



U.S. Department
of Transportation
**National Highway
Traffic Safety
Administration**



DOT HS 813 826

October 2026

Radar Congestion Testing And Simulation of a Forward Collision Warning System

This page is intentionally left blank.

DISCLAIMER

This publication is distributed by the U.S. Department of Transportation, National Highway Traffic Safety Administration, in the interest of information exchange. The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Department of Transportation or the National Highway Traffic Safety Administration. The United States Government assumes no liability for its contents or use thereof. If trade or manufacturers' names or products are mentioned, it is because they are considered essential to the object of the publication and should not be construed as an endorsement. The United States Government does not endorse products or manufacturers.

NOTE: This report is published in the interest of advancing motor vehicle safety research. While the report may provide results from research or tests using specifically identified motor vehicle models, it is not intended to make conclusions about the safety performance or safety compliance of those motor vehicles, and no such conclusions should be drawn.

Suggested APA Format Citation:

Buller, W., Gilbert, M., Wilson, B., Hopkins, R., Garbarino, J., Penhale, M., Hart, B., & LeBlanc, D. (2026, October). *Radar congestion testing and simulation of a forward collision warning system* (Report No. DOT HS 813 826). National Highway Traffic Safety Administration. <https://doi.org/10.21949/6m6b-rq17>

This page is intentionally left blank.

Technical Report Documentation Page

1. Report No. DOT HS 813 826	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Radar Congestion Testing and Simulation of a Forward Collision Warning System		5. Report Date October 2026	
		6. Performing Organization Code NHTSA	
7. Authors William Buller, Mark Gilbert, Brian Wilson, Ryan Hopkins, Joseph Garbarino, Miles Penhale, Benjamin Hart, David LeBlanc		8. Performing Organization Report No.	
9. Performing Organization Name and Address Michigan Tech Research Institute 3600 Green Court, Ann Arbor, MI 48105		10. Work Unit No. (TRAIS)	
		11. Contract or Grant No. DTNH22-14-D-00329L 693JJ918F000226	
12. Sponsoring Agency Name and Address National Highway Traffic Safety Administration 1200 New Jersey Avenue SE Washington, DC 20590		13. Type of Report and Period Covered Final Report Sept. 28, 2020 – Aug. 31, 2021	
		14. Sponsoring Agency Code	
15. Supplementary Notes Digital Object Identifier: https://doi.org/10.21949/6m6b-rq17			
16. Abstract. This project found that radar congestion could affect the behavior of an automotive forward collision warning system. During a choreographed test track evaluation designed to create a dense radar signal environment, some increased variability in the time to collision alerts was observed. The project developed and used tools to observe changes in the detections reported by automotive radars operating in a signal congested environment. The project demonstrated inclusion of measured RF backgrounds into simulation. Measurements were analyzed to produce empirical models of path-loss for automotive radars.			
17. Key Words automotive radar, mutual interference, safety tests, Advanced Driver Assist System, ADAS, forward collision warning, FCW		18. Distribution Statement Document is available to the public from the DOT, BTS, National Transportation Library, Repository & Open Science Access Portal, https://rosap.ntl.bts.gov .	
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No of Pages 89	22. Price

This page is intentionally left blank.

Table of Contents

Executive Summary	1
Empirical Evaluations of RF Interference Impact on Commercially Fielded Systems	2
Empirical RF Path-Loss Models for Automotive Radar.....	4
Updates to M2I2 Simulation of Automotive Radar	5
Findings and Products of Research.....	6
Summary of Results	6
Background and Organization of This Report	9
Empirical Evaluations of RF Interference Impact on Commercially Fielded Systems	11
Purpose.....	11
Approach.....	11
Metrics of Performance.....	11
Pre-Test Radar Waveform Collection.....	12
Scenarios	14
Test Protocols to Establish Metrics of Performance.....	15
Commercial Pre-Collision System Based on Integrated Camera and Radar	15
Commercial Automotive Radars Mounted on Test Vehicle.....	16
Experimental Setup and Test Protocol.....	17
Commercial FCW System	17
Commercial Automotive Radars Mounted on Test Vehicle.....	22
Collected Data.....	26
RF Backgrounds.....	26
Commercial FCW System	27
Commercial Automotive Radars.....	27
Analysis.....	29
Commercial FCW System	29
Commercial Automotive Radars.....	34
Empirical RF Path-Loss Models for Automotive Radar.....	41
Purpose.....	41
Approach.....	41
Experimental Setup	43
Collected Data.....	47
Analysis.....	49
Comparison to Two-Ray Model	51
Adjusted Path-Loss Exponent.....	52
Generalized Extreme Value Fit.....	52
Results and Discussion	54

Simulation of Automotive Radars With Interference	59
Purpose.....	59
Approach.....	59
Radar Congestion Study Software	59
Sensor Definition and Placement.....	60
Sensor Detection Modeling.....	61
Parameterized Empirical Path-Loss Models.....	64
Empirical Interference Model for M2I2 Simulation.....	67
Comparison of Radar Data, Measured and Simulated.....	69
Conclusions and Discussion	71
References	75

List of Figures

Figure 1. Comparison of detections reported by a short-range radar without interference, at left, and with interference at right.	3
Figure 2. Comparison of detections reported by a multi-mode long-range and mid-range radar without interference, at left, and with interference at right.....	3
Figure 3. Receiving system measures the power of radio frequency emitted by automotive radar.	4
Figure 4. Comparison of path-loss from measured data with theoretical two-ray model.....	4
Figure 5. Geometry of lead car occluding radar from opposing traffic.	5
Figure 6. Example spectrogram of RF background collected during tests to evaluate the impact of interference on automotive radars.	6
Figure 7. VSA software running on digital oscilloscope allowing researchers to get time-frequency waveform data for radar B.....	12
Figure 8. Spectral occupancy for 5 of the radars used in the radar congestion tests.	13
Figure 9. Radar F, a multi-mode automotive radar, appears as a zig-zag line of power, using 200 MHz of bandwidth.	13
Figure 10. Radar E, an adaptive cruise control radar, appears as a slowly changing line, overlapping in time and frequency with a fast-chirp waveform, Radar F, which appears as a zig-zag line.....	14
Figure 11. Aerial view of Mcity with transmitter and receiver collection geometry, as well as vehicles representative of a rural highway scenario for evaluation of system impact.	16
Figure 12. POV (left) and SV (right), with RTK antennas for measuring range.....	17
Figure 13. Test layout showing SV, POV, interfering vehicles and radars, and wideband receiver.....	18
Figure 14. View of the test area from wideband receiver.....	18
Figure 15. Location of test vehicles, interfering radars, and zone where SV encountered POV.....	20
Figure 16. GPS logging laptop in POV.	21
Figure 17. Radar A (short range) with RTK antenna.....	22
Figure 18. Radar B (mid/long range, lower unit) with RTK antenna.	23
Figure 19. Data acquisition system with RTK receiver and cell modem.	23
Figure 20. DAS monitor/keyboard and radar power switches.....	24
Figure 21. Survey of 10dB corner reflector location.	25
Figure 22. Data visualization software showing FCW alert (panel is intentionally obscured). ...	26
Figure 23. Spectrograms comparing the RF environment without and with interfering radars, left and right, respectively.....	27
Figure 24. SV obstructed camera fault presented in instrument cluster.	31
Figure 25. Time to collision at onset of forward collision warning.....	32
Figure 26. All radar returns from Radar A, All Trials, without interference at left, with interference at right, showing a larger number of returns at wider azimuths with interference present.	34

Figure 27. Radar returns with amplitude > 0 dB from Radar A, All Trials, without interference at left, with interference at right, showing a larger number of returns at wider azimuths with interference present.	35
Figure 28. All radar returns from Radar B, All trials, without interference at left, with interference at right, showing a smaller number of returns with interference present.	35
Figure 29. Detailed view of the area near the corner cube for trials where the interferers were on.	36
Figure 30. Plots of radar derived range versus ground truth (RTK GPS-based) range for Radar A, without interference at left, with interference at right, showing increased variability in range and a larger number of returns for the radar when exposed to interference.	37
Figure 31. Plots of radar derived range versus ground truth (RTK GPS-based) range for B, without interference at left, with interference at right, showing fewer and weaker returns for the radar when exposed to interference.	37
Figure 32. Plots of radar derived range-rate vs. ground truth (RTK GPS-based) range-rate for Radar A, without interference at left, with interference at right, showing increased variability in range-rate values for the radar when exposed to interference.	38
Figure 33. Plots of radar derived range-rate vs. ground truth (RTK GPS-based) range-rate for Radar B, without interference at left, with interference at right, showing fewer and weaker returns from the radar when exposed to interference.	39
Figure 34. Receiving system measures the power of radio frequency emitted by automotive radar.	41
Figure 35. Light traffic scenario shows the transmitting car last in line with eleven other cars separated by approximately 20 m.	42
Figure 36. Heavy traffic scenario shows the transmitting car last in line with eleven other cars separated by approximately 10 m.	43
Figure 37. Straight highway scenario with a single automotive radar transmitting (identified in red).	46
Figure 38. Two lane highway scenario including a tunnel with a single automotive radar transmitting (identified in red).	46
Figure 39. The receive antenna is connected directly to the W-band mixer, and mounted at a height at 50 cm.	47
Figure 40. Multiple Vehicle tracks from empirical path-loss model collections at Mcity.	48
Figure 41. Snippet from the collection notes, which has been scanned and archived with data.	48
Figure 42. Measured values of path-loss is plotted along with free space model.	49
Figure 43. Experiment with transmitting vehicle approaching receiver, straight on, in the four-lane highway scenario.	50
Figure 44. Vehicle approaching receiver in adjacent lane of opposing traffic in four-lane highway scenario with no traffic.	50
Figure 45. Comparison of empirical data and two-ray model for automotive radar approaching receiver, straight on, at left, and in the adjacent lane, at right.	52
Figure 46. Statistical density of values derived from the measured data for the straight highway case with no traffic.	54

Figure 47. Geometry of lead car occluding radar from opposing traffic.	55
Figure 48. Image shows the furthest location where the transmitting antenna is observed above the noise level of the receive antenna for the three traffic conditions in the straight highway scenario.	56
Figure 49. Image shows the location where the transmitting antenna is first observed above the noise level of the receiver antenna is approximately 170 m for the two-lane with tunnel scenario, regardless of traffic density.	56
Figure 50. Simulation processing flow.	60
Figure 51. Overhead view showing radar beam indicating azimuth field of view.	61
Figure 52. Example ROC curve relating SNR and PD given desired PFA.	62
Figure 53. Example of subdividing radar beam to identify point target responses.	62
Figure 54. Curve shows M2I2 estimates plotted through estimates made independently using Monte-Carlo simulations.	64
Figure 55. Calculations of mean interference power as a function of average vehicle spacing (inverse density).	66
Figure 56. Terminal tracks for long-range radar system simulated in M2I2 plotted as a function of cross range and distance without interference.	67
Figure 57. Terminal tracks for long-range radar system simulated in M2I2 plotted as a function of cross range and distance.	67
Figure 58. Plots of the empirical cumulative distribution function made from measurements collected with the scope in a test without interference and with interference.	68
Figure 59. Terminal tracks for long-range radar system simulated in M2I2 plotted as a function of cross range and distance without interference.	69
Figure 60. Terminal tracks for long-range radar system simulated in M2I2 plotted as a function of cross range and distance with interference levels drawn from empirical data.	69
Figure 61. Plots of radar derived range vs. ground truth range for a generic long-range radar, simulated in M2I2, without interference at left, and with interference at right.	70

List of Tables

Table 1. Based on two categories of radar waveforms in test hardware, we hypothesize the following potential impacts, if no mitigation is employed	14
Table 2. The 2014 AEB test matrix from Forkenbrock & Snyder (2015).....	19
Table 3. Commercial FCW system test schedule	22
Table 4. Commercial automotive radar test schedule	25
Table 5. Radar A (short-range) CAN bus channel data description	28
Table 6. Radar B CAN bus channel (mid/long-range) data description	28
Table 7. Radar B Ethernet channels.....	28
Table 8. Commercial FCW system test results	30
Table 9. Effects of interference on TTC and range to POV at FCW onset	33
Table 10. Effects of camera occlusion on TTC and range to POV at FCW onset.....	33
Table 11. Parameters used in data analysis.....	43
Table 12. Delphi ESR technical specifications, from Delphi Automotive Systems	44
Table 13. Technical specifications for Keysight N9020B MXA signal analyzer, 10 Hz to 50 GHz.....	45
Table 14. Parameters to generate statistically realistic path-loss values for six different scenarios (rows in table)	57
Table 15. Radar parameters for example simulation of interference impacts	66
Table 16. Results from 18 sequences (a total of 120 trials) of tests of an FCW system with combinations of camera system support and presence of other radars	73

Acronyms and Abbreviations

ADAS	Advanced Driver Assist System
AEB	automatic emergency braking
CDF	cumulative distribution function
CFAR	constant false alarm rate
Clutter	objects illuminated by radar, which the system needs to ignore
dB	decibels
dBm	decibel milliwatts
dBsm	decibel square meters (log unit of area)
Ego Vehicle	term used for vehicle under test
EIRP	effective isotropic radiated power
ESR	electronically scanning radar
FCW	forward collision warning
FMCW	frequency modulated continuous wave
FOV	field-of-view
GEV	generalized extreme value
Hz	Hertz (cycles per second)
lidar	light detection and ranging
M2I2	Michigan Technological University Mutual Interference Impact simulation
NCAP	New Car Assessment Program
OEM	original equipment manufacturer
PD	probability of detection
PL	path-loss
PFA	probability of false alarm
POI	probability of intercept
POV	principal other vehicle
RCS	radar cross section
RF	radio frequency
ROC	receiver operating characteristic
RTK	real time kinematic
RX	receiver
SINR	signal-to-interference-plus-noise ratio
SNR	signal-to-noise ratio
SV	subject vehicle
TX	transmitter
VUT	vehicle under test

Executive Summary

Radar is commonly used in the automotive industry as a sensor input to enable automatic emergency braking (AEB), as well as crash warning and crash avoidance applications. Development of automated features relies on sensing of the environment surrounding the vehicle. Typical sensors include cameras, lidars, and radars. Compared to lidar and cameras, radar is largely insensitive to environmental conditions like fog, rain, wind, darkness, or bright sun, and is well-suited for tracking the location and relative speed of vehicles and other road users.

However, with the increasing use of radar comes the potential for mutual interference. In large concentration, radars occupying the same frequency band run a risk of mixing signals and interfering with each other's performance. A radar may suffer performance degradation when unexpectedly receiving transmissions of other radars, whether directly or reflected from objects in the environment. Similarly, its transmissions may cause degradation of other radars that are not expecting energy propagating through the environment. The proliferation of Advanced Driver Assist System enabled vehicles with multiple sensors can result in densely concentrated frequency bands which may affect performance of safety critical functions when vehicles cohabit a complex operating environment. It is therefore prudent for the automotive industry and safety evaluation community to understand and predict challenges and possible unintended consequences that arise from the increased deployment of automotive radars throughout the national fleet.

In September 2016 NHTSA began the Radar Congestion Study Project (Buller et al., 2018) with the University of Michigan Transportation Research Institute and its primary subcontractor, the Michigan Tech Research Institute. The study goal explored the potential for interference in a full deployment situation and to understand the effect on the performance of radar-enabled safety systems. The study developed analytic tools based on stochastic models of interference power and the impact on a generic system in simulation. The study models showed that short-range radars, often used for lane-changing and blind-spot detection) could experience interfering power from a forward collision avoidance radar that is nearly five orders of magnitude, or 50 dB, greater than the power reflected from their intended targets. The results of this study are consistent with the MOre Safety for All by Radar Interference Mitigation (MOSARIM) study (Kunert, 2012a), and the estimates of interference by the simulation tool has been shown to align with expected values computed by Monte Carlo simulation (an independent method) (Terbas et al., 2019).

The Radar Congestion Testing Project aimed to advance understanding of mutual interference in automotive radars and develop better tools for automotive radar researchers and safety testing community. The program's statement of objectives focused on developing models of radar interference and its impacts, and execution of test plans for fielded radar systems.

The Radar Congestion Testing Project addressed these objectives through the following research activities.

- Tests, designed and performed to determine the impact of mutual interference on
 - i. Two commercial automotive radars, and
 - ii. The forward collision warning system on a commercial vehicle.

- The collection of measurements and analysis to develop an empirical Radio Frequency path-loss model for automotive radars.
- Updates to Michigan Technological University's Mutual Interference Impact (designated as M2I2) simulation to incorporate empirically derived RF interference for more realistic simulations, and evaluation of results.

Empirical Evaluations of RF Interference Impact on Commercially Fielded Systems

The project developed experimental designs to test the impact of mutual interference on commercially available, long- and short-range automotive radars and vehicles with FCW systems. The resulting tests demonstrate that these tests can be conducted safely, repeatably, and reveal measurable impacts of mutual interference on W-band radar systems. While these approaches may be useful in development of procedures for other radar bands, this project focused specifically on W-band systems due to their prevalence.

In cases with commercial systems, the analysis was done without knowledge of the systems beyond what is published in the specifications. The analysis shows that interference has an observable impact on the outputs of the automotive radars and the performance of FCW systems.

In the evaluation of impacts on commercial automotive radars, tests done without interference and with interference revealed differences in reported detections. In Figure 1 and Figure 2, detections reported by a radar under test are plotted as range on the dependent axis against the ground truth range, measured by real-time kinematic positioning. The points are color indexed on the "detection amplitude" as estimated by the radar in decibels. The detections are from 10 trials, and include all detections within 1 meter transversal, or cross-range, of the test target. The target is a corner reflector with a radar cross section of 10 decibel square meters.

In the presence of interfering radars, the short-range radar, Figure 1, reported a great number of detections near the test target, at ranges beyond those observed without interference, and these reports have amplitudes, which appear to be 10 dB higher than the test target. Many more detections were also observed at short ranges in the tests with interference.

In the presence of interfering radars, the multi-mode mid and long-range radar, Figure 2, shows an overall reduction in the number of detections.

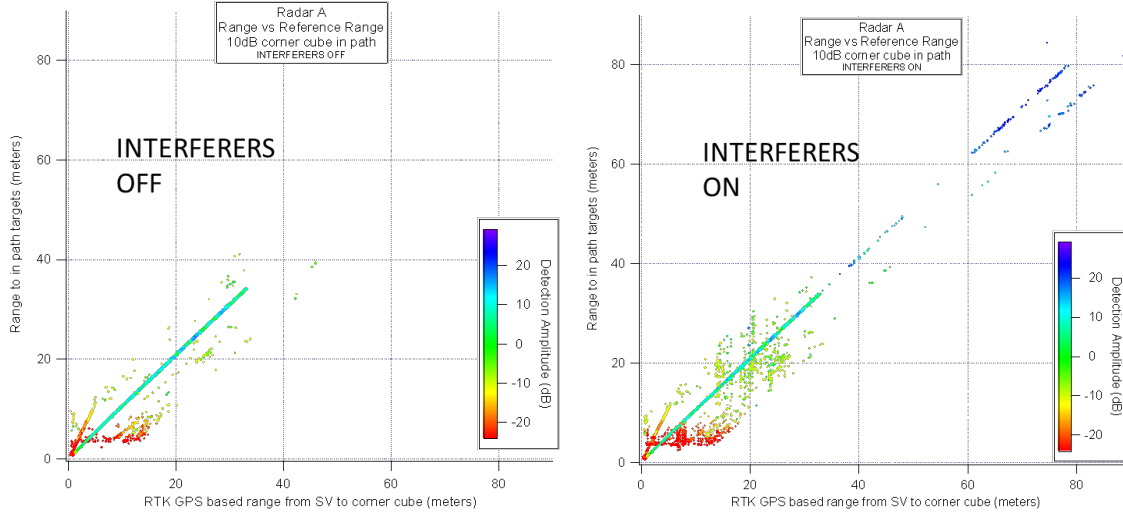


Figure 1. Comparison of detections reported by a short-range radar without interference, at left, and with interference at right.

The plots show radar derived range versus ground truth (RTK GPS-based) range. This radar reports increased variability in range and a larger number of returns for the radar when exposed to interference.

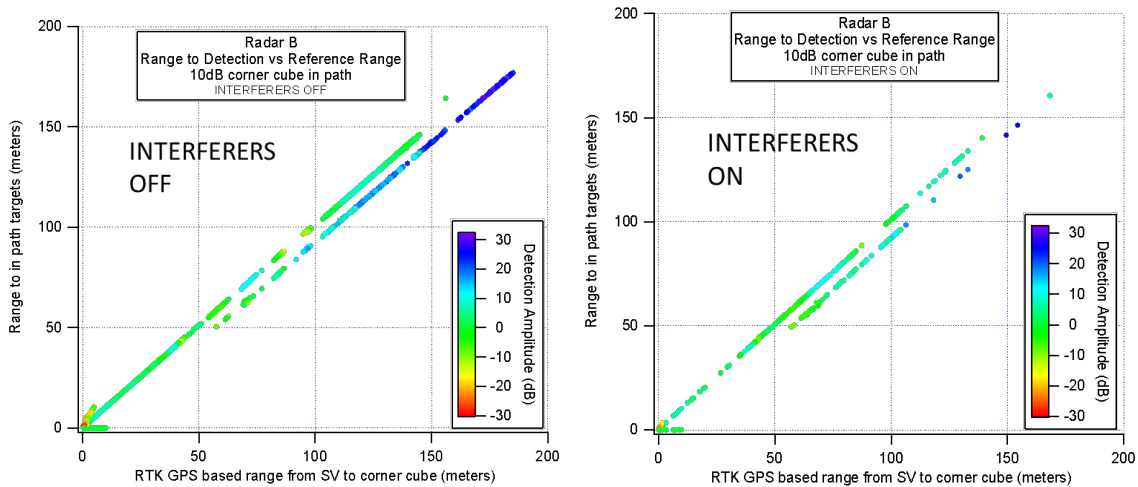


Figure 2. Comparison of detections reported by a multi-mode long-range and mid-range radar without interference, at left, and with interference at right.

