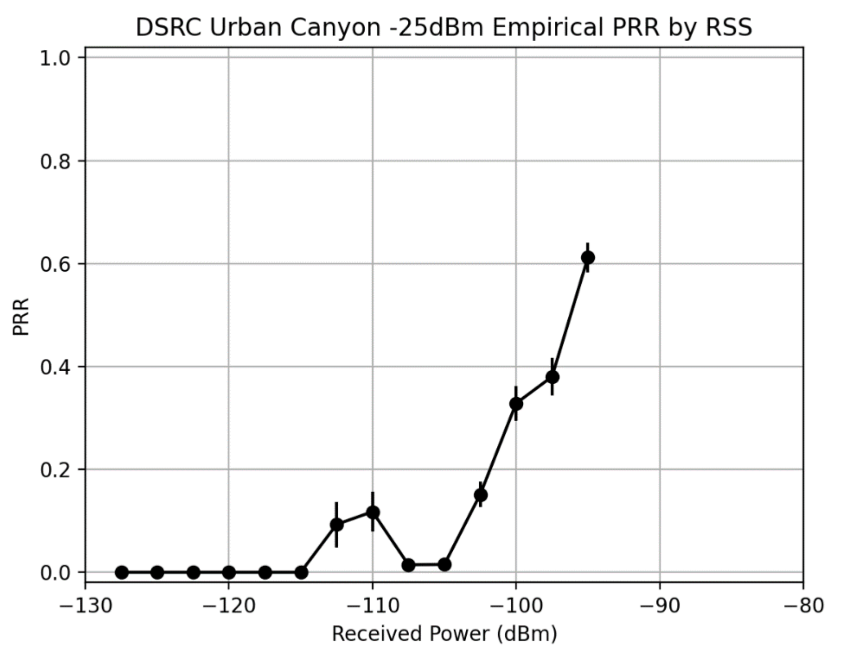

Fig. 24: Plot of PRR by simulated received power, DSRC urban canyon.

Taking the raw reception/loss points and their associated simulated reception power, we can once again build a logistic regression giving reception probability vs. simulated power, as shown in Figure 25.

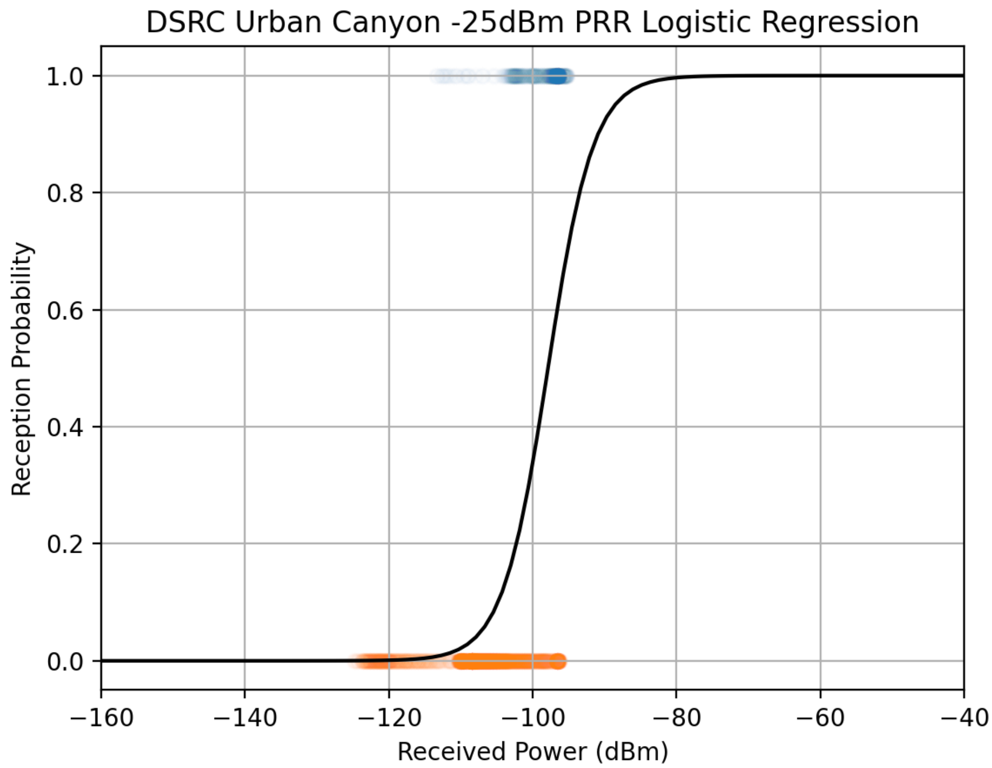

Fig. 25: Logistic regression of packet reception probability vs. simulated received power, DSRC urban canyon.

Findings

In our study of these scenarios, we have found and confirmed several important results. First of all, we must acknowledge that much of our results are based on an imperfect simulation. We only considered the most prominent reflecting surfaces in our models and ignored such features as the short grass, occasional low medians, and far away obstacles like trees. For this reason, we chose to validate our results with respect to laboratory tests for PRR vs. received power, as shown in Figure 26.

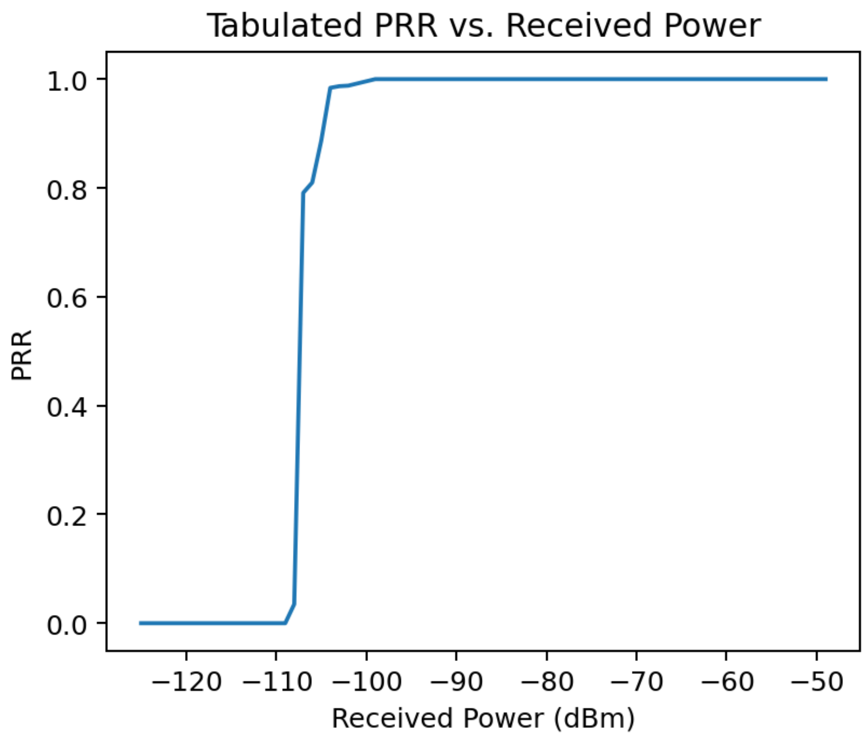

Fig. 26: Packet reception vs. received power in a cabled lab test.

This graph was produced from tabulated data from the 5GAA's V2X functional and performance test report [3] and represents the packet reception rate of a receiver connected directly to the transmitter via a controlled cable. Real wireless channels will necessarily be messier than this, and produce the smooth descent as seen in the logistic regression plots rather than a drop-off cliff, as well as additional noise potentially lowering the signal to noise ratio. Nevertheless, we do see some definite similarity between the average 50% PRR cut-off point of our CV2X data and the lab tests, provided we take into account the fact that 20dB of our attenuation occurs after the wireless channel immediately before the signal is processed, meaning it does not contribute much to the signal to noise ratio because most of the noise is attenuated along with the signal.

Recommendations

While we believe our final model gives a good estimate of the overall packet reception rate to be expected at a given simulated power level, we recommend additional testing on more scenarios, as differences between the scenarios could show a need for more complicated models that take into account the approximate scenario occluder setup.

Otherwise, we can recommend our model, as detailed below, for the purposes of approximating the probability of packet reception for CV2X based on the results of an electromagnetic power simulation such as WinProp.

Finally, we recommend the consideration of the relative reception probabilities of CV2X vs. DSRC that we observed in any decisions regarding which technology to employ for some purpose, along with other factors such as cost effectiveness, expected path loss, and ability to transmit power.

Outputs, Outcomes, and Impacts

Over the course of this project, we were able to develop our impact in a variety of ways, including the production of predictive models and methodologies for estimating how effectively CV2X or DSRC communication can take place when line-of-sight is obstructed, work on an independent simulation package which offers fast fully-3D simulation of arbitrary scenarios, publication of work featuring an earlier version of analysis as seen in this report, a pair of media publications which reported on our work on this project, and both regular and special meetings with partner organizations to review completed work and offer professional opinions on policy decisions regarding the implementation of CV2X and DSRC communications systems.