The plots show radar derived range versus ground truth (RTK GPS-based) range. This radar reports fewer and weaker returns for the radar when exposed to interference. This is especially evident at ranges above 100 m, and below 40 meters.

Due to the market prevalence of systems that fuse inputs from several sensor modalities, the tests here focused on an example FCW system that has both a camera and radar to support the FCW system.

Empirical RF Path-Loss Models for Automotive Radar

RF path-loss models for automotive radars are produced by fitting parametric equations to measured data in realistic automotive scenarios. These parameters include the path-loss coefficient, to account for non-free-space propagation, and statistical fitting of fluctuations, due to multi-path interference. The method of measurement is conceptually straightforward. A vehicle with a transmitting radar travels over a road in a realistic scenario, and a receiving system measured the received power. This setup is shown in Figure 3.

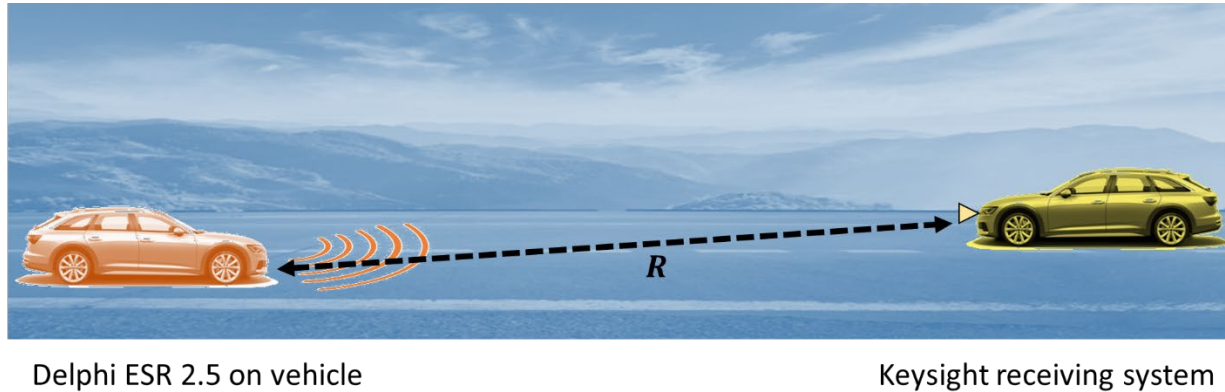


Figure 3. Receiving system measures the power of radio frequency emitted by automotive radar

In the case of no traffic, the empirical data appears to correlate with the prediction of a two-ray propagation model. The measured path-loss and theoretical two-ray model predictions are plotted in Figure 4. The measured path-loss is higher than the two-ray model prediction, in general. Peaks can be seen where destructive interference results in near total loss of signal. This suggests that the two-ray model provides a pessimistic (i.e., greater interference) prediction for interference in this scenario.

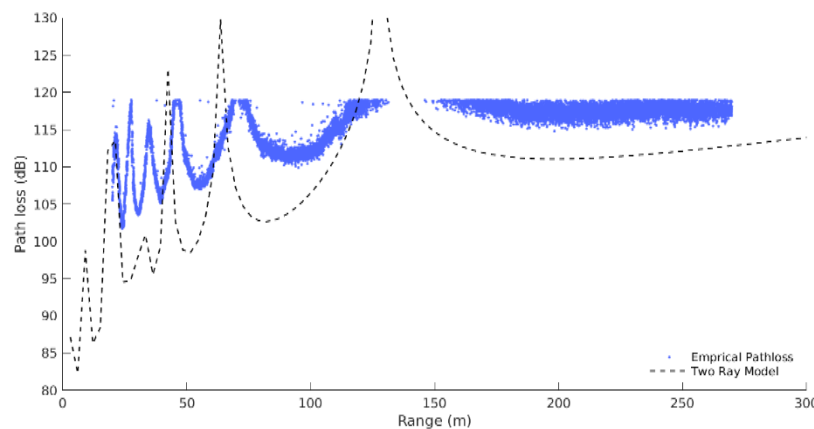


Figure 4. Comparison of path-loss from measured data with theoretical two-ray model

As the spacing between vehicles decreases, the maximum possible line of sight to interfering radars decreases, as shown in Figure 5. The maximum range for line of sight can be estimated by

considering the minimum distance down-range where the interfering radar is obscured. The opposing traffic is in a straight line in the adjacent lane. For example, with lane spacing, R_x , 3.7 m and the vehicle preceding the transmitter at 185 cm wide, $\Delta x = 1.85/2$ m. The maximum distance down-range, R_y , which is not occluded by this angle can be solved as $R_y = (\Delta y / \Delta x) R_x$, where Δy is the spacing between the transmitter and preceding vehicle. Experiments were conducted with Δy set to 20 and 10 m, which correspond to maximum values of R_y of 80 and 40 m.

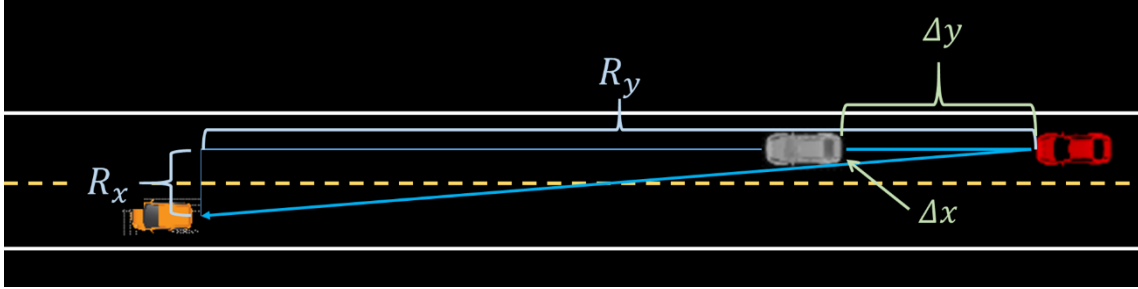


Figure 5. Geometry of lead car occluding radar from opposing traffic

Updates to M2I2 Simulation of Automotive Radar

Armed with empirical models, MTU updated its M2I2 simulation to answer, “How does mutual interference affect the performance of radar based advanced driver-assist systems?” using measured data. Measured RF backgrounds in the 76 to 77 GHz automotive long-range radar band were collected during tests to evaluate the impact of the interference on commercial systems.

The M2I2 simulation was updated to inject empirical RF background measurements as interference to characterize impacts on performance of the vehicle under test. An example plot of the RF background during a track test shows power as a function of time and frequency in Figure 6. The M2I2 simulation retains the ability to generate expected interference levels, following the model developed in the Radar Congestion Study. The importance of this update is that the M2I2 simulation can now operate simulations of radars using RF interference backgrounds similar to those in a test environment and allow comparisons of simulated and empirical test results with similar operating conditions.

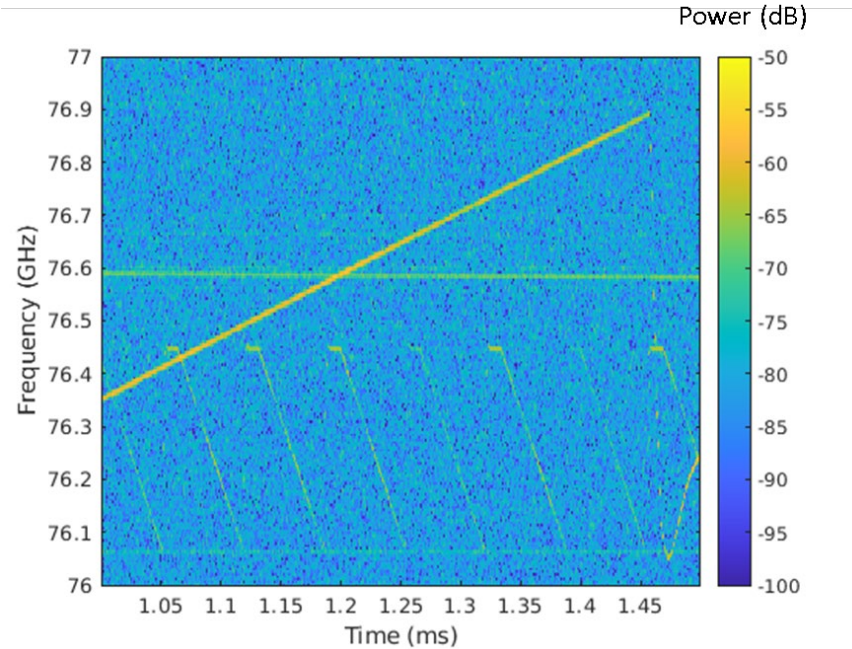


Figure 6. Example spectrogram of RF background collected during tests to evaluate the impact of interference on automotive radars.

Relative power is represented by color. Several radar waveforms are observed: (1) radar emitting a constant frequency tone, the horizontal feature, observed at 76.6 GHz, (2) radar emitting a rising linear frequency chirp, beginning at 76.35 and finishing at 76.9 GHz, and (3) radar emitting several descending linear frequency chirps, covering 76.45-76.05 GHz.

Findings and Products of Research

- Empirical path-loss models that generate interference levels for a set of real scenarios
- M2I2 simulation for comparing simulated sensors with test track experiments
- Experimental designs to test the impact of mutual interference on commercial automotive radars and vehicles with radar-supported ADAS features
- Methods to characterize RF backgrounds during experiments for direct comparison in simulation
- Analysis showing the impact of radar congestion on the tracking and detection output of commercial automotive radars
- Analysis of the impact on performance of a vehicle with a radar-supported FCW system

Summary of Results

The experiments on commercial automotive radars and a radar-supported FCW system show that the impact of RF interference is observable. Designs for experiments were conducted successfully, and the results provide initial measurements of the impact on system performance. Measurements of the RF environment were used to derive parametric models of the propagation

environment and introduce a representation of the RF background into a simulation of an automotive radar.

Several important conclusions result from this research.

- The impact of interference is observable in the detections and tracks of automotive radars. The details of the impact depend on internal functions of the radar, as well as the environment.
- The impact of interference on a vehicle with an FCW system can be observed in realistic tests, which can be conducted safely and reliably.
- The RF environment can be sampled with current network analyzers. This technology provided measurements suitable for modeling the propagation environment and used to replay the recorded interference in simulation.

This page is intentionally left blank.

Background and Organization of This Report

Radar is commonly used in the automotive industry to enable ADAS. For example, blind spot detection systems typically position a radar unit on each side of the vehicle that is aimed rearward to detect vehicles approaching in adjacent lanes. Further, crash avoidance systems may employ radar to detect pedestrians; support slow-speed automatic following (e.g., “traffic-jam assist”); detect vehicles entering intersections from the transverse direction; or as part of a suite of sensors providing input into an automated driving system. Such systems often use multiple radar units tailored (or optimized) to detect vehicles in varying ranges (e.g., short and long-range radar) and in specific orientations relative to the host vehicle.

As the number of radar equipped vehicles on the road increases, and as original equipment manufacturers of vehicles continue to leverage multiple radar units to expand detection capabilities, the possibility arises of interference among radar signals from vehicles within operating range of each other which may have an adverse effect upon the functioning of automotive safety applications. In September 2016 NHTSA began the Radar Congestion Study Project with the University of Michigan Transportation Research Institute and its primary subcontractor, the Michigan Tech Research Institute. The goal of that study was to explore the potential for interference and/or congestion among these radar-based collision avoidance systems in a full deployment situation and to understand the effect upon their performance.

The Radar Congestion Study began to characterize the environment in which automotive radars must operate. The project began with a literature search to provide a basis of the state of knowledge of radar congestion, particularly with respect to automotive radar applications, and covered the following areas:

- general physics of the problem,
- modeling and simulation of congested environments,
- testing of radars in a congested environment, and
- mitigation techniques.

This base of knowledge was further informed by a series of interviews with OEMs and radar suppliers. These interviews explored the industry’s assessment of projected deployment levels for the future, risk of interference, and the technology developments that may mitigate interference.

The Radar Congestion Study used modeling and simulation to focus on two issues:

- How much power does a given radar receive from other transmitters?
- How does this affect the performance of a collision warning system?

The Radar Congestion Study quantified the expected amount of interference power a receiver will see in several different traffic scenarios. It did this by computing the power overlapping in spectrum, time and space, using the parameters of the radar and stochastic equations based on the geometry of the radars in several scenarios of interest. Selection of the scenarios had been informed by questions and feedback during the interview process on challenging radar environments.

The Radar Congestion Study further predicted the impact on radar system performance. This was achieved computationally by taking the computed interference power in each scenario and introducing it as noise into a system simulation. This technique made the explicit assumption that

the interfering radars' waveforms are significantly different from each other. The simulation calculated the signal-to-interference-plus-noise ratio and the reduction in range at which a terminal track is formed for each scenario. The results of the simulation show that automotive radars operating in a congested environment will face significant interference that may affect their performance. The study compared the predicted SINR against mitigation techniques identified in the literature search and interviews and tabulated their effectiveness. Finally, the Radar Congestion Study recommended testing that can further improve the models of interference and evaluate the performance of fielded systems in challenging environments.

Given this background, this study extended examination of the radar congestion problem. The research developed tests to evaluate the impact of interference on commercial automotive radars, as well as the impact on a vehicle that uses automotive radar to inform its FCW system. This research measured RF interference power in realistic scenarios to produce realistic path-loss models for better estimates of interference levels. Measured RF interference levels, recorded during empirical evaluations of hardware, were used as inputs in simulation, to instantiate an approach to inject measured interference into simulation.

The remainder of this report describes the primary tasks in this project, organized into the following sections:

- 1) Evaluations of RF Interference Impact on Commercially Fielded Systems: This section details the methods, analyses and results of experiments with automotive radars, and a commercial vehicle with a manufacturer's FCW systems. The outputs of the commercial automotive radars were recorded and analyzed to show the impacts of interference on reported detections and tracking information. Tests for impact of interference were designed and performed on a commercial vehicle with an FCW system where the issuance of FCWs was recorded and analyses show the statistical impact.
- 2) Empirical RF Path-Loss Models for Automotive Radar: This section covers the measurements and analysis of the power received by an automotive radar from other radars in a set of realistic traffic scenarios. These measurements provide researchers in the field of automotive radar, empirical models for simulation of interference.
- 3) Simulation of Automotive Radars With Interference: The M2I2 simulation was updated to the newest version of Matlab's Automated Driving System toolbox (version 3). Previous versions of the code included stochastic geometric estimates of expected RF interference and was compared to similar estimates derived independently by other researchers. New capability was added using measured RF background data, allowing the tool to simulate radar operation in conditions similar to that experienced by a real subject vehicle.

Empirical Evaluations of RF Interference Impact on Commercially Fielded Systems

Purpose

The empirical evaluation component of the Radar Congestion Testing project developed testing protocols to assess the impact of interference on production radars, and executed those tests on two commercially available radars, as well as a commercial vehicle that featured a radar and camera supported FCW system. This research is exploratory and intended to help identify implementation issues with testing protocols, availability of measurements from commercial systems, complications due to interactions of FCW components, and achieving statistical significance.

Approach

Two types of commercial systems were tested in a realistic, congested radar environment, those being

- commercial automotive radars that report radar detections, radar tracks, and their position and kinematics
- commercial vehicle with an FCW system supported by a radar and a camera

Data was collected from each of these types of systems for analysis with, and without, interference sources in realistic environments to evaluate the impact on performance.

The metrics of evaluation of these types of systems are different. The radars were tested in scenarios without and with interference, and the output detections were compared for analysis. The FCW system is effectively a “black box,” where the only observable output is a visual alert to the driver. In this case, the timing of the alert relative to the kinematics of the SV and principal other vehicle was measured for analysis. It is noted that the impact of interference on both AEB and FCW systems is of interest. However, FCW alerts were chosen for this testing, as it is safer and simpler to execute FCW tests, and the results will have direct relevance to AEB performance.

For evaluations of the automotive radars, as well as the FCW system, data collections were performed in a baseline condition, with interfering radars off, and a treatment condition, with interfering radars on. Measurements of received power were additionally made with the wideband receiver during all tests to characterize the testing environment. Interference impacts were evaluated in scenes where the team previously measured the path-loss of the environment.

Metrics of Performance

Metrics of radar performance using the commercial vehicle with radar-camera based FCW system on the vehicle under test, closing on a lead vehicle:

- Distance to lead vehicle at onset of FCW
- Time to collision with lead vehicle at onset of FCW

Metrics of radar performance using commercial automotive radars on VUT approaching a stationary corner reflector:

- Target amplitude
- Measurement quality
- Distance of initial (accurate) detection
- Distance of first established (accurate) track

Pre-Test Radar Waveform Collection

Automotive radars vary greatly and their contribution to advanced driver assistance system functions depends on factors that are unknown to the research team. These factors include algorithm characteristics, fusion with other sensors such as machine vision systems, fault criteria, communication latencies, etc. What is certain is that the likelihood of mutual interference is a statistical problem, and the research team is attempting to develop protocols that focus on cases which have an elevated concern:

- Radars with overlapping spectrum
- High duty factor

Waveform data from each of the radars in the study was analyzed in the lab at Michigan Tech, Figure 7, to help predict the impact of mutual interference. While not visible, each radar under test was aimed at the wide band receiver antenna at a range of a few meters while the system collected data.

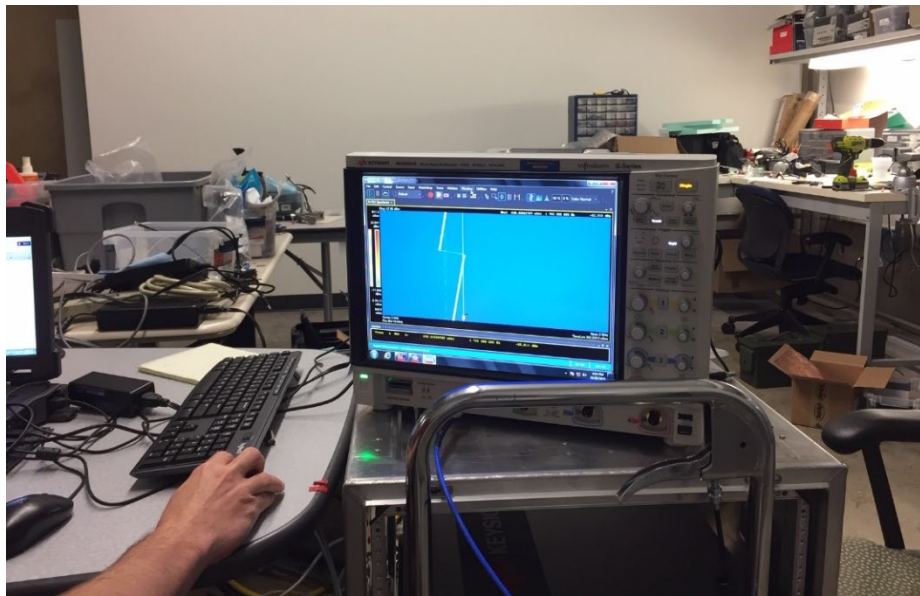


Figure 7. VSA software running on digital oscilloscope allowing researchers to get time-frequency waveform data for radar B

Significant mutual overlap was observed in the spectral occupancy of the radars. These radars are from different manufacturers and are not part of any suite. In Figure 8, the frequency span of five radars in the study are plotted. The spectral range of each of the five units partially overlaps the range of at least one other unit.

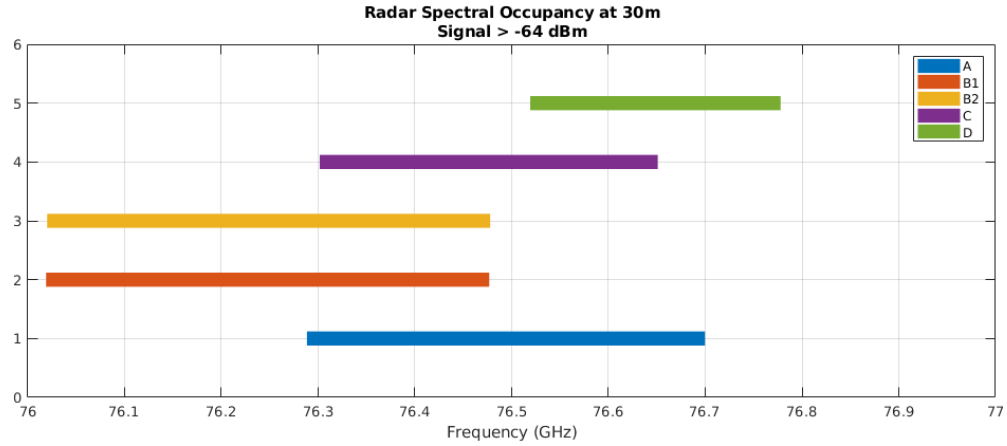


Figure 8. Spectral occupancy for 5 of the radars used in the radar congestion tests

The radars in our study typically transmit one of two waveform categories:

- Slow chirp rate FMCW
- Fast chirp rate FMCW

The first category, slow chirp rate FMCW, is typical of adaptive cruise control radars. The second, fast chirp rate FMCW, is usually found in multi-mode automotive radars. Both types of radars were included in the test setup.