Modelling, Data, and Lessons Learned

As a result of our analysis we developed an approximate model for determining the probability of packet reception using CV2X communication based on the simulated received power. Analytically, this model can be given as:

$$PRR = \frac{1}{1 + e^{-(29.31+0.2531x)}}$$

Where *x* is the simulated received power as measured in dBm. This can be plotted out to produce Figure 27.

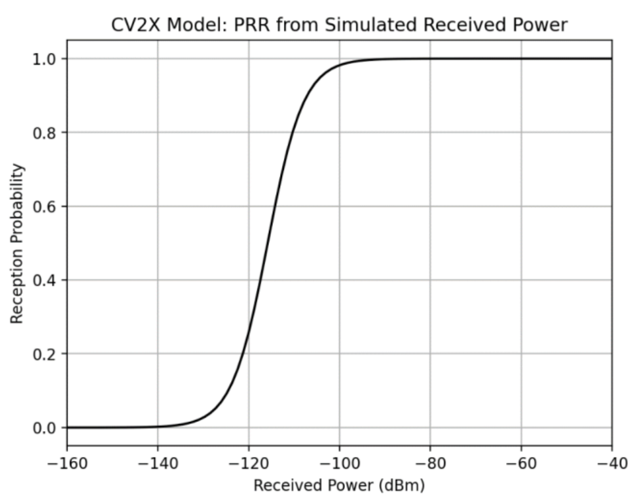

Fig. 27: PRR vs. simulated reception power in dBm, CV2X logistic regression model.

This model allows for a direct conversion between simulated field power and packet reception rate prior to physical testing, making estimations of circumstantial packet loss much simpler. This model was also verified against models created the same way using other power levels and all show good agreement within a couple of dB for a given PRR.

We also developed an analogous model for estimating receptions with DSRC communication. In order to have a truly representative sample of data to perform an accurate regression, we need to have plenty of data on both the low and high end of the regression, meaning a lot of lost and received packets. The power levels of -25 and -35 dBm we selected ensured that this would be the case for CV2X, but we would have had to select higher power levels to produce properly representative DSRC data – which would in turn produce less representative CV2X data, meaning we had to make a choice. That being said, Figure 28 shows the DSRC model based on the combination of data across the two scenarios, which should be within a few dB of accuracy with respect to the model we would have acquired had our testing been focused on DSRC at the expense of CV2X, rather than vice-versa.

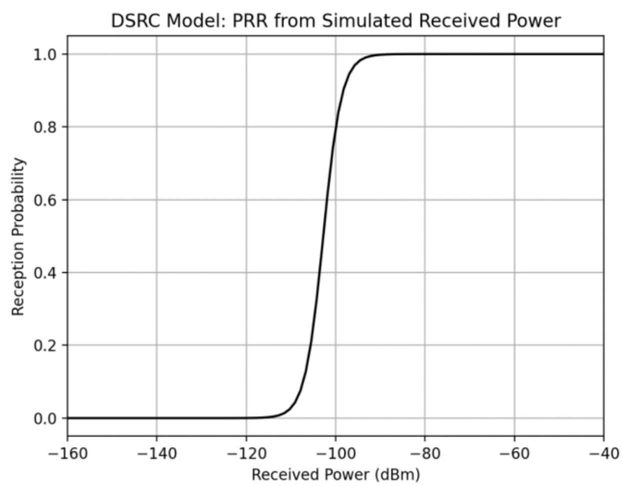

Fig. 28: PRR vs. simulated reception power in dBm, DSRC logistic regression model.

Which is given analytically as:

$$PRR = \frac{1}{1 + e^{-(50.47+0.4911x)}}$$

Where *x* once again refers to the simulated received power given in dBm.

We performed real-world testing at a variety of times and locations, collecting dozens of hours of driving data for both CV2X and DSRC setups. In addition to our interpretation and processing of this data, the data itself is also available for additional analysis and can be used to further consider the differences between CV2X and DSRC that our own analysis has shown.

Over the course of this project we drastically increased our understanding of the effects of occluding obstacles on wireless communication for both CV2X and DSRC radio networks. We learned important lessons about proper testing procedures including the importance of selecting a range of testing transmit powers to ensure a test is available which has a good mix of received and lost packets, the requirement to consider attenuation's effect on signal to noise ratio vs. only considering the effect on signal power, and more.