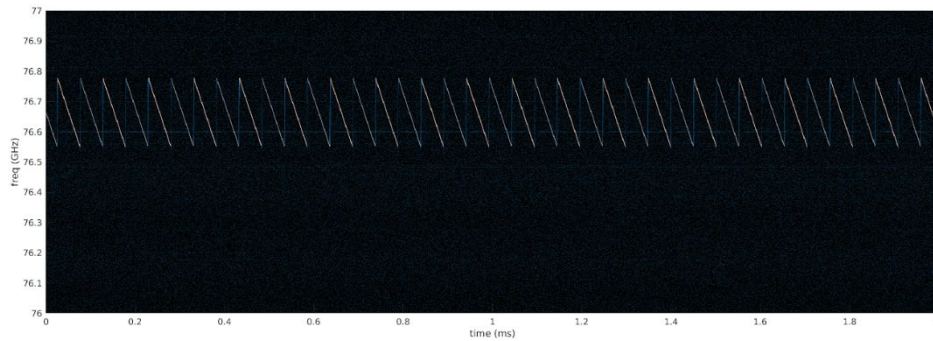


Figure 9. Radar F, a multi-mode automotive radar, appears as a zig-zag line of power, using 200 MHz of bandwidth.

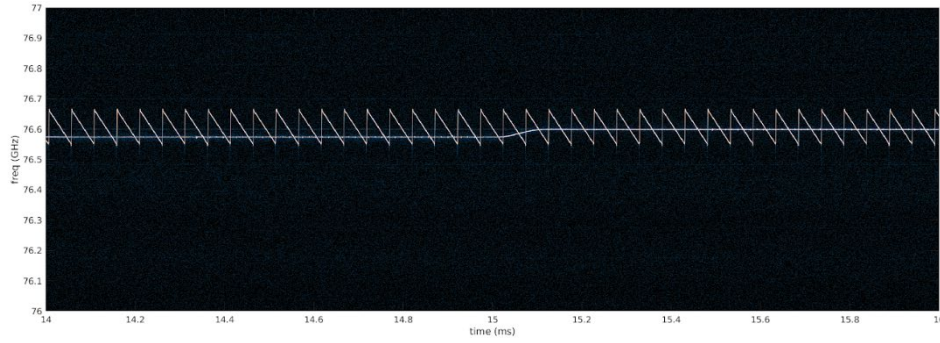


Figure 10. Radar E, an adaptive cruise control radar, appears as a slowly changing line, overlapping in time and frequency with a fast-chirp waveform, Radar F, which appears as a zig-zag line.

In this epoch, Radar F, is using 100 MHz of bandwidth.

Based on the waveforms in the evaluation tests, a summary of expected impacts is tabulated in Table 1. For this discussion, the SV is replaced by the “victim radar.” The victim radars, used in the evaluation of impacts on commercial automotive radars, are fast chirp FMCW radars. The interfering radars are a mixture of slow and fast chirp FMCW waveforms. Therefore, it is reasonable to expect both decreases in sensitivity and false detections in the analysis of the measured data.

Table 1. Based on two categories of radar waveforms in test hardware, we hypothesize the following potential impacts, if no mitigation is employed.

Victim radar	Interfering radars	Potential impacts
Slow chirp FMCW waveform	Slow chirp FMCW waveform	False reports of target distance and speed (lowest probability)
Slow chirp FMCW waveform	Fast chirp FMCW waveform	Decreased sensitivity due to degraded SINR
Fast chirp FMCW waveform	Slow chirp FMCW waveform	Decreased sensitivity due to degraded SINR
Fast chirp FMCW waveform	Fast chirp FMCW waveform	False (ghost) target reports (low probability)

Scenarios

Experiments were executed at the Mcity Test Facility, a proving ground for testing connected and automated vehicles and technologies under controlled and realistic conditions. Mcity sits on a 32-acre site at the University of Michigan, with more than 16 acres of roads and traffic infrastructure. Interference tests were conducted along the highway stretch at Mcity with stationary vehicles in the opposing traffic lane. This setting is representative of a rural highway scene.

Researchers conducted two types of tests for this program:

- Commercial FCW system on VUT using ACC radar with and without forward ranging camera obstructed
 - Test was conducted with the VUT approaching a lead POV with a closing speed sufficient to initiate FCW in cases with no interference
- Commercial multimode radar and short-range radar on VUT
 - Test was conducted with VUT approaching stationary 10 dBsm target

All of the radars in these tests operate in the 76 GHz band.

Test Protocols to Establish Metrics of Performance

Commercial Pre-Collision System Based on Integrated Camera and Radar

Vehicles entered the scenario with a gap, sufficiently large enough that the vehicle under test is expected to not have a track on the lead vehicle at the beginning of the test, and a closing speed that yields a collision-point along the straight away. The test staging was developed empirically, such that the vehicle under test provided a consistent FCW at a repeatable track location in baseline tests with no interference. This ensured the alert was given with plenty of lead time to make the test safe and allow for a long enough window of time that a test driver could initiate a hard brake if no alert was issued in such time that the test driver believed braking was necessary.

The initial gap between the cars was set at approximately 100 m. The lead vehicle was set at a constant speed of 32 km/h (20 mph), the vehicle under test followed it at a constant speed of 72 km/h (45 mph). The closing speed difference was 11 m/s. The total time for each test was on the order of 30 seconds.

Figure 15 shows the location of the test vehicles, interfering radars (both vehicle and post mounted), and the region where the FCW was elicited. All the interfering radars were oriented to point in the direction of the approaching test vehicles – angled towards them just enough that the interfering radar’s line of sight cleared the vehicle ahead of it. While retaining plausibly realistic interfering vehicle positions, this provided a higher level of received power at the SV, increasing the likelihood that any susceptibility to interference would be detected.



Figure 11. Aerial view of Mcity with transmitter and receiver collection geometry, as well as vehicles representative of a rural highway scenario for evaluation of system impact

Tests were conducted both with the camera system unobstructed and with its field of view covered, using black tape. Each test was repeated at least 10 times without and with interference. These tests can demonstrate if the interference has an impact on a complete commercial FCW system; however, the tests cannot identify the causes of the impact on performance and are not expected to yield a statistically significant sampling capable of predicting the likelihood of the impacts on performance.

Commercial Automotive Radars Mounted on Test Vehicle

A second set of tests were designed using a vehicle with commercially available radars, which report low-level data, including target range, range-rate, and amplitude.

The vehicle under test approached a stationary target, a corner reflector, at a constant speed. The vehicle must stop to avoid colliding with the test target.

The tests were conducted for two commercial radars:

- Radar A, a wide field-of-view, short-range radar
- Radar B, a multi-purpose radar with interleaved mid-range and long-range operations

Each test was repeated at least 10 times without and with interference. These tests will demonstrate if the interference has an impact on the quality of the radar observations. These tests are hoped to provide a better understanding of the likelihood of encountering interference.

Experimental Setup and Test Protocol

Commercial FCW System

Two UMTRI-owned vehicles were instrumented – the SV and POV. The POV was equipped with an RTK GPS receiver capable of centimeter level accuracy. Data from the receiver was logged with a laptop. The antenna for the receiver was mounted on the rear of the POV, as shown in Figure 12. The SV was similarly equipped with an RTK receiver but also included a UMTRI data acquisition system which recorded the RTK receiver output synchronized with audio inside the vehicle cabin, forward-looking video, and video from a camera pointed at the instrument cluster. The antenna for the receiver was mounted on the front of the SV, also shown in Figure 12. The two RTK receivers were provided with real-time correction data over a cellular modem from UMTRI's nearby reference base station.

This instrumentation system allowed accurate measurement of range, range-rate, and locations of the two test vehicles relative to the stationary interfering radars. The video and audio collected were used to determine the specific moment at which the vehicle presented an FCW to the driver. Centimeter level accuracy from RTK receivers or a commercial system such as an RT-Range is a requirement for evaluating the impact on interference on both ADAS performance and raw radar outputs.



Figure 12. POV (left) and SV (right), with RTK antennas for measuring range

The wide-band receiver was placed at the rear of a vehicle located adjacent to the test area. The receiver was used to confirm that all transmitting radars were operating (for treatment tests) or not (for baseline tests) before beginning test execution. Collections of the signals received were made during each test. The receiver vehicle can be seen at the right side of Figure 13. The view of the test area from the receiving antenna is shown in Figure 14.



Figure 13. Test layout showing SV, POV, interfering vehicles and radars, and wideband receiver

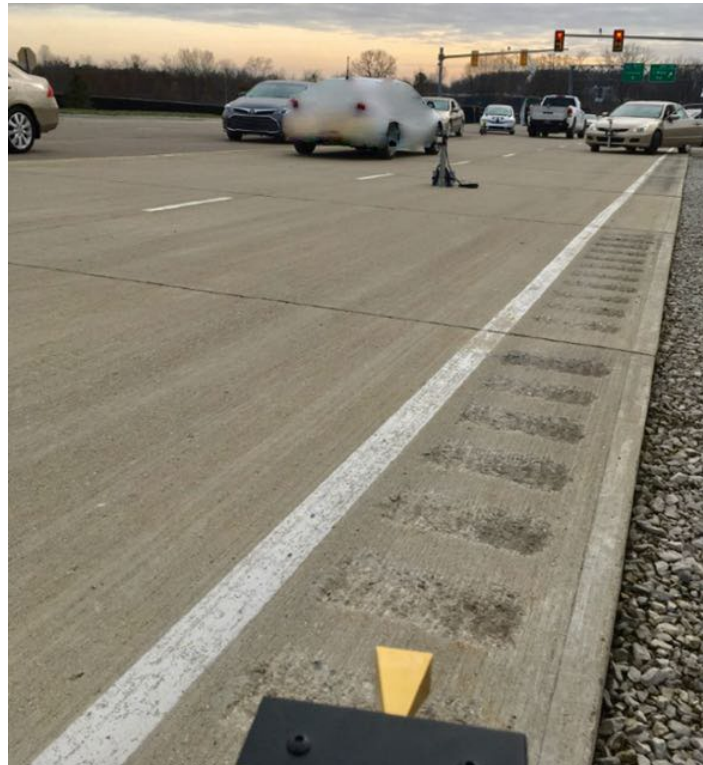


Figure 14. View of the test area from wideband receiver

The experiments were executed at the Mcity Test Facility. Mcity was reserved for December 3, 2019, to conduct a number of trials to determine the scenario most likely to produce repeatable baseline results at the location. The straightaway at Mcity is 300 m long, providing limited distance to conduct such tests. A number of scenarios (stopped POV, deceleration POV, etc.) were evaluated before settling on the NHTSA NCAP conditions (POV at 32km/h, SV approaching at 72 km/h) in place at the time of the testing for the SV encountering a slower POV. The 2014 AEB test matrix from US DOT is shown in Table 2.

Table 2. The 2014 AEB test matrix from Forkenbrock & Snyder (2015)

Maneuver	Test Speeds; mph (km/h)		Initial Headway; ft (m)	Brake Apply Headway (DBS only); ft (m)
	SV	POV		
Stopped Lead Vehicle (LVS_25_0)	25 (40)	0	>187 (>57)	40 (12)
Slower Moving Lead Vehicle LVM_45_20	45 (72)	20 (32)	>183 (>56)	37 (11)
Slower Moving Lead Vehicle LVM_25_10	25 (40)	10 (16)	>34 (>110)	22 (7)

With practice, the drivers of the POV and SV could accelerate and reach stable speeds so that an FCW was issued consistently in the same location on the track. Timing of the SV start was adjusted to move the FCW position to the desired location near the middle of the straightaway. Both vehicles started from a stop at the NE corner of the North Circle. Test driver and data collection system operator in vehicles and at the receiver, used hand-held radios to synchronize vehicle movement and collection start. Figure 15 shows the location where the FCW was elicited (red box). Locations of all interfering radars, test vehicles, and the receiver are also shown in Figure 15. The locations of all interfering radars were surveyed by positioning the RTK antenna of the test vehicle directly over or under each radar. This provided a precise reference location for use during analysis.

The locations of the interfering radars were selected to create an area of high interference in the area where the FCW alert conditions were met and also be representative of dense oncoming traffic. Vehicles were positioned with 6 to 9 m of distance between each other, as they might be during a traffic jam. The intent was to stage a worst case, yet realistic, interference scenario, if all the vehicles in the environment were equipped with at least one transmitting radar.



Figure 15. Location of test vehicles, interfering radars, and zone where SV encountered POV

There were 22 interfering radars in total, all W-band.

- 11 vehicles with integrated long-range radar model D
- 1 vehicle with OEM radar/camera-based system, radar model E
- 1 vehicle OEM radar/camera-based system identical to SV, model C
- 1 long-range radar F, post mounted
- 1 long-range radar F, vehicle mounted
- 2 long-range radar D, post mounted
- 1 mid/long-range radar, model B, post mounted
- 1 short-range radar, Model A, post mounted
- 1 infrastructure radar
- 2 vehicles – test vehicles or SV not used in active test (radars model A, B, or C)

Post-mounted radars were positioned at the manufacturer's preferred height, and oriented to point towards the oncoming vehicle. The infrastructure radar was mounted to a lamp post at the manufacturer's specified height.

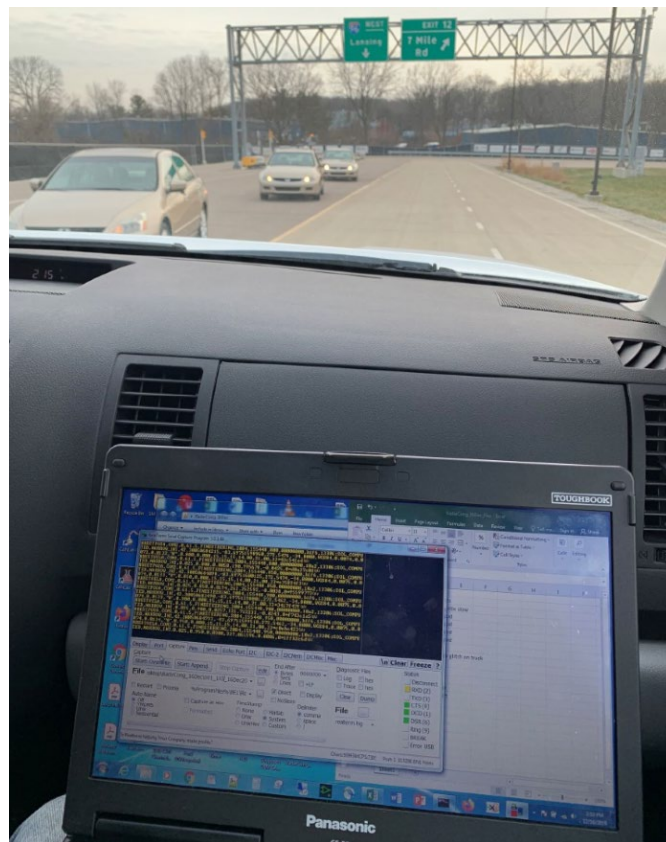


Figure 16. GPS logging laptop in POV

Table 3 shows a timeline of all the data collection trials, which were performed over the course of three full days of track testing. Protocol development trials were executed with a variety of initial and final conditions. Baseline tests were collected once the protocol was finalized and the test drivers were proficient at executing the test. The first round of baseline trials was conducted

on an empty track – no interfering radars or vehicles were present, with the sole exception being the UMTRI collection vehicle with the wideband receiver parked off to the side.

Table 3. Commercial FCW system test schedule

Test Date	Vehicle under evaluation	Other vehicles	Interfering radars	Test	Number of trials
12/3/2019	Production vehicle	None	N/A	Protocol development	36
	Production vehicle	None	N/A	Baseline	24
12/16/2019	Production vehicle	Present	OFF	Baseline	31
	Production vehicle	Present	ON	Treatment	22
12/17/2019	Production vehicle	Present	OFF	Baseline	14
	Production vehicle	Present	ON	Treatment	29

Commercial Automotive Radars Mounted on Test Vehicle

The two radars under evaluation were retrofitted to the front of test vehicles, following the manufacturer's recommended mounting instructions. As with the commercial FCW system testing, vehicles were also equipped with an RTK GPS receiver, with the antenna mounted directly above the radar. The radars' communication interfaces (ethernet and CAN bus) were connected to a DAS mounted in the vehicle, as was the GPS receiver. Images of the two radars mounted to the test vehicles are shown in Figure 17 and Figure 18. The DAS monitor and keyboard, along with the radar power switch, are shown in Figure 19.

The same interfering radars and locations were used for these tests as in the vehicle with FCW testing.



Figure 17. Radar A (short range) with RTK antenna



Figure 18. Radar B (mid/long range, lower unit) with RTK antenna



Figure 19. Data acquisition system with RTK receiver and cell modem



Figure 20. DAS monitor/keyboard and radar power switches

The 10dB corner reflector was positioned in the center of the lane used by the SV, approximately 200 m from the SV's starting location. To avoid spurious reflections, radar absorptive foam obscured the tripod supporting the corner reflector. The corner reflector's location was surveyed with the SV's RTK GPS receiver. This is shown in Figure 21.



Figure 21. Survey of 10dB corner reflector location

Data collection began with the SV at a stop, 200 m north of the corner reflector. The SV then accelerated gently to 40 km/h, maintaining that speed until approximately 35 m from the corner reflector. The SV then decelerated gently, stopping 1 m from the corner reflector. In addition to the data from the SV GPS and radar outputs, the wide-band receiver collected both spectral and time-history data for each trial.

Since the test protocol did not require coordination between two vehicles (as in the commercial FCW system testing), only a limited number of pilot test runs were performed. A timeline of the data collection trials is shown in Table 4.

Table 4. Commercial automotive radar test schedule

Test Date	Test Vehicle	Interfering Vehicle	Interfering Radars	Test	Number of Trials
12/17/2019	Test vehicle with retrofit radar A	Present	OFF	Baseline	10
	Test vehicle with retrofit radar A	Present	ON	Treatment	11
12/18/2019	Test vehicle with retrofit radar A	Present	OFF	Baseline	10
	Test vehicle with retrofit radar A	Present	ON	Treatment	10
	Test vehicle with retrofit radar B	Present	OFF	Baseline	10
	Test vehicle with retrofit radar B	Present	ON	Treatment	10

During the night between the first and second day of testing, about 1 inch of snow fell. Snow was cleared from the roadway between the corner reflector and the SV path, and the previous day's trials repeated in case the presence of the snow impacted results.

At the end of each test day, team members downloaded files from the POV laptop and the SV data acquisition system to UMTRI's servers. These files were parsed and loaded into an SQL database for analysis and review. This review included playback of video, audio, and objective data from the SV using a viewer application shown in Figure 22. This application allowed identification of the exact frame of video, and time of the audio playback where the FCW was issued. These measures were then added to the SQL database for further analysis.

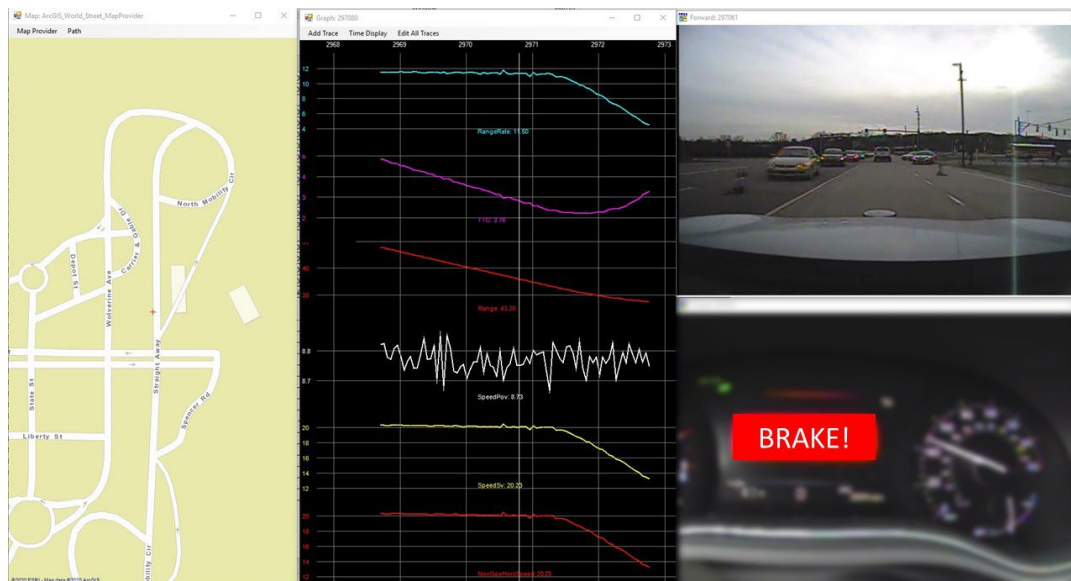


Figure 22. Data visualization software showing FCW alert (panel is intentionally obscured)

Collected Data

RF Backgrounds

The RF backgrounds were collected during the experiments. Spectrograms displaying power as function of time (along the horizontal axis) and frequency (along the vertical axis) are shown in Figure 23.

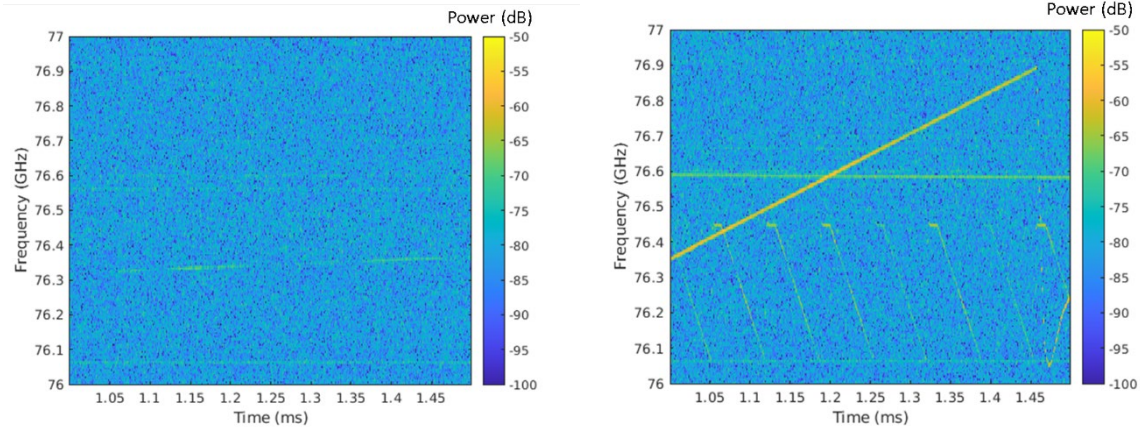


Figure 23. Spectrograms comparing the RF environment without and with interfering radars, left and right, respectively.