Finally, we were able to successfully show a concrete difference in packet reception probability for similar power levels and SNR for CV2X and DSRC and determined that all else being equal, CV2X offers improved performance in the NLOS tests we performed and can be recommended. The difference of about 10 dB in reception cutoff power is reflected in other testing such as the 5GAA's V2X functional and performance test report.

Intellectual Property

While not covered in any real detail here, we began development on a novel simulation algorithm which uses stochastic ray-tracing to simulate electromagnetic field power over an entire 3D volume in a single pass, which is much more efficient than existing methods which simulate only a single plane of power and do so by iterating slowly over every point on the plane. Our method [4] builds on existing techniques in computer rendering and reapplies them to the problem of spatial field simulation. An invention disclosure has been filed with the University of Michigan Technology Transfer Office pertaining to this stochastic ray-tracing method we developed [5].

Community Engagement

Our work was published in, and presented at, the 2020 Antenna Measurement Techniques Association (AMTA) 2020 conference. This publication and our presentation of it were part of the Automotive Radar, Sensors, and Applications session of the conference which included participants from the Automotive, Aerospace, and Test and Measurement communities. An extended version of this work is currently being developed for publication in the IEEE Transactions on Instrumentation & Measurement Special Section.

The results of this project have also been presented in October 2019, March 2020 and February 2021 to the Connected Environment Working Group, consisting of representatives from Honda*, MDOT, State Farm*, Aptiv*, Verizon, Econolite, WSP*, GM*, Toyota*, Denso*, the City of Ann Arbor, Mcity*, the University of Michigan College of Engineering, UMTRI*, and the Ford Motor Company*. Groups which had members in attendance during one or more of those presentations are marked with a *. These presentations impact the decisions that they will make regarding the implementation of DSRC/CV2X.

Project personnel have been working very closely with project partner personnel at the Ford Motor Company since the beginning of the project. This working relationship included bi-weekly meetings and a joint publication, and fostered opportunities for bidirectional learning between us as we presented our latest findings and responded to and posed questions regarding the testing data, simulation parameters, physical expectations, and where to take our work next.

The Principal Investigator for our project, Dr. Sridhar Lakshmanan, was the inaugural presenter at the CCAT Research Review on September 6^{th}, 2019, where 28 attendees from various industries, positions in government, and academic institutions attended. Our review offered important information and perspectives on the topics of our research to parties interested in the field, and gave a fuller picture of the state of these technologies to individuals who are in positions to advocate for public and industrial policies or may be in the future.

Work performed for this project and adjacent efforts by funded personnel was featured in scientific media reports twice, including discussions of vehicle autonomy and what to expect in the near future, fuel efficient highway platooning of transport vehicles, safety and confidence in inter-vehicle communication, and more. These stories help to offer very public accounts of the state of both our own research as well as the collective experience and understanding present in the field.

A full account of all tabulated information concerning the selected performance indicators has been included in the Appendix.

References

[1] C. Adam et al., (2021) "Performance of DSRC V2V communication networks in an autonomous semi-truck platoon application" to appear 2021 SAE World Congress, Detroit MI, USA.

[2] T. Kleinow et al., (2020) "A Validated Model for Non-Line-of-Sight V2X Communications" 2020 Antenna Measurement Techniques Association Symposium (AMTA), Newport, RI, USA, pp. 1-6.

[3] 5G Automotive Association, (2019) "V2X functional and performance test report - test procedures and results"

[4] T. Kleinow, (2020) "Simulating RF Field Propagation with Stochastic Ray Tracing", Master's Thesis, Department of Electrical and Computer Engineering, University of Michigan-Dearborn.

[5] T. Kleinow et al., (2020) "A System for the Simulation of EM Field Propagation via Stochastic Ray Tracing" OTT # 2021-031, University of Michigan Technology Transfer Office, August 2020.

Appendix

Synopsis of key performance indicators.