In both cases, the ego vehicle radar is on.

Commercial FCW System

The dataset for these collections consisted of

- 20 Hz GPS speed, heading, and position data from both the SV and POV. This included quality metrics, timestamps, and status of correction data.
- Video of instrument cluster at 15 fps. This was used to identify the time the FCW was issued.
- Video of the forward scene.
- Audio from the SV cabin. Not used in analysis, but during data review it provided an additional confirmation that the FCW was issued and captured any comments by the driver or experimenter.

Commercial Automotive Radars

The dataset for these collections included:

- 20 Hz GPS speed, heading, and position data from the SV. This included quality metrics, timestamps, and status of correction data.
- Data from the radar under evaluation. Radar A, the short-range, wide-angle radar, output its data over a CAN bus interface at 20 Hz. Radar B, the long/mid-range radar, also output its target data over a CAN bus interface at 20 Hz, but also output raw detection data over an Ethernet interface. Detailed descriptions of the data channels for each radar is below.
- Video of the forward scene.

Table 5. Radar A (short-range) CAN bus channel data description

Channel Name	Description	Units
Angle	Azimuth of the target	Degrees
Amplitude	Returned power of the target	dBsm
TargetStatus	Whether data was available for this target index	True/False
Range	Distance to the target	meters
RangeRate	Relative velocity of the target	meters/sec
ScanIndex	Counter of radar scans, increments each scan	Count
ValidityLevel	Metric of target quality (0=suspect, 3=high quality)	Enumerated

With the exception of ScanIndex, the radar output each of these channels for all 64 target indexes each scan, whether a target was detected or not. If TargetStatus was false for a target index, all other channels were set to zero by the radar.

Table 6. Radar B CAN bus channel (mid/long-range) data description

Channel Name	Description	Units
Azimuth	Azimuth of the tracked object	Degrees
BridgeObject	Flag if tracked object is a bridge or not	True/False
GroupingChanged	Indicator that number of detections associated with track has changed	True/False
LateralRate	Lateral velocity of the tracked object	meters/sec
Oncoming	Flag if tracked object is oncoming or not	True/False
Range	Distance to tracked object	meters
RangeAcceleration	Relative acceleration of tracked object	meters/sec
RangeMode	Indicates whether mid or long range mode updated the fused track	Enumerated
RangeRate	Relative velocity of tracked object	meters/sec/sec
TargetStatus	Measurement status - new, updated, coasted, etc.	True/False
Width	Width of tracked object	meters

The radar provided output for each of these channels for all 64 target indexes each scan, whether a target was detected or not. If TargetStatus was “NoTarget” for a target index, all other channels were set to zero by the radar.

Table 7. Radar B Ethernet channels

Channel Name	Description	Units
Amplitude	Detection amplitude	dB
Azimuth	Radial angle of the target	Degrees
Range	Distance to tracked object	meters
RangeRate	Relative velocity of tracked object	meters/sec/sec
ScanType	Whether this packet contains data from a mid or long range scan	Enumerated
NumTargets	Number of targets reported in packet	count

With the exception of ScanType and NumTargets, the radar provided output for each of these channels for all 64 target indexes each scan, whether a target was detected or not. Where no detection was made for a target, all channels were set to zero.

Analysis

Commercial FCW System

At the end of each test day, team members downloaded files from the POV laptop and the SV data acquisition system to UMTRI's servers. These files were parsed and loaded into an SQL database for analysis and review. This review included playback of video, audio, and objective data from the SV using a viewer application. This application allowed identification of the exact frame of video, and time of the audio playback when the FCW was issued. These measures were then added to the SQL database.

Data from the SV and POV were both synchronized to GPS time. In SQL this common timestamp was used to generate a table of relative measures based on those GPS data, such as TTC, range and range-rate. Those GPS based relative kinematic measures were then joined to the table of FCW timing data for the analysis which follows.

The experimental results of the commercial FCW system were made more difficult to interpret due to an unexpected issue during the second day of testing which could not be otherwise replicated in the time available. As noted in the Experimental Setup and Test Protocol section, the first testing day was spent performing baseline trials with no interferers present on the track, and the system's camera both unobstructed and obstructed. Those trials were performed without incident, and FCW alerts were elicited on all trials, whether the system's camera was obstructed or not. Note that the system did not present a camera obstruction fault until after 6 trials had been executed with the camera obstructed. At that time, the team concluded that while the camera could supplement the radar's data in generating an FCW, the camera was not essential, even after the system had identified the obstruction. The test sequences and results for all three FCW testing days are shown in Table 8.

The tests appear in chronological order. On Day 1, tests began with the camera unobstructed, and 11 trials were collected. In all cases where the camera was obstructed, there was a delay before the system presented a fault to the driver. The next set of tests were done with the camera obstructed. The six trials were collected without a report of a fault by the vehicle, as identified by the fault status in the second row as "none." Row 3 of the table shows that the vehicle had detected the camera was obstructed, identified by the fault status "Active," and the team collected seven more trials. At no point during tests did the vehicle issue any faults about the status of the radar.

Table 8. Commercial FCW system test results

Test day	Test conditions		# Trials	Result	Fault status	TTC in Seconds (at FCW onset if occurred, at min TTC if not)		
	Camera	Interferers				Min	Mean	Max
Day 1	unobstructed	No interferers	11	FCW elicited	none	2.74	2.88	3.02
Day 1	OBSTRUCTED	No interferers	6	FCW elicited	none	2.82	2.93	3.1
Day 1	OBSTRUCTED	No interferers	7	FCW elicited	Active	2.83	2.99	3.32
Day 2	unobstructed	Interferers OFF	15	FCW elicited	none	2.43	2.87	3.07
Day 2	unobstructed	Interferers ON	12	FCW elicited	none	2.62	2.85	3.11
Day 2	OBSTRUCTED	Interferers ON	10	no FCW	none	0.94	1.31	1.87
Day 2	OBSTRUCTED	Interferers OFF	1	no FCW	none	0.98	0.98	0.98
Day 2	OBSTRUCTED	Interferers OFF	11	no FCW	Active	1.04	1.27	1.53
Day 2	unobstructed	Interferers OFF	2	FCW elicited	none	2.94	2.99	3.04
Day 2	OBSTRUCTED	Interferers OFF	2	no FCW	none	1.08	1.22	1.36
Ignition was only turned off at end the second day's testing								
Day 3	unobstructed	Interferers OFF	3	FCW elicited	none	2.85	2.91	2.97
Day 3	OBSTRUCTED	Interferers OFF	8	FCW elicited	none	2.89	2.97	3.07
Day 3	OBSTRUCTED	Interferers ON	14	FCW elicited	Active	2.08	2.81	3.09
Day 3	unobstructed	Interferers ON	13	FCW elicited	none	2.23	2.91	3.11
Day 3	OBSTRUCTED	Interferers ON	5	FCW elicited	none	2.75	2.89	2.97

Note: The rows of the table are ordered chronologically.

During the second day of testing, interfering vehicles and post mounted radars were staged on the track. For the first set of trials the interfering radars were all left turned off. On the second set of trials, the interfering radars were turned on. While a final calculation of TTC was not available during testing, the drivers did not note any subjective difference in FCW timing after the radars were turned on. Their perceptions were supported by the TTC values determined during post-processing.

The third set of trials the interfering radars were left on, and the system's camera was obstructed using black tape. For all subsequent trials in this set, no FCW alerts were elicited. Test drivers held off braking until the last possible moment, reaching TTC values of between 1 and 2 seconds before braking onset. The team's assumption at this point was that the system would not function with both an obstructed camera AND a radar subject to interference. After 10 trials without an FCW, it was clear that this was not a statistical outlier.

Next the interfering radars were turned off. No FCW was elicited on the subsequent trial. Eleven additional trials were conducted with the same conditions (radars off, camera obstructed), but with a camera obstruction fault active – and the same result, no FCW. Because the effect on FCW was the same regardless of whether the interfering radars were active, it may be attributable to the test protocol obstructing the camera in a way that is not electrically detectable, thereby potentially affecting sensor fusion performance.

At this point the tape covering the camera was removed, and the interfering radars powered off. Two trials were executed with an FCW elicited on both trials – and the fault cleared with no other action taken.

The camera was obstructed again, the interfering radars left off, and two more trials executed. Again, no FCW occurred, and the driver braked at the last moment to avoid collision.

The car was finally powered off – the ignition had not been cycled at any point once testing was begun on the second day. Since no fault was observed, other than the camera obstruction fault,

the team speculates that the system had responded to the RF interference from other radars in the environment and suppressed any FCW alerts where the camera was obstructed. Without OEM support or documentation, it is difficult to know exactly what happened. It is clear, however, that the system did not present an alert in 24 trials where one was expected, and on 13 of those trials, there was no indication to the driver that the system was disabled or operating at reduced performance.

Note that across all trials where an FCW did not occur, the drivers held off until a TTC of no more than 1.87 seconds was reached – which is less than the lowest TTC value observed at FCW onset for any of the trials where an FCW was elicited.

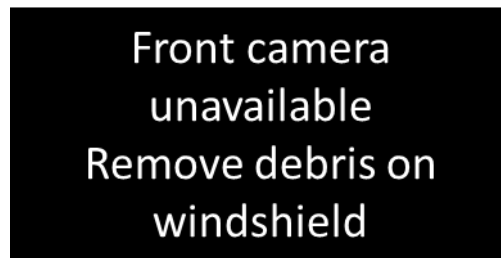


Figure 24. SV obstructed camera fault presented in instrument cluster

On the third day of testing of the FCW system, the team attempted to replicate the issue observed on the previous day. Trials were executed with all combinations of camera obstructed/unobstructed and interferers on/off. An FCW was elicited in all trials, including a total of 19 trials with both the camera obstructed and the interfering radars on. Fourteen of those trials had an active “obstructed camera” fault, and five did not.

Figure 33 shows the distribution of TTC values at FCW onset, by test conditions, for all those trials where an FCW was elicited.



Figure 25. Time to collision at onset of forward collision warning

Statistical analyses were performed to assess the impact of radar interference on the TTC and range between the SV and POV at FCW onset. $P=.05$ was used for all tests. These analyses included all of the trials where an FCW was elicited. Test results are presented in Table 14.

- Two-sample t tests for comparison of means showed no statistically significant effect of radar interferers on either TTC or range.
- A two-sample F test did show a statistically significant effect of radar interferers on variance of TTC. There was no statistically significant effect of radar interferers on range.

Similar analyses of the TTC and range between the SV and POV at FCW onset were also conducted for the effect of camera obstruction. $P=.05$ was used for all tests. Test results are presented in Table 15.

- No statistically significant effects of camera obstruction were observed on the mean or variance for either TTC or range.

Table 9. Effects of interference on TTC and range to POV at FCW onset

Interferer Effect					
TTC (Seconds)		N	Mean	SD	Variance
	Interferers Off	54	2.90751	0.14785	0.02186
	Interferers On	40	2.86717	0.20816	0.04333
At the 0.05 level, the two population means ARE NOT significantly different					
At the 0.05 level, the two population variances ARE significantly different					
Range (Meters)		N	Mean	SD	Variance
	Interferers Off	54	31.35961	2.54983	6.50162
	Interferers On	40	31.91308	2.52514	6.37636
At the 0.05 level, the two population means ARE NOT significantly different					
At the 0.05 level, the two population variances ARE NOT significantly different					

Table 10. Effects of camera occlusion on TTC and range to POV at FCW onset

Camera Effect					
TTC (Seconds)		N	Mean	SD	Variance
	Camera Uncovered	55	2.88324	0.15955	0.02546
	Camera Covered	39	2.90036	0.19898	0.03959
At the 0.05 level, the two population means ARE NOT significantly different					
At the 0.05 level, the two population variances ARE NOT significantly different					
Range (Meters)		N	Mean	SD	Variance
	Camera Uncovered	55	31.32641	2.54869	6.49582
	Camera Covered	39	31.9741	2.51289	6.31463
At the 0.05 level, the two population means ARE NOT significantly different					
At the 0.05 level, the two population variances ARE NOT significantly different					

Commercial Automotive Radars

Secondary measures for the commercial radar analysis were derived in a similar manner to the FCW measures, except the surveyed location of the corner reflector was used instead of the dynamic location of a POV. Raw data from the radar logs was processed with the GPS positioning data to generate target returns in geographical coordinates, as well as in vehicle coordinates.

The radar returns from Radar A, from 40 trials (20 with interferers off, 20 with interferers on) are overlaid on an aerial view of Mcity in Figure 26. These plots are an aggregate of all returns, logged from locations starting at the top of the image and including all locations the vehicle passed through before stopping approximately 1 meter from the corner cube. The radar returns are notably denser and cover a broader area in the plot with interferers on than in the plot with interferers off. This is more visible in Figure 27, where only returns with an amplitude of greater than 0 dB are included.

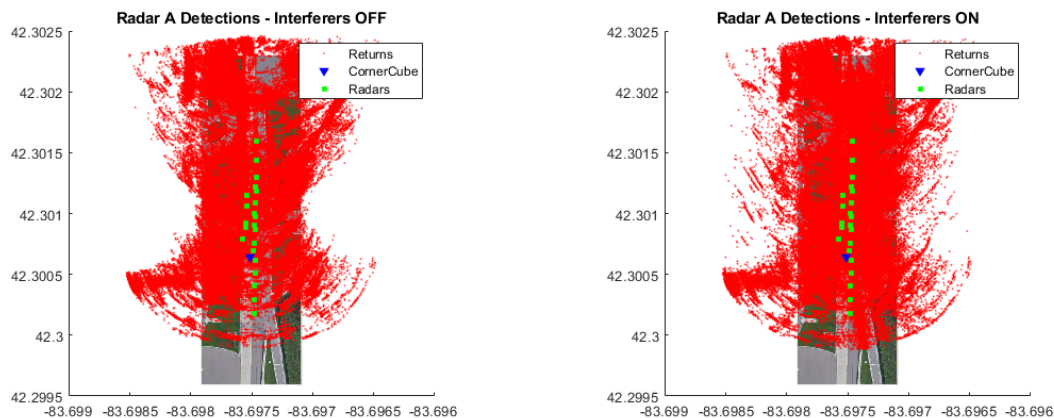


Figure 26. All radar returns from Radar A, All Trials, without interference at left, with interference at right, showing a larger number of returns at wider azimuths with interference present

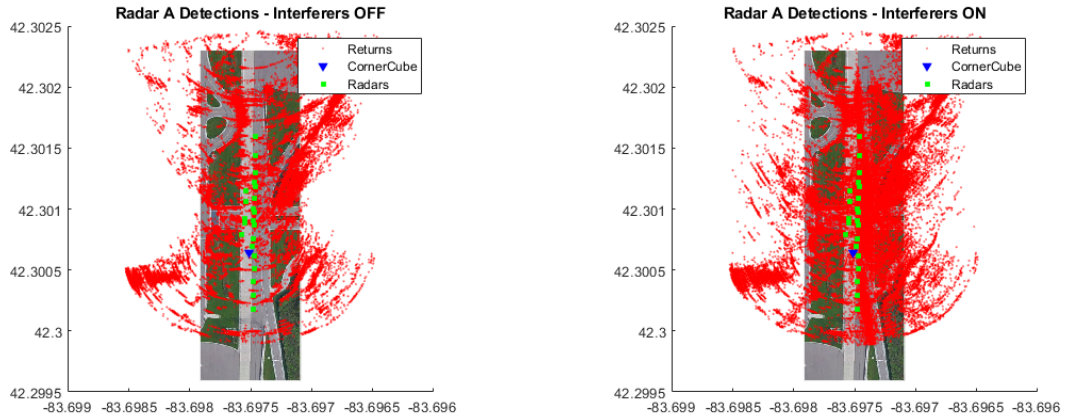


Figure 27. Radar returns with amplitude > 0 dB from Radar A, All Trials, without interference at left, with interference at right, showing a larger number of returns at wider azimuths with interference present

Similar plots for Radar B returns are shown in Figure 28. However, in this case, the plot for trials with interferers on shows fewer returns over a smaller area. Figure 29 provides a detailed view of the area near the corner cube for trials where the interferers were on. Clusters of returns are clearly visible at the locations of radar equipped interfering vehicles, lamp posts, overhead signs, and the corner cube.

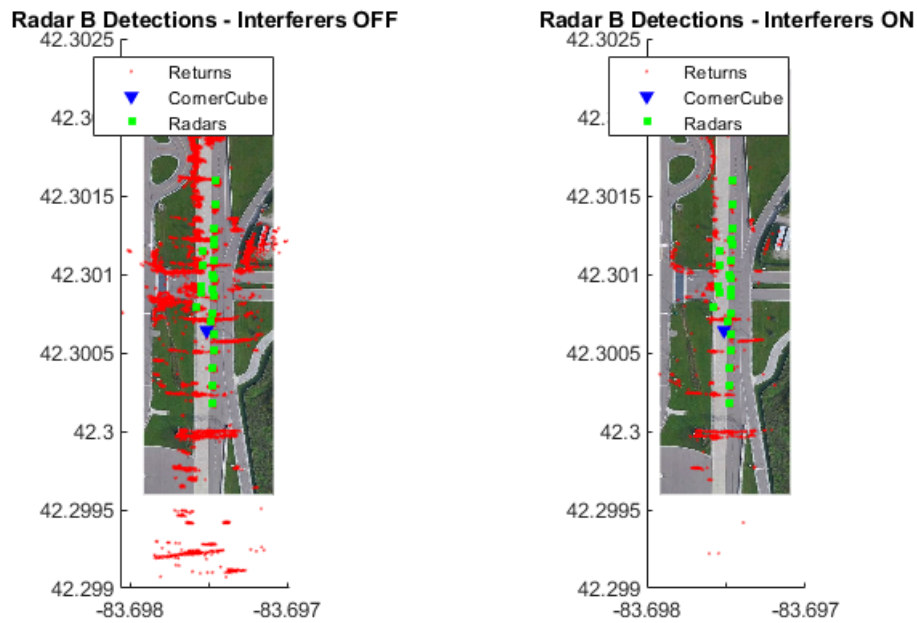


Figure 28. All radar returns from Radar B, All trials, without interference at left, with interference at right, showing a smaller number of returns with interference present

Radar B Detections - Interferers ON



Figure 29. Detailed view of the area near the corner cube for trials where the interferers were on.

Note alignment of returns with interfering vehicles, lamp posts, and overhead signage.

Given the “black box” nature of the radars under test, it is not possible to determine the cause for the differences in the radar returns.

Figure 30 shows the range reported by the RTK GPS versus the range reported by Radar A. Each plot aggregates data from 20 trials, either with or without interferers on. Every point plotted represents a detection reported by the radar which met the following criteria.

- Lateral position was within 1 meter of the corner cube
- Range was within 10 m of the corner cube

These constraints were intended to eliminate out of path targets. The amplitude of each detection as reported by the radar was used to color the plotted points. Note that the corner cube, while not calibrated, was sized to provide a 10 dBm RCS. If the radar were to perform in an ideal manner, and only the corner cube was represented in the returns, the plot would show a line with a slope of 1 extending to the limit of the radar’s usable range.

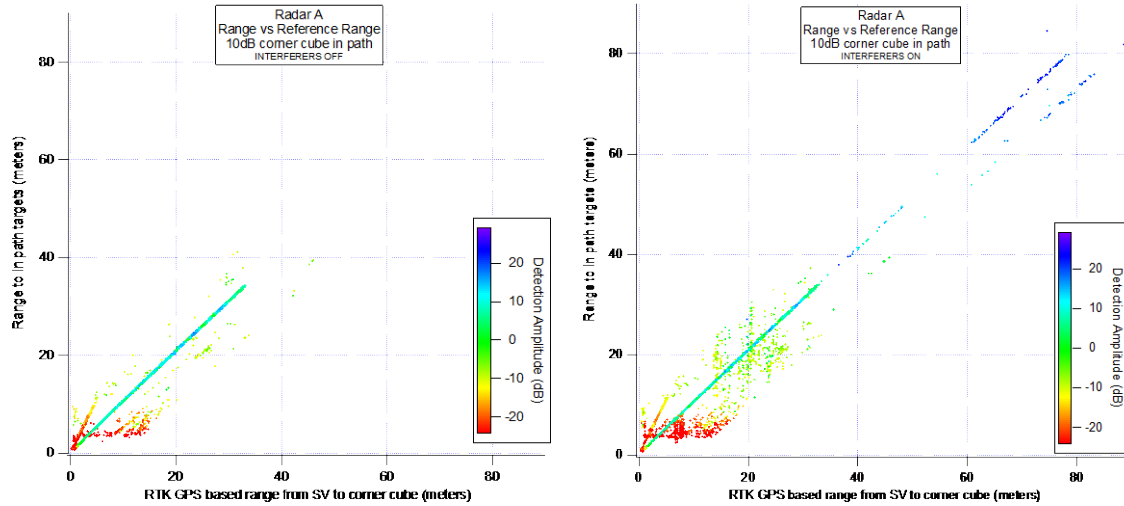


Figure 30. Plots of radar derived range versus ground truth (RTK GPS-based) range for Radar A, without interference at left, with interference at right, showing increased variability in range and a larger number of returns for the radar when exposed to interference

Consistent with the aerial view in Figure 26, more radar returns are evident for the plot showing trials where interferers were on – particularly at long ranges. Also, there is a larger distribution of errors at ranges under 40 meters. For both plots, the amplitude of the returns plotted at equal ranges is consistent with the RCS of the corner cube, at 10 dB.

Similar plots are shown in Figure 31 for the targets from Radar B. In this case each plot aggregates the data from 10 trials, either with or without interfering radars turned on.

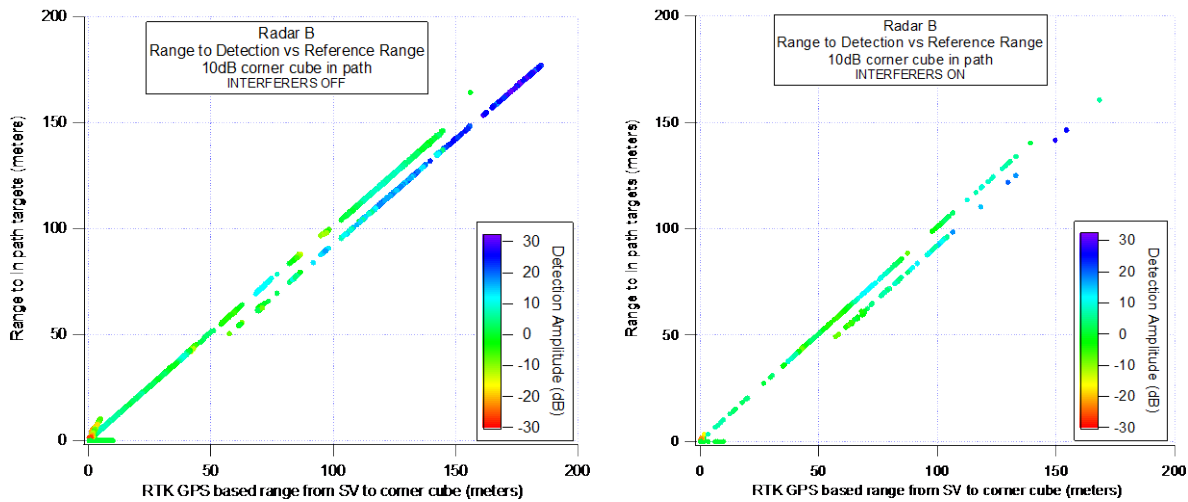


Figure 31. Plots of radar derived range versus ground truth (RTK GPS-based) range for B, without interference at left, with interference at right, showing fewer and weaker returns for the radar when exposed to interference.

This is especially evident at ranges above 100 m, and below 40 meters.

These plots are also consistent with the aerial view of this radar's returns. There are fewer returns with interferers on, but the range plot provides the additional detail that high amplitude targets at long range are less evident, and at closer ranges, less than 40 m, there are times when returns for the corner cube are not present.

Figure 32 shows plots of the range-rate from the RTK GPS system versus Radar A's range-rate to in-path targets shows a marked increase in the distribution of values from the radar with interferers on.

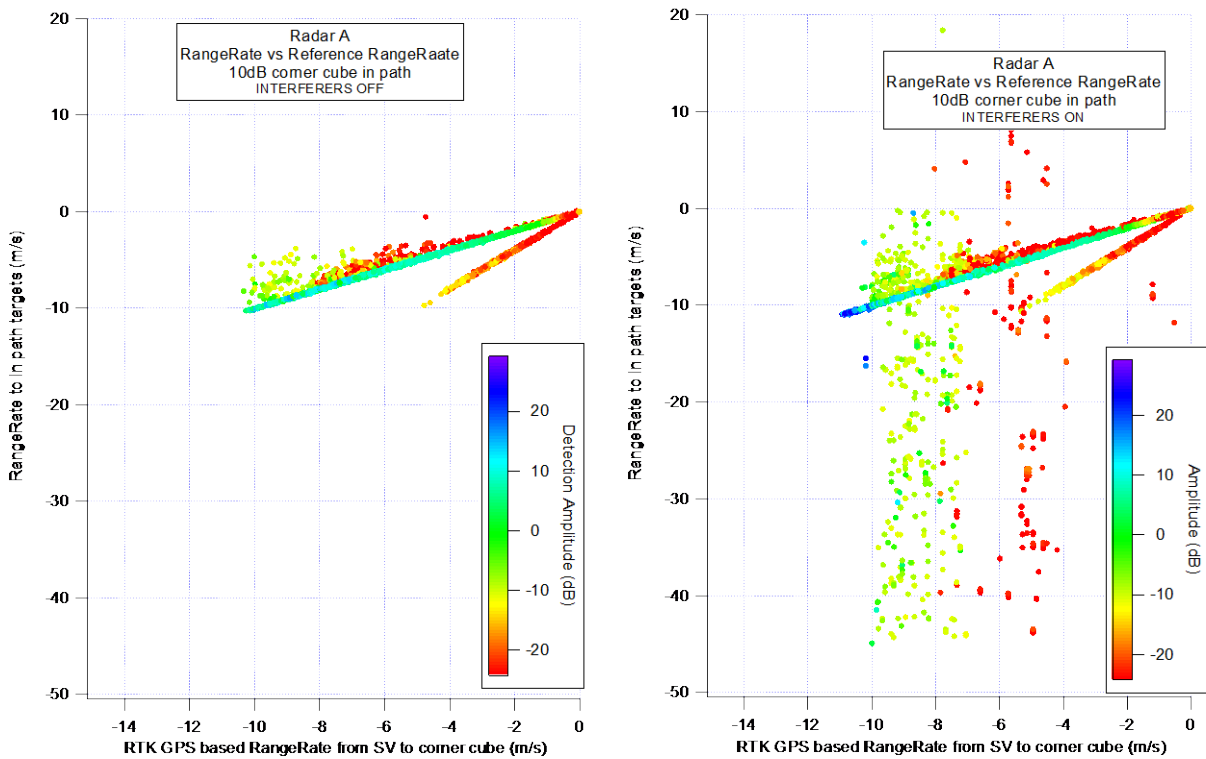


Figure 32. Plots of radar derived range-rate vs. ground truth (RTK GPS-based) range-rate for Radar A, without interference at left, with interference at right, showing increased variability in range-rate values for the radar when exposed to interference

Similar plots for Radar B, shown in Figure 33, show the significant reduction in number of returns with interferers on.

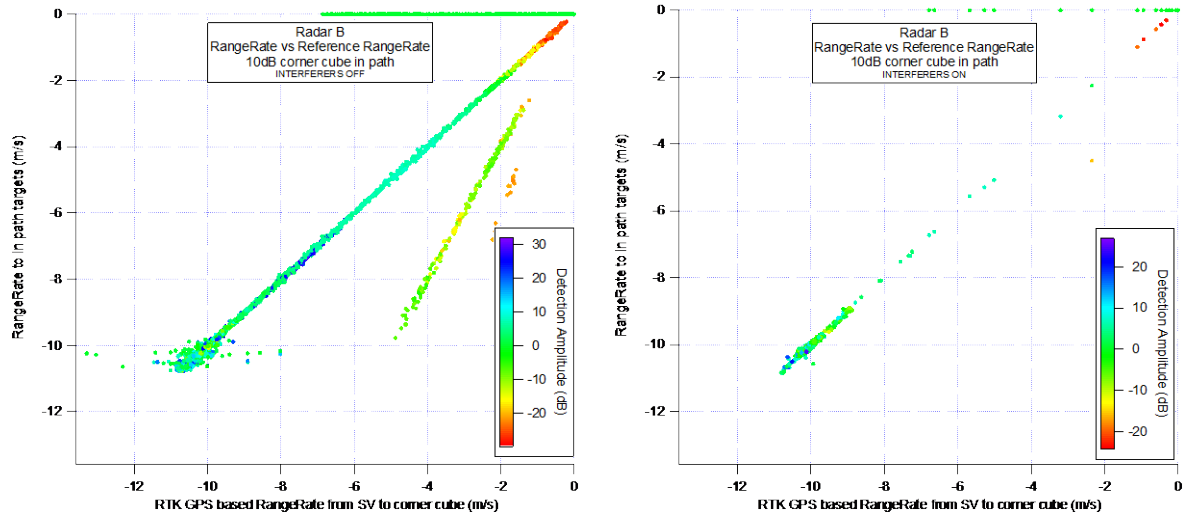


Figure 33. Plots of radar derived range-rate vs. ground truth (RTK GPS-based) range-rate for Radar B, without interference at left, with interference at right, showing fewer and weaker returns from the radar when exposed to interference

While it is strictly speculation, the differences in the outputs from the short-range radar (Radar A), and the mid- and long-range radar (Radar B), suggest differences in design choices. The short-range radar appears to allow a number of false targets to appear, visible in Figure 30 and Figure 32. However, the mid and long-range radar shows the opposite behavior, observable by the loss of detected targets in Figure 31 and Figure 33.

This page is intentionally left blank.

Empirical RF Path-Loss Models for Automotive Radar

Purpose

The purpose of this section is to describe the methods and analyses of RF power received from automotive radars in realistic scenarios. The measurements are used to develop parametric RF path-loss models for representative traffic scenarios, and the collected data can be reprocessed to develop path-loss models by a variety of approaches found in the literature, for which a helpful survey appears in Rappaport and Milstein (1990).

The path-loss relates the power received to the transmitted power, as shown in decibels, in Equation 1, which follows:

$$P_{RX} = P_{TX} + G_{TX} + G_{RX} + PL \text{ (dB)} \quad \text{Equation 1}$$

where

P_{RX} is the received power

P_{TX} is the transmitted power

G_{TX} is the gain of the transmitting antenna

G_{RX} is the gain of the receiving antenna

PL is the path-loss

Approach

The approach for the empirical path-loss model collection is to use a receiving system to measure the power from a transmitting automotive radar in realistic traffic situations, as shown in Figure 34.

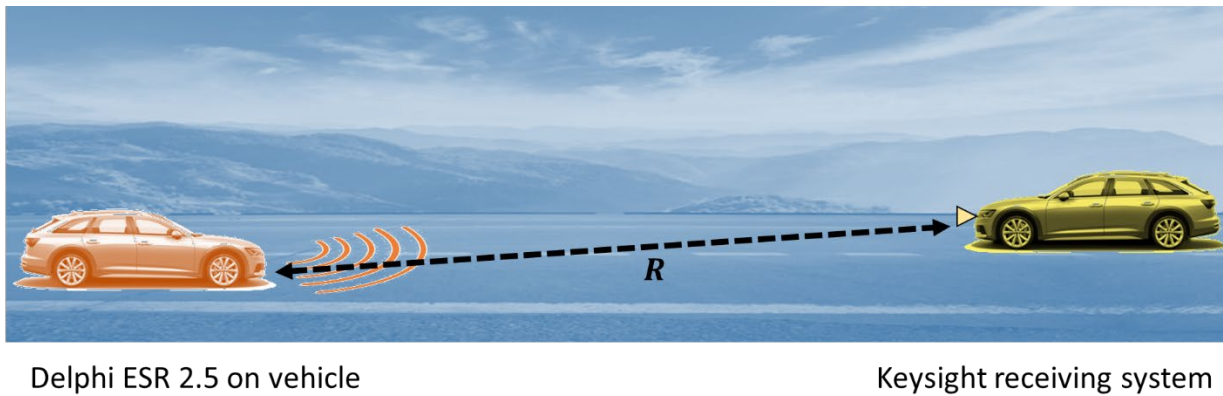


Figure 34. Receiving system measures the power of radio frequency emitted by automotive radar.

Propagation channel measurements were made with a variety of traffic conditions in three distinct environments.

- Straight highway with opposing traffic
- Tunnel transit with opposing traffic
- Urban intersection with complicated clutter in scene

The scenarios were conducted with several trials in three traffic conditions.

- None: Only the transmitting vehicle is on the test track
- Light: The transmitting car travels last in line with eleven other cars separated by approximately 20 m, as in Figure 35. As the radar is pointed forward, vehicles ahead of the transmitter will have the predominant impact on the propagation.
- Heavy: The transmitting car is in traffic travels last in line with eleven other cars separated by approximately 10 m, as in Figure 36.



Figure 35. Light traffic scenario shows the transmitting car last in line with eleven other cars separated by approximately 20 m.



Figure 36. Heavy traffic scenario shows the transmitting car last in line with eleven other cars separated by approximately 10 m.

The experiments used representative geometry, mounting transmitters and receivers at heights consistent with typical forward collision radars. All of the systems operated in the 76-77 GHz band.

Experimental Setup

In each of the environments, a receiver was used to measure the power incident at a static location with height and lane position typical for an automotive radar. The transmitting interferer, as well as any other vehicles moved through the scene, so that the relative positions of transmitter and receiver vary. The position and heading of the transmitting radar were recorded and time-stamped and correlated to the power received. This allows measurements of power received to be associated with the range between transmitter and receiver for the scenario.

The Delphi electronically scanning radar, ESR 2.5, was selected as the transmitter for the RF propagation measurements in this study. This radar interleaves mid-range and long-range functions. The mid-range operating mode uses a wider band than the long-range mode, and a frequency unique to the mid-range transmissions, in Table 11 is selected for path-loss modeling, to ensure the transmitter power and gain remain consistent.

Table 11. Parameters used in data analysis

Frequency (GHz)	Transmit Antenna Height (m)	Receive Antenna Height (m)	Transmit Antenna Gain (dBi)	Receive Antenna Gain (dBi)	Transmit Power (dBm)
76.71	0.5	0.5	15	24	15

The receiving system consists of an antenna fed into a down-conversion RF mixer with an intermediate frequency (IF) of 75 GHz. The mixer output is then input to a signal analyzer for power measurements. The signal analyzer measures and records the power of over the air transmissions received by the antenna.

The specifications for the Delphi ESR 2.5 are given in Table 12, and the specifications for the Keysight N9020B MXA Signal Analyzer receiving system appear in Table 13.

Table 12. Delphi ESR technical specifications, from Delphi Automotive Systems

Parameter	ESR Long-Range Requirement	ESR Mid-Range Requirement
Minimum Range	< 1m (> 10dB target) < 1m (> 0dB target)	< 1m (> 10dB target) < 1m (> 0dB target)
Maximum Range	> 175m (> 10dB target) > 100m (> 0dB target)	> 60m (> 10dB target) > 50m (> 0dB target)
Range Accuracy	< +/-0.5m noise component with +/- 5% bias component	< +/-0.25m noise component with +/- 5% bias component
Range Discrimination for two targets at same angle & range rate	< 2.5m	< 1.25m
Minimum Range Rate	< -100m/s	
Maximum Range Rate	> +40m/s	
Range Rate Accuracy	< +/- 0.12m/s	
Range Rate Discrimination for two targets at same range & angle	< 0.5 m/s	
Acceleration	Acceleration to be generated as an output of the Tracker	
Minimum Lateral Relative Velocity	< -20 m/s	
Maximum Lateral Relative Velocity	> +20m/s	
Lateral Relative Velocity Accuracy	Lateral velocity is derived in the tracker based on change in measured angle vs. time. Accuracy in m/sec is a function of range.	
Azimuth Field of View	> 20deg	> 90deg
Azimuth Angle Centroid Accuracy	< +/- 0.3deg (corner reflector targets) < +/- 0.5deg (other targets)	< +/- 1.0deg
Azimuth Angle Resolution of two targets at same range & range rate	< 3.5 deg	< 12 deg
Vertical Field of View	4.2deg – 4.75deg	
Minimum Amplitude	< -10dB	
Maximum Amplitude	> 40dB	
Minimum Update Interval	>= 20Hz	
Minimum Target Tracking	64 fused targets total	

Table 13. Technical specifications for Keysight N9020B MXA signal analyzer, 10 Hz to 50 GHz

Frequency	10 Hz to 50 GHz; Mixers to 1.1 THz
Frequency Options	3.6,8.4,13.6,26.5,32,44,50 GHz, Mixers to 1.1 THz
Standard Attenuator Range	70 dB
Standard Attenuator Step	2 dB
Real-Time Bandwidth Options	85, 125, 160 MHz
DANL @1 GHz	-172 dBm
Maximum Analysis Bandwidth	160 MHz
Phase Noise @1 GHz (1 MHz offset)	-136 dBc/Hz
Phase Noise @1 GHz (10 kHz offset)	-114 dBc/Hz
Phase Noise @1 GHz (30 kHz offset)	-114 dBc/Hz
Spur Free Dynamic Range	72 dBc
TOI @1 GHz (3rd Order Intercept)	+20 dBm
Applications Available	Yes
Maximum Real-Time Bandwidth	160 MHz
Overall Amplitude Accuracy	± 0.23 dB
Bandwidth Options	25 standard, 40, 85, 125, 160 MHz

The layout of the straight highway at Mcity is shown in Figure 37. The layout for the two-lane highway with the tunnel is shown in Figure 38. An annotated photograph of the hardware setup is shown in Figure 39.

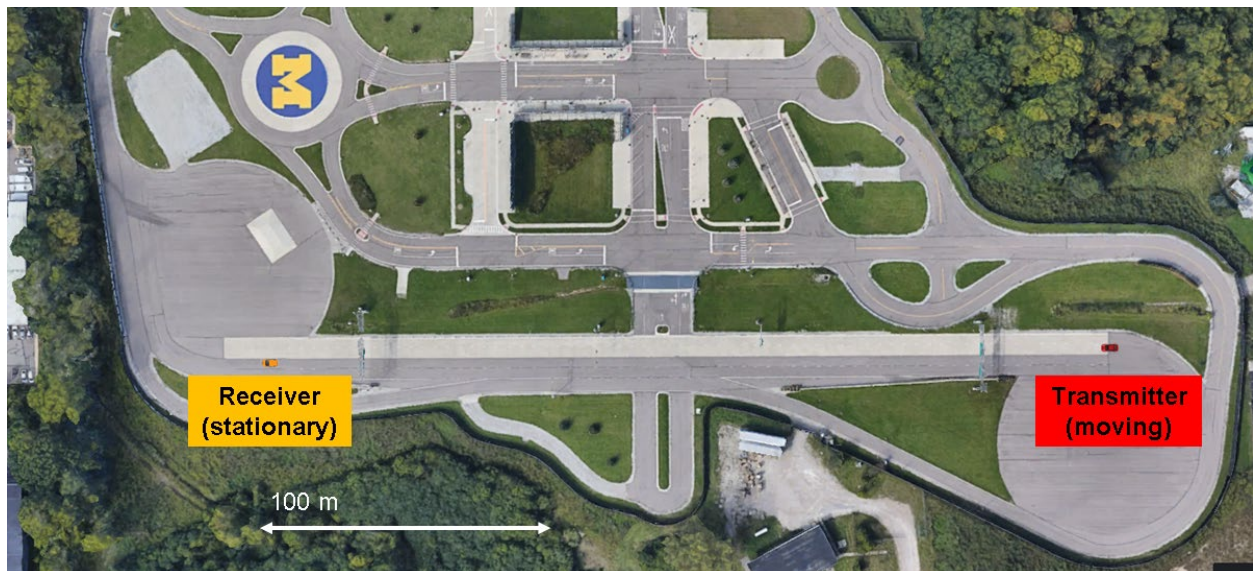


Figure 37. Straight highway scenario with a single automotive radar transmitting (identified in red).

The receiving antenna is stationary.

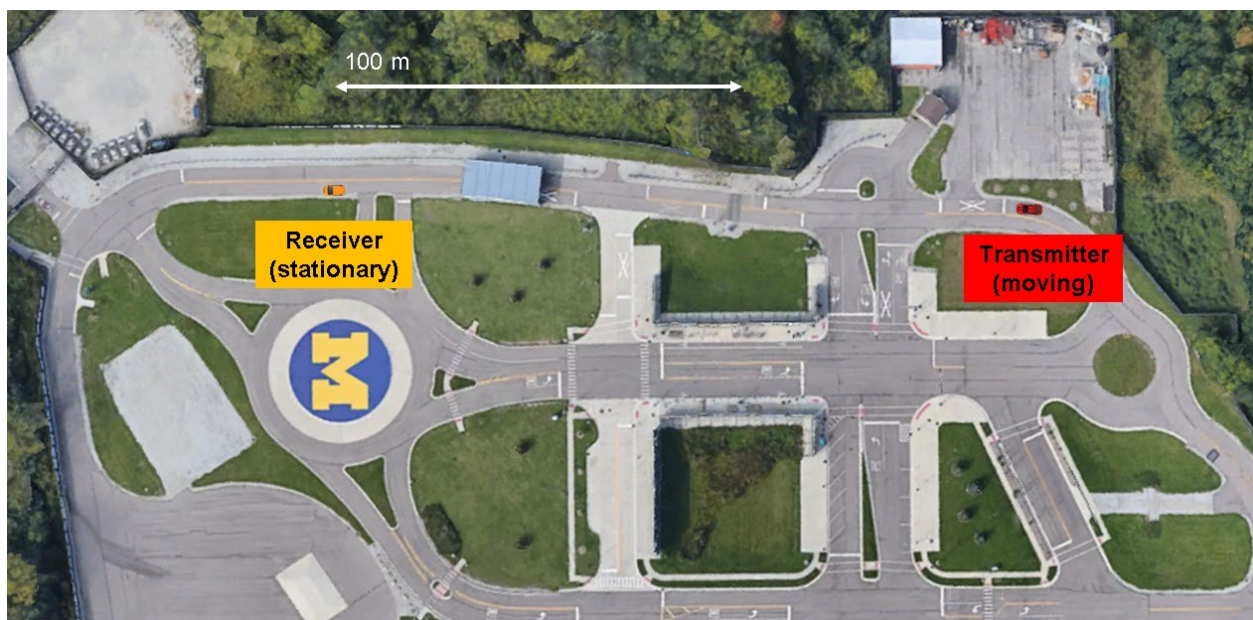


Figure 38. Two lane highway scenario including a tunnel with a single automotive radar transmitting (identified in red).

The receiving antenna is stationary.