Part I: UTC Program-Wide Performance Indicators Project Name: Reliable V2V Communication Networks		
OSTR Goals		
METRIC	**Research Performance Measures**	**Project Total**
1. Number of transportation-related courses offered during the reporting period that were taught by faculty and/or teaching assistants who are associated with the UTC.	Undergraduate courses	3
	Graduate courses	2
2. Number of students participating in transportation research projects during the reporting period funded by this grant.	Undergraduate students in research	2
	Graduate students in research	3
3. Number of transportation-related advanced degree programs that utilize grant funds during the reporting period to support graduate students.	Masters level programs	2
	Doctoral level programs.	1
4. Number of students supported by this grant during the reporting period.	Undergraduate degrees	2
	Masters degrees	2
	Doctoral degrees	
5. Number of students supported by this grant who received degrees during the reporting period.	Undergraduate degrees	1
	Masters degrees	1
	Doctoral degrees	
6. Number and total dollar value of research projects selected for funding during the reporting period using UTC grant funds (Federal and/or Recipient Share) that you consider to be applied research and advanced research.	Number of applied research projects	2
	Dollar value of applied research projects	$732,237
	Number of advanced research projects	
	Dollar value of advanced research projects	

Part II: CCAT UTC Specific Performance Indicators
Project Name: Reliable V2V Communication Networks

Technology Transfer Goals

1. **OUTPUTS**	**Research Performance Measures**	**Project Total**
1.A. Disseminate research results through publications, conference papers, and policy papers	Technical reports	1
	Papers at conferences, symposia, workshops, and meetings	1
	Peer-reviewed journal articles *to be submitted	1*
1.B. Develop inventions, new methodologies, or products	Annual number of research deployments	1
1.C. Research projects funded by sources other than UTC and matching fund sources	Number of projects	2
	Dollar amount of projects	$732,237
2. **OUTCOMES**	**Research Performance Measures**	**Project Total**
2.A. Incorporate new technologies, techniques or practices	Number of technology transfer activities that offer implementation or deployment guidance	1
2.B. Improve the processes, technologies, techniques in addressing transportation issues	Number of research deliverables disseminated from each research project	2
3. **IMPACTS**	**Research Performance Measures**	**Project Total**
3.A. Increase the body of knowledge and safety of the transportation system	Number of instances of technology adoption or commercialization	1
	Number of conferences organized by the CCAT consortium members	1
3.B. Improve the operation and safety of the transportation system	Number of instances of research changing behavior, practices, decision making, policies (including regulatory policies), or social actions	1

Leadership Development Goals

1. **OUTPUTS**	**Research Performance Measures**	**Project Total**
1.A Keynote speeches or invited speaker presentations	Number of media engagements	
	Number of academic engagements	4
	Number of industry engagements	4
2. **OUTCOMES**	**Research Performance Measures**	**Project Total**
2.A Leadership positions held	Regional organizations	
	National organizations	
	International organizations	1
2.B CCAT affiliated students holding leadership positions	Number of students	

Education and Workforce Development Goals

1. **OUTPUTS**	**Research Performance Measures**	**Project Total**
1.A Number of Workforce Online learning modules created and developed toward the certification of completion training for the emerging CAT field technician	Number of learning modules	

1.B Development of Articulation agreements for C++ software programs and Applied Data Science program with partner institutions	Number of Articulation/Transfer Programs	
1.C Development of an active WCC Pre-Engineering Program in STEM disciplines leading to an AAS degree	Number of students completed Associates Degree for Pre-Engineering Science Transfer	
	Number of students completed Associates Degree for Engineering Technologist-Manufacturing Degree	
1.D Number of curriculum development and professional development activities for instructors in related CAT technologies	Number of Professional Dev. Activities in IT [CAT]	
	Number of participants	
1.E Number of K-12 Career pathways activities related to CAT career fields.	Number of K-12 Activities in CAT Career Areas	
	Number of participants	
Outreach Goals		
1. **OUTPUTS**	**Research Performance Measures**	**Project Total**
1.A Media stories referencing CCAT, CCAT research or other activities	Number of media stories	2
	Number of agencies participating in CCAT events	10
	Number of agencies committed to CCAT projects	
	Number of individuals from external agencies attending CCAT events	28
1. B Newsletters, press releases, and website	Number of newsletters	1
	Number of press releases	
	Number of website hits	1204
2. **OUTCOMES**	**Research Performance Measures**	**Project Total**
2.A Research Champions	Industry principals	1
	Number of industries represented	1
	Government principals	
	Number of government agencies represented	
Collaboration Goals		
1. **OUTPUTS**	**Research Performance Measures**	**Project Total**
1. A Collaboration with other agencies	Number of agencies providing matching funds	1
	Number of agencies participating in CCAT events	
	Number of agencies committed to CCAT projects	
	Number of individuals from external agencies attending CCAT events	
1. B Collaboration with other organizations	Number of organizations providing matching funds	2
	Number of organizations participating in CCAT events	2
	Number of organizations committed to CCAT Projects	2
	Number of individuals from external organizations attending CCAT events	4