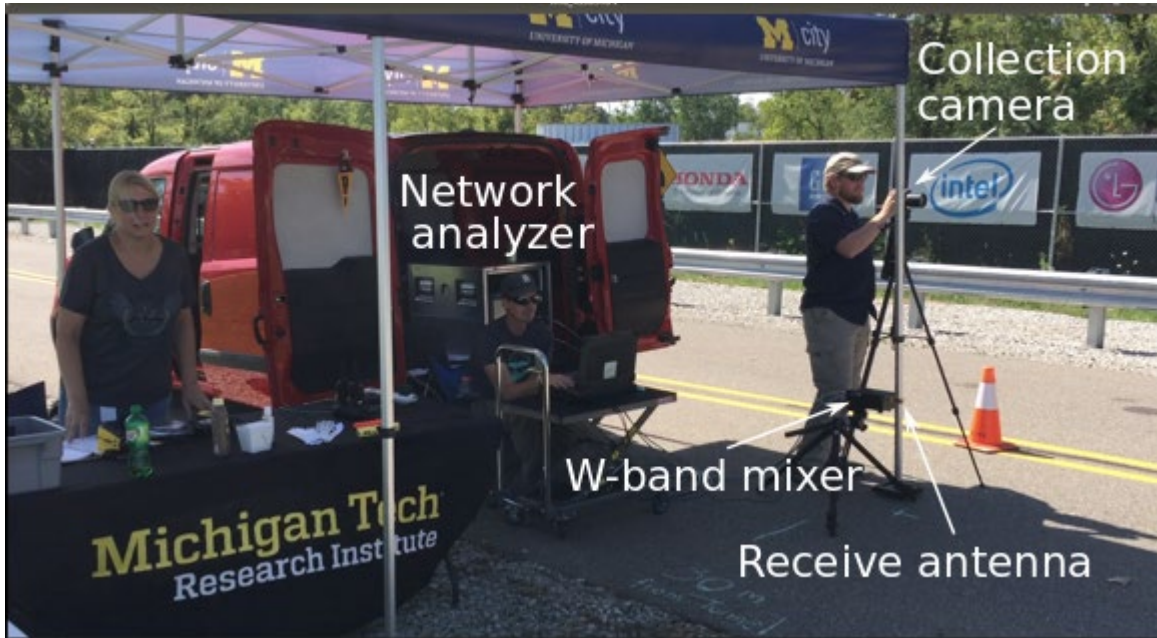


Figure 39. The receive antenna is connected directly to the W-band mixer, and mounted at a height at 50 cm.

The mixer is cabled to the network analyzer which samples the mixed signal. The collection camera is used to capture still images during the experiments.

Software was developed to provide data checks in the field to ensure the hardware was working properly.

Collected Data

The collected data consists of navigational information for all vehicles, including the vehicle with transmitter, the power received by the receiving system, and various sources of ground truth, including notes and photographs.

The University of Michigan collected navigational data on the transmitting vehicle and processed the raw data into comma separated variable formatted files for each test point with the following fields: Experiment, Site, Scenario, Radar, Trial, NumCars, Range, FileName, TimeLocal, LatitudeWGS84, LongitudeWGS84, HorizSpeed_m_s, Heading_deg, RangeToRx_m, BearingToRx_deg.

Michigan Technological University recorded the locations of all other vehicles in test using Reach RTK units, the raw data from each test was organized into a single Matlab formatted (.mat) file. Example traces of vehicles during one test are shown in Figure 40.

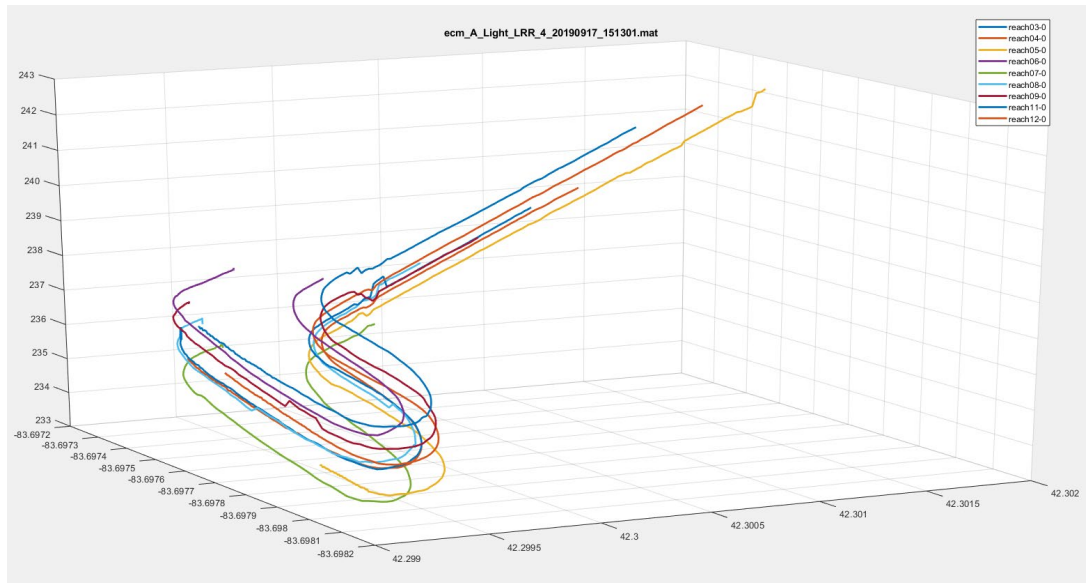


Figure 40. Multiple Vehicle tracks from empirical path-loss model collections at Mcity

The power at the receiver was time-stamped. The received power was next associated with the range to the transmitting vehicle by time-aligning the data. An example of the processed data, showing power as a function of range to transmitter can be found in Figure 45.

All data was organized as test points and notes made in the field were scanned and archived along with the data file. An example entry from the collection notebook is shown in Figure 41.

Sept 17

Test Point:	<u>04</u>	Take:	<u>4</u>
Location:	<u>A</u>	Traffic:	<u>None</u>
Radar	<u>MRR</u>		
Description:	<u>ecm_A_None_MRR_4</u>		
Picture #'s:	<u>40 - 46</u>	Time:	<u>11:44</u>
Notes:	<u>76.71 GHz</u>		
Duration:	<u>35</u> Seconds	# of Samples:	<u>50,001</u>

Figure 41. Snippet from the collection notes, which has been scanned and archived with data

Analysis

This project sought to provide higher fidelity models of RF path-loss as measured in realistic environments. It is worth comparing a plot of the measured path-loss compared to the free space path-loss. Free space path-loss is a function of the wavelength, λ and range between transmitter and receiver, R , expressed as $(\lambda/4\pi R)^2$. The free space path-loss is plotted along with empirical measurements for a vehicle approaching the receiver in Figure 42.

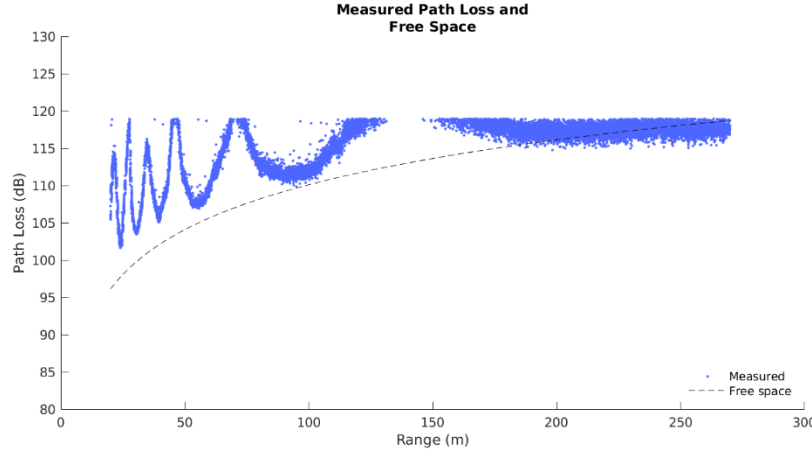


Figure 42. Measured values of path-loss is plotted along with free space model.

The beam shape of the transmitter and receiver are observed to affect the path-loss estimate below 50 meters. The automotive radar is mounted on the front of a vehicle directly approaching the receiver.

The empirical measurements can also be compared to path-loss according to a model that considers two paths: directly from the transmitter and reflected from the road. This is typically referred to as a two-ray model. This model for propagation was explored for use in simulation. In the least cluttered scene in our study, shown for a vehicle directly approaching the radar, in Figure 43, and then for a vehicle in the adjacent lane, in Figure 44, the path-loss predicted by the two-ray model does not match all of the nulls and peaks due to multipath interference, as shown in the plots in Figure 45. This may be for several reasons that require further investigation.



Figure 43. Experiment with transmitting vehicle approaching receiver, straight on, in the four-lane highway scenario



Figure 44. Vehicle approaching receiver in adjacent lane of opposing traffic in four-lane highway scenario with no traffic

Comparison to Two-Ray Model

The power measured by the RF receiver was compared with the power predicted by a two-ray. The model is evaluated following propagation from the transmitter to the receiver over a flat plane. This model was investigated as a model for vehicle-to-vehicle RF propagation in (Davis & Linnartz, 1994). This fairly represents the straight highway scenario, and a vehicle moving in the opposing direction, coming straight at the ego vehicle.

The model considers the propagation of the line-of-sight wave in free space as well as the multipath effects of a ground reflection off of a flat plane. Following the derivation in Etinger et al. (2017).

Assuming that the magnetic permeability of the medium (air and ground) is identical to that of the vacuum $\mu_0 = 4\pi \cdot 10^{-7} H/m$. The reflectivity of the ground, ρ_0 , for transverse electrical mode is used. Note that this value varies not only with materials but the environmental conditions, such as temperature and rain.

$$\rho_0 = [\cos(\theta_0) - \sqrt{\epsilon' - \sin^2(\theta_0)}] / [\cos(\theta_0) + \sqrt{\epsilon' - \sin^2(\theta_0)}]$$
$$P_{RX} = P_{TX} G_{RX} G_{TX} (\lambda/4\pi R)^2 \cdot 4 (\sin^2(2\pi h_{RX} h_{TX}/\lambda R))$$

The path-loss in Equation 2, is the inverse of the ratio of the transmitted power to how much is received, that is $PL = P_{TX}/P_{RX}$

$$PL = (4\pi R)^2 / [G_{RX} G_{TX} \lambda^2 4 \sin^2(2\pi h_{RX} h_{TX}/\lambda R)] \quad \text{Equation 2}$$

where

R is the distance between the transmitter and the receiver

G_{RX} is the gain on the receiving antenna

G_{TX} is the gain on the transmitting antenna

λ is the wavelength of the transmitted energy

h_{RX} is the height of the receiving antenna

h_{TX} is the height of the transmitting antenna

The first half of the equation can be recognized as the Friis transmission formula. The second half of the equation uses modified image theory and geometry to determine when constructive interference will occur and when destructive interference may occur with respect to range.

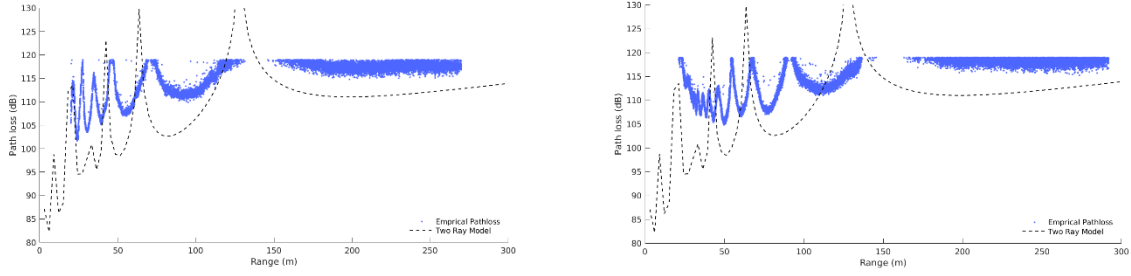


Figure 45. Comparison of empirical data and two-ray model for automotive radar approaching receiver, straight on, at left, and in the adjacent lane, at right.

At left, the model aligns better with the measured path-loss, than at right, where the model and measured data show less agreement in the locations of peak loss. Measured path-loss estimates below 50 m show artificially high values due to unaccounted beam pattern roll off for the adjacent lane case at right.

Adjusted Path-Loss Exponent

The adjusted path-loss exponent model is a modified version of the free space path-loss formula. This is computed as the maximum likelihood estimate of the path-loss exponent α using least squares regression to the free space path-loss formula (Rappaport & Milstein, 1990), as expressed Equation 3

$$PL_{\alpha} = -\alpha \, 10 \log_{10} \left(\frac{\lambda}{4\pi R} \right) \quad (dB) \quad \text{Equation 3}$$

where

α is the path-loss exponent

Generalized Extreme Value Fit

The motivation for this section is to develop a method to draw path-loss estimates from a parametric model with statistical properties of the measured values. The path-loss is then estimated by $\widehat{PL}$, using the adjusted path-loss exponent expression, and draws from a distribution function which estimates the measured data. Estimates of path-loss, which are statistically similar to the measured data for each of the scenarios can be drawn using the following formula in Equation 4:

$$\widehat{PL} = PL_{\alpha} + F_{GEV}^{-1}(\mu, \sigma, \xi) \quad (dB) \quad \text{Equation 4}$$

where

PL_α : Adjusted path-loss model with exponent, α .

$F_{GEV}^{-1}(\mu, \sigma, \xi)$: Inverse cumulative distribution function of the generalized extreme value distribution, parameterized by μ , the location parameter, σ the scale parameter, and ξ the shape parameter.

Maximum likelihood estimates of the parameters of the GEV distribution are used to generate realistic values of received power based on the empirical measurements. The utility of the GEV is shown in (Song et al., 2011). The CDF is described by Equation 5

$$F_{GEV}(z) = \exp\left(-\left[1 + \xi \frac{z - \mu}{\sigma}\right]^{-\frac{1}{\xi}}\right) \quad \text{Equation 5}$$

where

$\sigma > 0$ and $1 + \xi((z - \mu)/\sigma) > 0$

The following parameters are used to compute the models in the analysis that follows.

- Sampling frequency is 76.71 GHz
- The height of each antenna is 0.5 m
- The transmitting antenna gain is 15 dBi
- The receiving antenna gain is 13 dBi
- The power transmitted is 15 dBm
- The noise threshold is set at -35 dBm
- The dielectric for asphalt is estimated at $\epsilon = 3.18$ (Etinger et al., 2017)

The statistical parameters tabulated in Table 14, generate path-loss values, in decibels, according to the GEV distribution, which best fits the measured data.

An example of the relative likelihood of path-loss generated by this method is shown in Figure 46. The plot shows the probability density of drawing a value of path-loss, on the y-axis, as a function of range between transmitter and receiver, on the x-axis. This heat map uses the values in Table 14 for the scenario of the straight highway with no traffic.

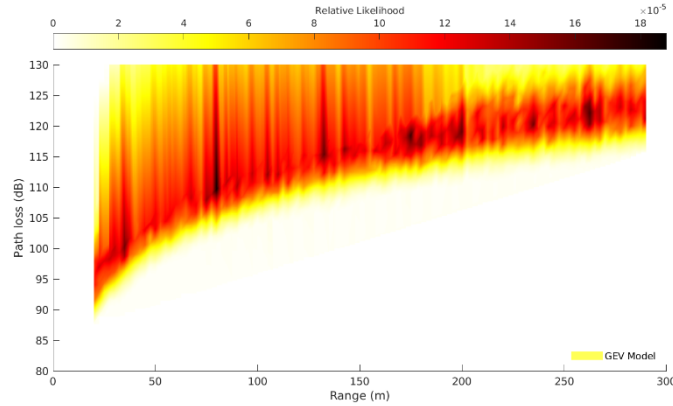


Figure 46. Statistical density of values derived from the measured data for the straight highway case with no traffic.

The plot is generated using the path-loss estimates from Equation 4.

Results and Discussion

A key result of this research project is the set of empirical path-loss models that provide realistic models of interference, based on measured data. These are parameterized in Table 14 near the end of this section for implementation into a broad range of calculations and simulations. The tabulated values can be used to generate path-loss estimates similar to those observed, through Equation 4.

These estimates are only valid when the receiver has a line of sight to the transmitting radar. The minimum range constraint will vary for any pair of radars based upon beam width and geometry. The maximum range is constrained by the geometry of the vehicles and scene.

The collected data is used to estimate the path-loss coefficient and the parameters for a generalized extreme value distribution, as well as the maximum range at which the interfering radar is observed.

The results for the straight, and tunnel transit scenarios are tabulated in Table 14. The values in the table can be used to generate path-loss values, which are statistically similar to those measured at Mcity. The parameters in this table allow researchers to generate values with the statistical variation of empirical data.

The parameters tabulated are

- *Maximum range*: farthest observed,
- α : adjusted path-loss exponent, and
- GEV parameters ξ : shape, σ : scale, μ : location.

The maximum distances to the observed transmitter are shown graphically on aerial views of the track in Figure 48 for the straight highway experiments, and Figure 49 for the two-lane highway with a tunnel.

The maximum range of observed interference can be estimated by considering the minimum distance down-range where the line of sight is obscured, as shown in Figure 47. In the case of the four-lane highway scenario, the opposing traffic is in a straight line in the adjacent lane. For these scenarios, the lane spacing, R_x , is 3.7 m and the vehicle preceding the transmitter is 185 cm wide, so that $\Delta x = 185/2$. The maximum distance down-range, R_y , which is not occluded by this angle can be solved as $R_y = (\Delta y / \Delta x) R_x$, where Δy is the spacing between the transmitter and preceding vehicle.

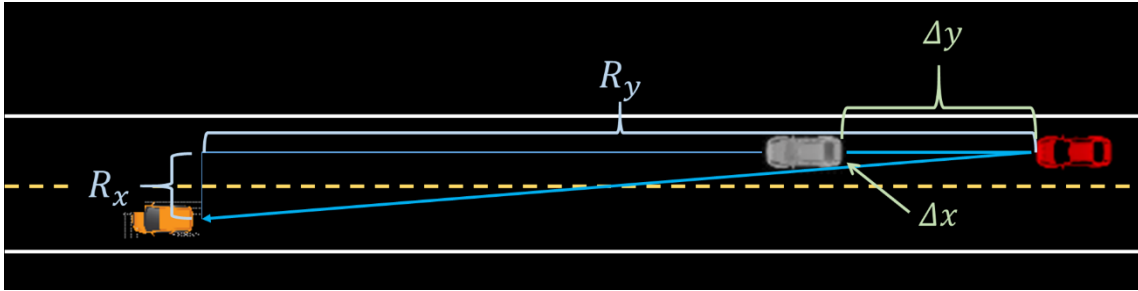


Figure 47. Geometry of lead car occluding radar from opposing traffic

For vehicle spacing, Δx of 20 m, R_y , is 80 meters; and for vehicle spacing of 10 m, R_y , is 51 meters. These values can be compared to the values observed in the empirical data, 58 and 91 m in Table 14, in the maximum range for the scenarios Straight / Light and Straight / Heavy, respectively.

The maximum range of observation for the tunnel scenario is complicated by the curvature of the road and the presence of the tunnel.

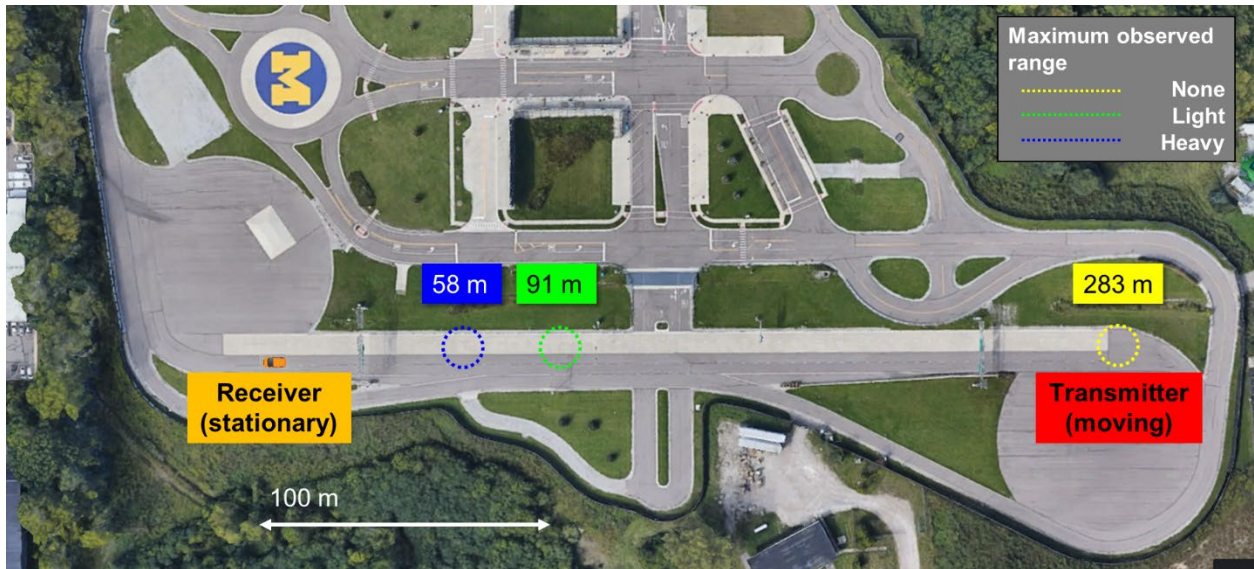


Figure 48. Image shows the furthest location where the transmitting antenna is observed above the noise level of the receive antenna for the three traffic conditions in the straight highway scenario.

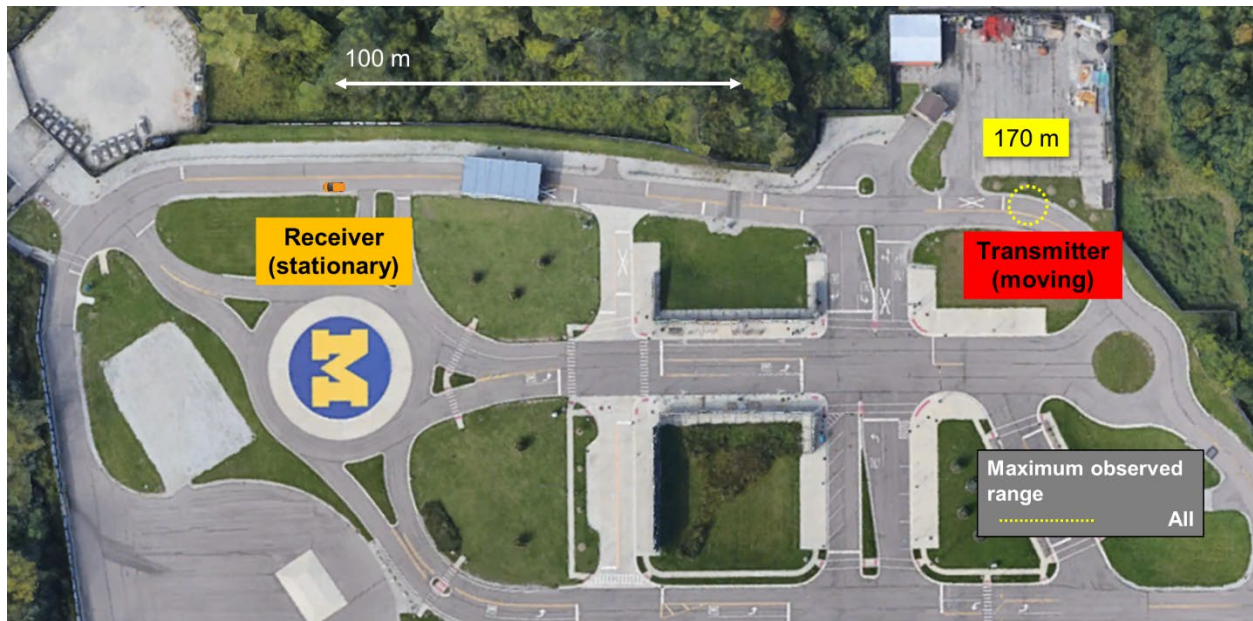


Figure 49. Image shows the location where the transmitting antenna is first observed above the noise level of the receiver antenna is approximately 170 m for the two-lane with tunnel scenario, regardless of traffic density.

Table 14. Parameters to generate statistically realistic path-loss values for six different scenarios (rows in table)

Scenario /Traffic	Maximum Range (m)	PL Exponent α	Shape ξ_{GEV}	Scale σ_{GEV}	Location μ_{GEV}
Straight /None	270	2.44	0.124	3.59	15.7
Straight /Light	292	2.43	0.016	3.95	17.0
Straight /Heavy	101	2.60	-0.044	3.41	13.7
Tunnel /None	66	2.68	-0.231	3.41	13.5
Tunnel /Light	169	2.47	0.017	2.56	13.6
Tunnel /Heavy	151	2.51	-0.062	2.73	13.1

This page is intentionally left blank.

Simulation of Automotive Radars With Interference

Purpose

The purpose of simulating mutual interference is to help characterize the impacts through a method that allows us to sample many realizations. Armed with empirical models, MTU updated its M2I2 simulation to allow two additional modes:

- Empirical path-loss for calculating mean interference, and
- Measured test track RF interference in the simulation.

The software predicts mean interference power through a stochastic geometric approach that has been favorably compared with independent calculations made using Monte Carlo trials (Terbas et al., 2019).

Approach

The improvements in this study include incorporating empirical path-loss models into our simulation, aid in the adoption of empirical path-loss models in simulations for the greater automotive radar research community. A more complete description of the Radar Congestion Study simulation can be found in (Buller et al., 2018). The content here is focused on the incorporation of empirical models.

Radar Congestion Study Software

To estimate the impact of interference on a collision warning system, the study introduced the interference powers, calculated as in the preceding sections, and modeled the interfering transmissions as uncorrelated noise. The MTU Mutual Interference Impact (M2I2) simulation tool estimates the impacts of interference. This tool was developed under the Radar Congestion Study (Buller et al., 2018). The approach taken for M2I2 is common in past studies (Heuel, 2016; Al-Hourani et al., 2017) and assumes the waveforms of the interfering radar are substantially different, so that their mutual energy does not correlate. This requires a minimum of assumptions about the signal processing chain behind the receiving radar's front end. While the approach neglects the possible impacts of interfering signals, which generate false tracks (ghost targets), the impact of elevated noise is generally independent of hardware architecture.

For our simulations, we implemented the processing flow in Figure 50.

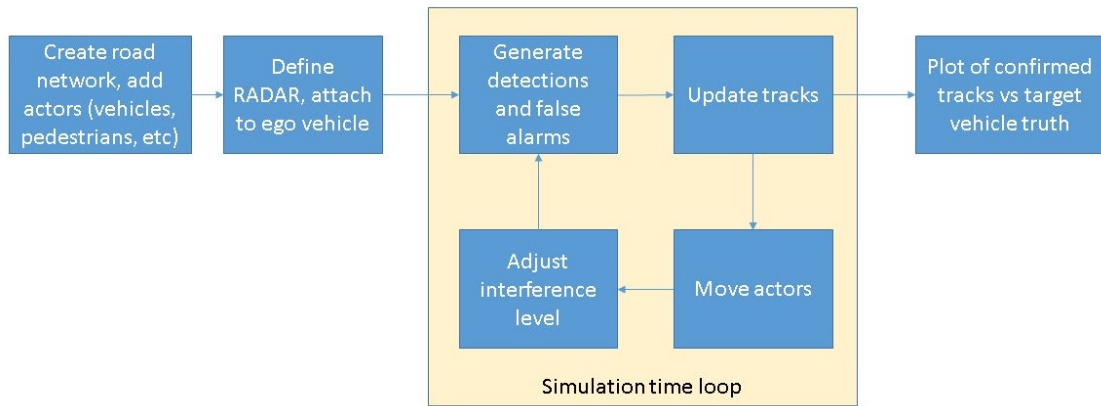


Figure 50. Simulation processing flow

Scenario setup involves creating the roadway, adding scenario actors, and defining sensor and sensor attachment to actors. For each time step, sensor detections are generated, along with any false alarms. These detections and false alarms are fed to the tracking algorithm, which creates, maintains, and prunes tracks. Actors are then moved to their next positions, and interference levels are adjusted based on changed interactions between the ego vehicle and other radar systems in the scene. Finally, plots and metrics measuring performance of the ego vehicle sensor are produced.

To implement our simulations, we chose to use the MATLAB platform (from MathWorks), with the add-on Automated Driving Toolbox. M2I2 is supported on MATLAB 2017a and 2019b, and Automated Driving Toolbox version 3.0. Introduced in 2017, the Automated Driving Toolbox provided most of the capability needed to simulate a vehicle with sensor support for automated features and provided methods to extend the capabilities needed.

Sensor Definition and Placement

To measure the dynamic environment, sensors can be attached to the vehicles. The goals of our simulations were to measure radar detections and performance, but the software can also simulate vision systems.

Sensors are attached to vehicles. Once a sensor is attached, it moves with the vehicle as it traverses the roadway. Each sensor has an update rate, which controls the number of detections the sensor generates, and may be different than the update rate of the scenario (i.e., movement of the vehicles).

An example display of an ego vehicle radar azimuth field of view is shown in Figure 51.

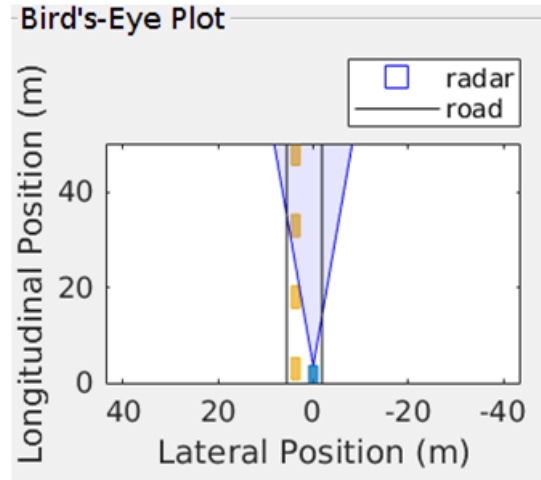


Figure 51. Overhead view showing radar beam indicating azimuth field of view

Sensor Detection Modeling

Detectability of targets is governed by three inter-related parameters: probability of false alarm, probability of detection, and signal-to-noise ratio. PFA relates to the number of false detections that are allowed to occur. To ensure that detections of real targets are generated, some amount of false alarms must be allowed. For our simulations, the PFA was set to $1e-6$, meaning that a false alarm will occur every 10 million detections. This PFA was selected to be reasonable, and valid within the assumptions in MATLAB's Automated Driving Toolbox (Richards, 2005). At an SNR of 13 dB, this threshold has a detection rate of 90%.

Once an acceptable level of false alarms has been set, the relationship between the PD and SNR is defined via a receiver operating characteristic curve, an example of which is shown in Figure 52. This ROC curve is derived from well understood radar reflection phenomenology. In the MATLAB Automated Driving Toolbox, radar reflections are assumed to be from non-fluctuating targets, with non-coherent pulse integration, generated via Albersheim's detection equation (Richards, 2005).

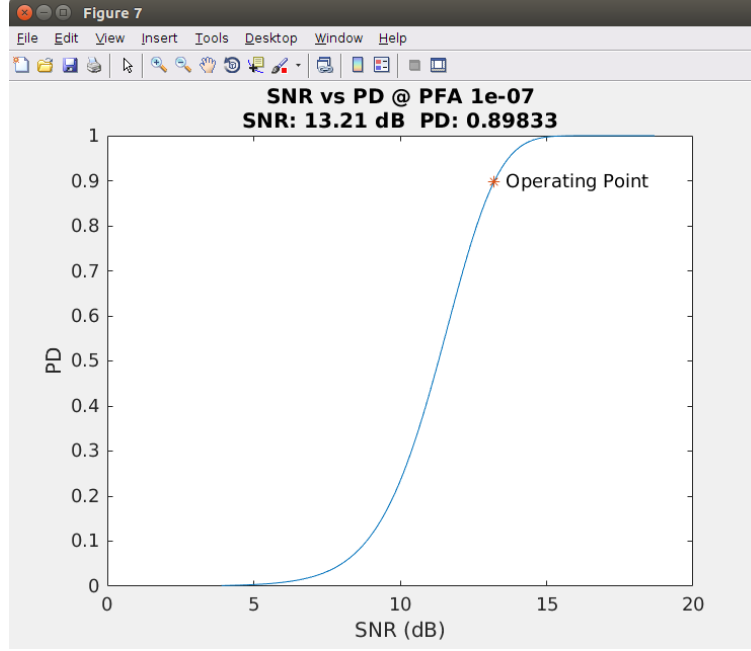


Figure 52. Example ROC curve relating SNR and PD given desired PFA

Detections are generated on a per-time-step basis. First, actors within the scenario are moved to their current position. Next, point targets are generated for the scene. The region-of-interest (ROI) is defined by the orientation and field-of-view of the radar. This ROI is sub-divided based on the minimum spacing defined by the azimuth and range resolutions as demonstrated in Figure 53, (in these simulations, elevation resolution is infinity, i.e., responses cannot be separated by height). Actors are represented as 6-sided cuboids. At most three sides of an actor are visible to the radar at any time. Point targets are generated wherever the side of an actor occupies one of the sub-divisions of the ROI.

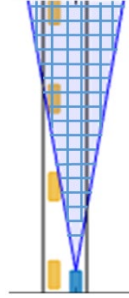


Figure 53. Example of subdividing radar beam to identify point target responses

Each point target is assigned an RCS value. This is the idealized response of the target at the given angle, without accounting for distance between the sensor and the target. Each actor is assigned a set of RCS values, which can differ with illumination angle. These set of RCS values are interpolated to get the point target response given the per-time-step illumination angle of the target. For our simulations, all vehicles are assigned an RCS value of 10 dBsm for all angles, which has been found in previous work (Buller & LeBlanc, 2012) to be a good estimate of vehicle cross-section.

Point targets are then eliminated based on range-rate. Range-rate is a measure of the radar's ability to discern changes in relative range between the ego and target vehicles. The limit on this ability comes from the rate at which the radar can transmit pulses, driven by an engineering tradeoff between expected maximum vehicle velocities, maximum range extent, and cost of the radar system. Point targets outside the minimum/maximum range-rate are considered spurious and ignored.

Since the RCS of the target does not account for the distance between the sensor and point target, this number must be converted into the SNR at the point target. The SNR for each point target is derived using the following equation:

$$SNR_T = SNR_R - RCS_R + 40\log_{10}(Rng_R) - 40\log_{10}(Rng_T) + RCS_T$$

where SNR_T is the calculated SNR of the point target (in dB), SNR_R is the reference SNR (in dB) derived from the SNR versus PD ROC curve, RCS_R is the reference RCS (in dBsm), Rng_R is the reference range (in meters), Rng_T is the range to the point target (in meters), and RCS_T is the target RCS (in dBsm) at the location of the point target.

Once the SNR at the point target is known, a noise model is applied to the point target positions, to simulate uncertainty in location measurement accuracy. This noise model is driven by the SNR at the point target, with separate models for azimuth, elevation, range, and range-rate. Each of the models is based on a zero mean normal distribution, with user settable standard deviation:

$$est = truth + \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{x^2}{2\sigma^2}}$$

where *truth* is the azimuth, elevation, range, or range-rate derived from the ground truth, σ is the user defined per-estimate standard deviation, x is a uniform random number, and *est* is the resulting perturbed estimate.

Point targets that occupy the same resolution cell are then merged, since the radar would be unable to distinguish between the separate points. The SNR in the resolution cell becomes the sum of the merged point targets, with the response position information coming from the point target with the highest SNR.

Those resolution cells that contain a non-zero response are then examined to determine if a detection should be generated. To decide if a detection is to be generated, the PD versus SNR ROC curve is indexed using the SNR at the resolution cell to determine the probability that a detection will be generated. A uniformly distributed random number is generated, and a detection is generated if the random number is below the PD. If a detection is generated, error statistics for the azimuth, range, and range-rate estimates are also computed.

The total number of false alarms generated are chosen by calculating the total number of resolution cells for one sweep of the radar and multiplying that number by the false alarm rate. If false alarms are generated, the range and azimuth locations of the false alarms are chosen at random from a uniform distribution. False alarms are assumed to be marginal detections; therefore, the SNR of each false alarm is set by applying Albersheim's equation (Richards, 2005) at the detection threshold level. Finally, the false alarms are grouped together with the target detections into one set of radar detections.

The radar detections are then fed into a tracking algorithm in order to attempt to group the current detections with previous detections and tracks. Any current detections that cannot be

assigned to previous tracks are used to create new tracks. Previous tracks that are assigned new detections are updated and confirmed. Any tracks that did not get a new detection are initially coasted and, if they continue to not obtain detections in the future, are eventually deleted. The default tracker used in the Automated Driving Toolbox, and also our study, is a constant velocity linear Kalman filter.

The main metric used in determining the ability of the radar to detect a target in the presence of interference and noise is the terminal track range. This is the maximum range of a continuous track of the target. In other words, this is how far out the radar was able to initially detect the target and maintain that track through the completion of the simulation.

The mean interference power predicted in M2I2 is compared to the calculation of mean interference power for a forward-looking radar, which appears in (Terbaş, 2019, Figure 4(a), p. 179). The results of the Monte-Carlo simulations are plotted as squares in Figure 54, along with the curve generated using Equation 6 for the same radar parameters. This method is the method used to calculate mean interference power in M2I2. The plot is made assuming forward looking radars with the following parameters.

- Carrier frequency of 77 GHz
- Receive antenna gain of 15 dB
- Effective isotropic radiated power of 40 dBm
- Field of view in azimuth is 15 degrees
- Lane spacing is 10 meters

The ratio of overlap of the interfering systems varies from 0.1 to 1.0. It should be noted that in real world conditions, this overlap is a dynamic variable.

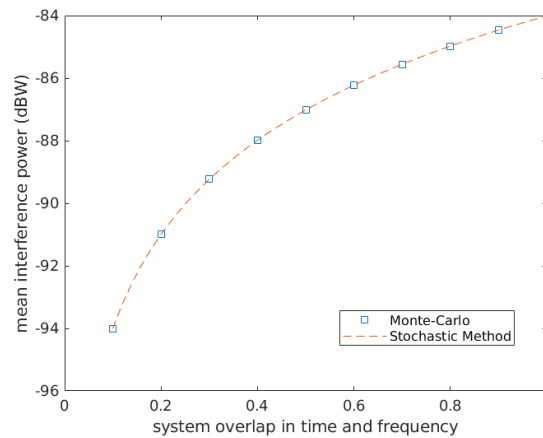


Figure 54. Curve shows M2I2 estimates plotted through estimates made independently using Monte-Carlo simulations.

Parameterized Empirical Path-Loss Models

The empirical path-loss models can be incorporated into simulations of mutual interference for vehicle-based radars.

Path-loss is computed from empirically derived propagation loss parameters:

- $\min(R)$: nearest observable interference, due to beam width
- $\max(R)$: farthest observable interference, due to occlusion by other vehicles
- α : adjusted path-loss exponent
- GEV parameters ξ : shape, σ : scale, μ : location

The statistical functions can be implemented from the parameters reported in the Empirical RF Path-Loss Models for Automotive Radar section of this report. For a given scenario, the parameterized Radar Congestion Testing empirical path-loss models can be used to characterize the RF background statistically.

For M2I2, the free space path-loss model, as implemented in prior work, was updated, for Scenario 1, to include the empirical path-loss exponent, α , and the maximum range value. This was achieved by considering equation 12 from Al-Hourani et al. (2017), which estimates the mean interference power, I_{PPP} , for an automotive radar, is shown in Equation 6

$$\overline{I_{PPP}} = \xi \lambda P_0 L^{-\alpha} \left(\left[\frac{2\sqrt{\pi} L \Gamma\left(\frac{\alpha+3}{2}\right)}{(\alpha^2-1)\Gamma\left(\frac{\alpha}{2}\right)} \right] - \delta_0 {}_2F_1\left(\frac{1}{2}, \frac{\alpha}{2}; \frac{3}{2}; -\frac{\delta_0^2}{L^2}\right) \right) \quad \text{Equation 6}$$

where ξ is the time-frequency overlap factor that accounts for the probability of collision, λ is the mean interferer density, P_0 is the transmitter power, $\delta_0 = L/\tan(\theta/2)$ is the minimum distance away from the ego radar an interferer with FOV θ must be to illuminate the ego receiver, and α is the path-loss exponent. $\Gamma()$ is the Gamma function and ${}_2F_1()$ is the hypergeometric function.

To account for line-of-sight constraints, the equation can be modified to subtract the mean power contributed beyond the range where there is no line of sight. This results in the expression in Equation 7,

$$\overline{I_{PPP}}(\delta_0) - \overline{I_{PPP}}(\delta_{MAX}) \quad \text{Equation 7}$$

where $\delta_{MAX} = \text{atan}(\Delta x \times \lambda)$, where Δx is half the width of the average vehicle.

The estimates of mean interference power are plotted in Figure 55 for three separate models:

- Free space propagation and no maximum range condition (Equation 6, $\alpha = 2.0$)
- Measured path-loss and no shadowing (Equation 6, $\alpha = 2.44$)
- Measured path-loss, and shadowing (Equation 7, $\alpha = 2.44$, $\Delta x = 0.9 \text{ m}$).

As can be observed in Figure 55, the line-of-sight constraint, has relatively little impact on the empirical path-loss calculation for traffic densities less one vehicle per 10 m, observed as vehicle inverse density greater than 10 meters.

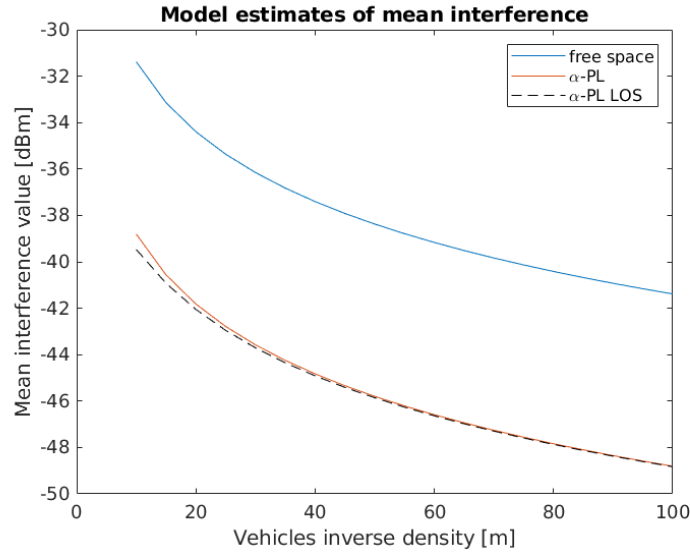


Figure 55. Calculations of mean interference power as a function of average vehicle spacing (inverse density).

The plot shows the calculation for free space propagation ($\alpha = 2.0$), measured path-loss exponent ($\alpha = 2.44$), and measured path-loss exponent with line-of-sight constraint (shadowing). The addition of the line-of-sight constraint has a small impact on the mean interference.

Using a path-loss exponent of 2.44, selected as an example, the impact of mutual interference was simulated in M2I2. The results are shown in Figure 56 and Figure 57. The plots show the range and cross-range of tracks formed by the radar. Only tracks, which persist to the end of the simulation, where the SV collides with the target vehicle, are plotted. These tracks are referred to as terminal tracks. Multiple terminal tracks appear when the SV is close enough that target vehicle spans two or more beams in azimuth. With interfering radars in opposing traffic at density of 1 vehicle per 25 m, the terminal track is formed at about 75 m until collision, as opposed to over 190 m without interference. The radar parameters used in this simulation are listed in Table 15.

Table 15. Radar parameters for example simulation of interference impacts

Radar Parameters	Values for Results Below
Reference range	100 meters
Reference RCS	10 dBsm
Maximum unambiguous range	250 m
Power transmitted	23 dBm
Bandwidth	100 MHz
Field of View (Azimuth)	20 degrees
Azimuth resolution	3 degrees
Transmit antenna gain	21 dB
Noise factor	10

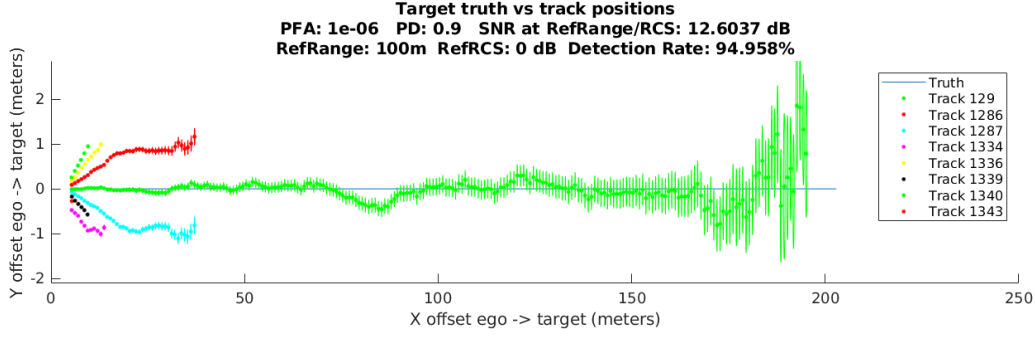


Figure 56. Terminal tracks for long-range radar system simulated in M2I2 plotted as a function of cross range and distance without interference

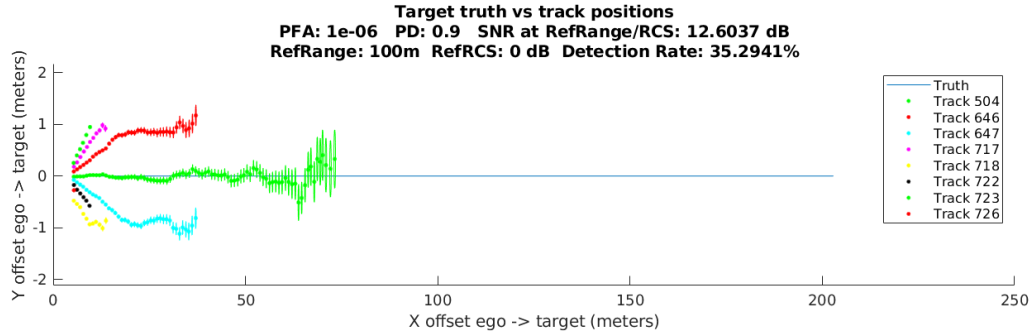


Figure 57. Terminal tracks for long-range radar system simulated in M2I2 plotted as a function of cross range and distance.

Interference is produced by similar radars on vehicles in opposing traffic with a mean density of 1 vehicle per 25 meters.

Empirical Interference Model for M2I2 Simulation

Measured levels of interference, made during the impacts on commercial systems, can be substituted into the simulation, allowing the simulation to mimic interference as observed in test track experiments.

As described above in the Sensor Detection Modeling section, the calculation of the interference power is used to adjust the signal-to-interferer/noise at the target ($SINR_T$), where P_I is the mean interference power:

$$SINR_T = SINR_T + \underbrace{N_{dB} - 10 \log_{10}(P_I + N)}_{\text{Adjustment for interferers}} + \underbrace{10 \log_{10}(P_{tx})}_{\text{Adjustment for RADAR power level}}$$

The measurements of received power are used to generate empirical CDFs of the RF environment, without and with, interferers. These are used to inform the background levels in the M2I2 simulation. The power levels from the scope from a collection without interference, and with interference, are used to generate empirical CDFs. These are plotted in Figure 58. The M2I2

simulation uses the inverse CDF method to draw levels of RF background power at random with statistical properties that match the measured background.

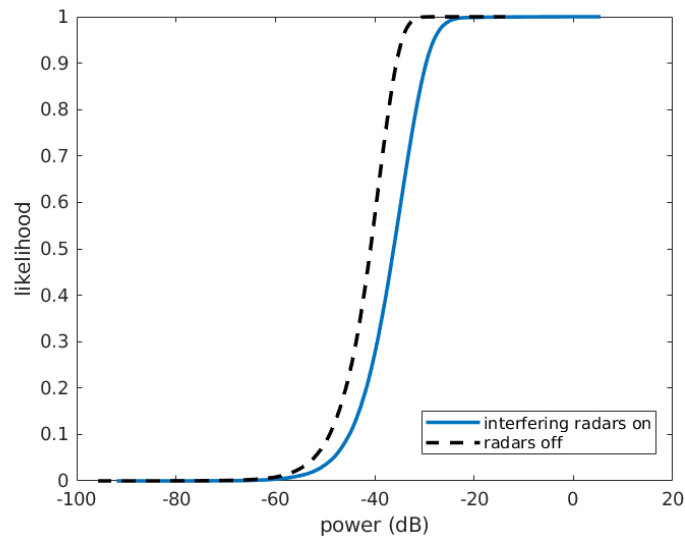


Figure 58. Plots of the empirical cumulative distribution function made from measurements collected with the scope in a test without interference and with interference.

These functions are used to generate realistic interference conditions in M2I2 simulations.

This CDF allows M2I2 to draw interference powers at each time step using the inverse transform sampling method (Devroye, 1986). This allows a vehicle simulated in M2I2 to experience interference with the same levels as the vehicle under test in the experiments at Mcity.

Using the inverse CDF method to generate interference levels, the impact of mutual interference was simulated in M2I2. The results are shown in Figure 59, with no interference, and Figure 60, using measured interference. The plots show the cross-range and range of terminal tracks formed in the simulation. As noted previously, multiple terminal tracks appear when the SV is close enough that the target vehicle covers two or more beams in azimuth. The impact of the interference is observed in the reduction in range at which the terminal track, in green, is formed (125 m compared to 190 meters), and the increased number of tracks needed to form the terminal track (852 compared to 296).

With interference, the radar of the SV forms the terminal track at a range of 125 m from the POV, as shown in green in Figure 60.

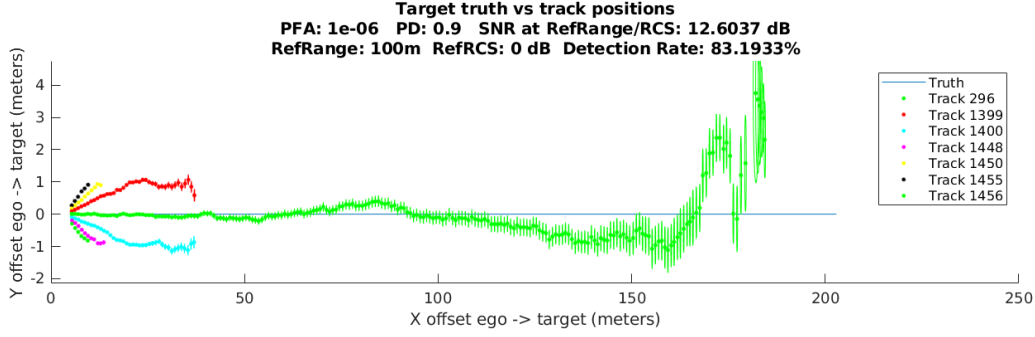


Figure 59. Terminal tracks for long-range radar system simulated in M2I2 plotted as a function of cross range and distance without interference

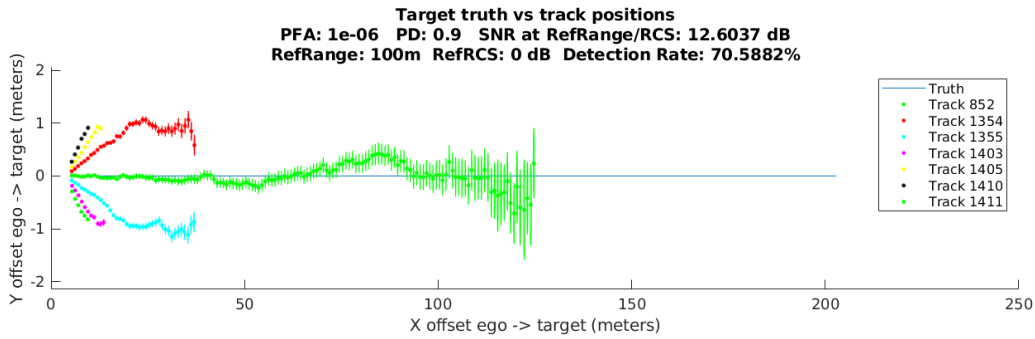


Figure 60. Terminal tracks for long-range radar system simulated in M2I2 plotted as a function of cross range and distance with interference levels drawn from empirical data

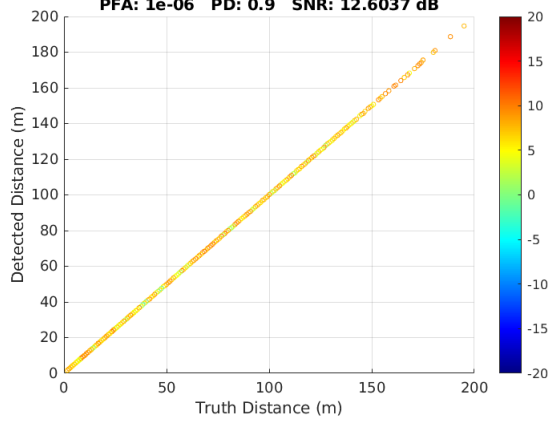
Comparison of Radar Data, Measured and Simulated

The comparison plots for the long-range radar, in Figure 31, help illuminate the impact of interference. A corresponding simulation was run, using M2I2. As with the experiment at Mcity, the vehicle under test is approaching a 10 dBsm target. In one case, the background noise draws levels from the in situ measured background *without* interfering radars. In the other case, draws are made using in situ measurements *with* interfering radars on. The levels drawn in the simulation use the inverse CDF method. This ensures the levels of RF background power, experienced by the simulated radar, has the same statistical properties as the in-situ measurements.

In both the empirical observations using Radar B, shown in Figure 31, and the long-range radar simulated in M2I2, shown in Figure 61. The impact on the radar is that the interference results in fewer and weaker returns.

Correlation of Simulated Radar Detection Distances vs Truth

PFA: 1e-06 PD: 0.9 SNR: 12.6037 dB



Correlation of Simulated Radar Detection Distances vs Truth

PFA: 1e-06 PD: 0.9 SNR: 12.6037 dB

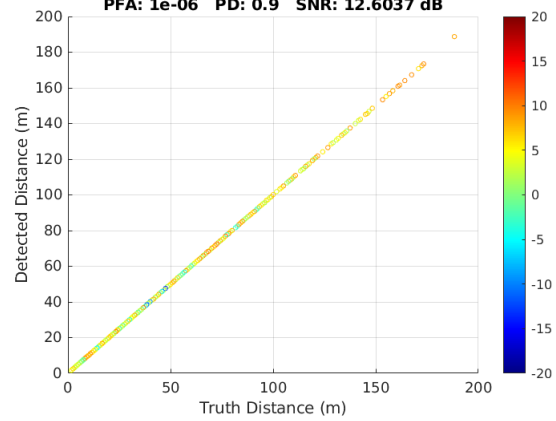


Figure 61. Plots of radar derived range vs. ground truth range for a generic long-range radar, simulated in M2I2, without interference at left, and with interference at right.

As with the measurements from Radar B, the plot at right shows fewer and weaker returns for the radar when exposed to interference.

Conclusions and Discussion

This project found that radar congestion affects the behavior of an automotive FCW system. In some trials this was observed as an increased variance in the time to collision when alerts were given. In other trials, this resulted in alerts not being issued as expected. The project developed tools and used them to observe changes in the detections reported by automotive radars operating in congested environments. The project demonstrated inclusion of measured RF backgrounds into simulation. Measurements were analyzed to produce empirical models of path-loss for automotive radars.

The Radar Congestion Testing project resulted in several products to better characterize the production and impacts of mutual interference for automotive radars.

- Empirical path-loss models that provide realistic models of interference
- M2I2 simulation for comparing simulated sensors with test track experiments
- Experimental designs to test the impact of mutual interference on commercial automotive radars and vehicles with radar supported ADAS features
- Methods to characterize RF backgrounds during experiments for direct comparison in simulation
- Analysis showing the impact of radar congestion on the tracking and detection output of commercial automotive radars
- Analysis of the impact on performance of a vehicle with a radar-enabled FCW system

Several important conclusions resulted from this research.

- The impact of interference is observable in the detections and tracks of automotive radars. The details of the impact depend on internal functions of the radar, as well as the environment.
- The impact of interference on a vehicle with an FCW system can be observed in realistic tests. These tests can be conducted safely and reliably.
- The RF environment can be sampled with current network analyzers. This technology provided measurements suitable for modeling the propagation environment and used to replay the recorded interference in simulation.

The empirical evaluations of RF interference impact on commercially fielded systems looked at the impact on the tracking and detection outputs of commercial automotive radars, and the performance of a vehicle with radar-enabled FCW system. In each case, the analysis is done without knowledge of the systems, beyond published specifications. The analysis shows that interference has an observable impact on the detections and tracks of automotive radars, and on the issuance of FCWs by a vehicle equipped with a radar supported system.

On one of the days in the test schedule, the vehicle did not issue FCWs without the support of the camera. This system behavior began during a test with active interference and persisted after they were powered off. This behavior, of not issuing FCWs, was not observed on the other day in the test schedule that included active interferers.

The FCW alerts in the Result column of Table 16 require some context. The first three test sequences were conducted with only the SV and POV, and no other vehicles were on the track. These tests demonstrated that the vehicle issued FCWs reliably, even with the camera obscured, and that there was sufficient time for a skilled driver to stop the vehicle with time to spare. The researchers noted that the system would issue a fault for the FCW system, with some delay after the camera had been obscured.

All of the following test sequences included other radar-equipped vehicles on the test track, as well as a road-side traffic control radar. These units were stationary. In some tests, these interfering radars were ON, and in others, the interfering radars were OFF, as noted in Table 16. Test sequences 4 through 11 were all conducted on a single key cycle of the SV. Tests 4 and 5 demonstrated that the vehicle issued FCWs with the camera unobscured, without and with, interfering radars in the scene.

In Test sequences 6, the camera was covered, and the interfering radars were left in the scene. This resulted in a complete loss of FCWs, without report of a system fault. The remaining tests on this key cycle show that the system would only issue FCWs once the camera was unobscured again, suggesting that the system had ceased consulting the radar in determining FCWs.

Test sequences 12 to 18 were on a separate key cycle. In all of the 43 trials here, the system appropriately resulted in FCW. As noted in the analysis in the section Empirical Evaluations of RF Interference Impact on Commercially Fielded Systems, there is an observable increase in the variance of the onset of the FCWs; however, the average response of the system is similar.

These tests on the SV with an FCW system, supported by camera and radar, encountered a series of tests where the system did not issue alerts without support of the camera. FCW alerts were recorded as an observable measurement, but the researchers had no access to other system information, or details of the algorithms responsible for the declarations. In some cases, test sequences 6, 7, 10 and 11, in Table 16, the vehicle under test did not report a fault to the operator, even though its performance appeared compromised.

The tests developed and conducted in this study to evaluate commercially fielded systems identify potential protocols that can be safely conducted in a test track environment. Over 150 trials were conducted, and a statistically significant impact was observed during this track testing of radar-based systems. This was accomplished over a few days. Improved test protocols could increase efficiency to the point that large numbers of trials can be completed for several vehicles.

Table 16. Results from 18 sequences (a total of 120 trials) of tests of an FCW system with combinations of camera system support and presence of other radars

Test Sequence	Interfering Radars	SV Camera	Result	# Trials
1	NONE	unobscured	FCW	11
2	NONE	OBSCURED	FCW	6
3	NONE	OBSCURED	FCW w/ fault	7
4	OFF	unobscured	FCW	15
5	ON	unobscured	FCW	12
6	ON	OBSCURED	NO FCW	10
7	OFF	OBSCURED	NO FCW	1
8	OFF	OBSCURED	NO FCW w/ fault	11
9	OFF	unobscured	FCW	2
10	OFF	OBSCURED	NO FCW	1
11	OFF	OBSCURED	NO FCW	1
12	OFF	unobscured	FCW	3
13	OFF	OBSCURED	FCW	8
14	OFF	OBSCURED	FCW w/ fault	3
15	ON	OBSCURED	FCW w/ fault	11
16	ON	unobscured	FCW	13
17	ON	OBSCURED	FCW	2
18	ON	OBSCURED	FCW	3
Note: In all trials, an FCW was expected to be elicited. “NO FCW” indicates an FCW was not elicited for that block of trials. Results marked “w/fault” indicates that a “front camera unavailable” fault was presented on the instrument cluster for that block of trials.				

Parameterized empirical path-loss models, which provide realistic models of interference based on measured data, are one such product. The models’ parameters are tabulated for implementation by researchers into any simulation that considers the propagation of interfering radars.

The models of RF propagation for automotive radar may be used to improve the fidelity of automotive radar simulation. The measured data shows that RF propagation between vehicles in the same lane is consistent with a two-ray model, Figure 45. However, it is very difficult to capture all of the physics relevant to mutual RF interference and is best treated statistically. Predicting the likelihood of system failure due to RF interference has not been addressed in this study. The possibility for power levels from interfering radars exceeding the typical power levels expected for a radar’s own signals by several orders of magnitude, creates the potential for failures due to non-linear effects (e.g., sensor saturation), which are exceedingly difficult to treat analytically, or in simulation. These observations suggest the use of empirical models and HWIL tests are invaluable to assessing the impact of radar interference.

M2I2 has been updated to allow the insertion of measured interference into the simulation. M2I2 has been updated to the current version of Matlab’s Automated Driving Toolbox. Data collected

during experiments, detailed in the section Empirical Evaluations of RF Interference Impact on Commercially Fielded Systems, were used to reproduce the environment in the experiments in Mcity in M2I2 simulations.

The project developed experimental designs to test the impact of mutual interference on commercially available automotive radars and vehicles with radar based FCW systems. The resulting tests demonstrate that these tests can be conducted safely, repeatably, and reveal measurable impacts of mutual interference on W-band radar systems. While these approaches may be useful in development of procedures for other radar bands, this project focused specifically on W-band systems due to their prevalence.

Measurements of the interfering power *in situ* during the empirical evaluations of the impact on commercially fielded systems were used to characterize the RF background for comparison to backgrounds in other studies, and to provide a statistical model for simulation with similar backgrounds to the tests. This can be used to conduct test track experiments, in parallel with simulations that have the same interference conditions.

References

- Al-Hourani, A., Evans, R. J., Kandeepan, S., Moran, B., & Eltom, H. (2017). Stochastic geometry methods for modeling automotive radar interference. *IEEE Transactions on Intelligent Transportation Systems*, 19(2), 333-344.
- Buller, W. T., & LeBlanc, D. J. (2012, July 8-13). *Radar characterization of automobiles and surrogate test-targets for evaluating automotive pre-collision systems*. 2012 IEEE International Symposium on Antennas and Propagation, Chicago, IL.
- Buller, W., Wilson, B., Garbarino, J., Kelly, J., Thelen, B., & Belzowski, B. M. (2018). *Radar congestion study* (No. DOT HS 812 632). National Highway Traffic Safety Administration.
www.nhtsa.gov/sites/nhtsa.gov/files/documents/13790_radarstudy_092518_v2b-tag.pdf
- Davis, J. S., & Linnartz, J. P. M. (1994, October). Vehicle to vehicle RF propagation measurements. In *Proceedings of 1994 28th Asilomar Conference on Signals, Systems and Computers* (Vol. 1, pp. 470-474). IEEE.
- Devroye, L. (1986, December). Sample-based non-uniform random variate generation. In *Proceedings of the 18th conference on Winter simulation* (pp. 260-265).
- Etinger, A., Litvak, B., & Pinhasi, P. (2017). Multi ray model for near-ground millimeter wave radar. *Sensors* 2017, 17; <https://doi.org/10.3390/s17091983>
- Forkenbrock, G. J., & Snyder, A. S. (2015, June). *NHTSA's 2014 automatic emergency braking test track evaluations*. (Report No. DOT HS 812 166). National Highway Traffic Safety Administration.
www.nhtsa.gov/sites/nhtsa.gov/files/812166-2014automaticemergencybrakingtesttrackeval.pdf
- Heuel, S. (2016). Automotive radar sensors must address interference issues. *Microwave Journal*, 59(12), 22-36.
- Kunert, M. (2012a, October). The EU project MOSARIM: *A general overview of project objectives and conducted work*. In 2012 9th European Radar Conference (pp. 1-5). Institute of Electrical and Electronics Engineers.
- Kunert, M. (2012b, December 21). *Publishable summary* (Report No. MOSARIM 248231). [Web page]. MOre [sic] Safety for All by Radar Interference Mitigation.
- Rappaport, T. S., & Milstein, L. B. (1990, December). Effects of path loss and fringe user distribution on CDMA cellular frequency reuse efficiency. In *[Proceedings] GLOBECOM'90: IEEE Global Telecommunications Conference and Exhibition* (pp. 500-506). IEEE.
- Richards, M. A. (2005). *Fundamentals of radar signal processing*. Tata McGraw-Hill Education.
- Song, H., Kwan, R., & Zhang, J. (2011). Approximations of EESM effective SNR distribution. *IEEE Transactions on Communications*, 59(2), 603-612.
- Terbas, D., Laghezza, F., Jansen, F., Filippi, A., & Overdevest, J. (2019, October 2-4). *Radar to radar interference in common traffic scenarios*. 2019 16th European Radar Conference, Paris, France.

DOT HS 813 826
October 2026



U.S. Department
of Transportation
**National Highway
Traffic Safety
Administration**



16984-092526-v2b