	Title	RPS Ex Parte Response May 20 2020				
	Document No	DC42005				
	Date	09 Jun 2020	Author	ML	Rev	1.0

REVISION HISTORY					
Issue	Date	Author	Details	Approved By	Date
1.0	09/06/20	Matt Langhelt	Initial document release	David Leonard	09/06/20

CONTENTS

Purpose

This document outlines the RPS response to questions raised during the call with the FCC on 20th May 2020. These questions mainly related to the ETSI limit calculations in the 15th April 2020 Ex Parte submission [1] (specifically what these numbers were once free space path loss was taken into consideration), and for clarity on the calculations submitted by RPS in response to the NHTSA radar congestion study [2].

This document aims to present a comprehensive set of calculations, based on 3 key bodies of work, that fully take into account factors arising from practical installation scenarios.

References

[1] RPS, "RPS Ex Parte Report 15th April 2020," DC42001, 22 Apr 2020.

[2] W. Buller, B. Wilson, J. Garbarino, J. Kelly, N. Subotic, B. Thelen and B. Belzowski, "Radar Congestion Study (Report No. DOT HS 812 632)," National Highway Traffic Safety Administration, Washington, DC., (2018, September).

[3] M. Kunert, ""Final report"," European Commission: MOre safety for all by radar interference mitigation (MOSARIM), Luxembourg, Tech. Rep. 248231, 2012-12-21. [Online]. Available: https://cordis.europa.eu/project/rcn/94234/reporting/en.

[4] ETSI, "EN 301 091-1: Short Range Devices; Transport and Traffic Telematics (TTT); Radar equipment operating in the 76 to 77 GHz range; Harmonised Standard covering...article 3.2 of Directive 2014/53/EU; Part 1: Ground based vehicular radar," v2.1.1, 2017-01.

[5] ETSI, "EN 302 264: Short Range Devices; Transport and Traffic Telemetrics (TTT); Short Range Radar equipment operating in the 77 GHz to 81 GHz band; Harmonised Standard covering the essential requirements of article 3.2 of Directive 2014/53/EU," v2.1.1, 2017-05.

[6] FCC, "Modernizing and Expanding Access to the 70/80/90 GHz Bands," WT Docket No. 20-133, Notice of Proposed Rulemaking and Order, May 19, 2020.

[7] RPS, "RPS NHTSA 2018 Radar Study Response," DC42004, 19 May 2020.

[8] W. T. Buller and D. J. LeBlanc, "Radar characterization of automobiles and surrogate test-targets for evaluating automotive pre-collision systems," in *Proceedings of the 2012 IEEE International Symposium on Antennas and Propagation*, Chicago, July 8-14, 2012.

1 Brief Answer to FCC Questions

In answer to some specific questions from the FCC, RPS offers analysis of two key factors, free space path loss and geometry, that establish a framework for deployment of RPS MiRTLE units in a manner that avoids any credible risk of interference with vehicular radar. RPS observes that 1) based on a worst-case **free space path loss** analysis, not taking antenna geometry into account, the RPS MiRTLE unit will not interfere with a vehicular radar 21 meters or more away from the unit, and 2) when installation **geometry** is included, an RPS MiRTLE unit installed at a height of 2.4 meters or higher will not interfere with vehicular radar due to the misalignment of the transmit and receiver antennas[1]. RPS MiRTLE units will be installed at a minimum height of 2.4m when within 21 meters of a roadway. The details are presented in the sections below and in the appendices.

2 Executive Summary of Analysis

RPS, prompted by questions raised in our last meeting with the FCC (20th May 2020), has done extensive analysis of the interaction of the RPS MiRTLE system and vehicular radar systems. In doing this, we have referenced three cardinal reports which serve to define both basic scenarios of interaction between vehicular radar systems with possible interfering systems, and also define basic performance goals associated with vehicular radar systems. The reference reports included in our analysis are:

- The NHTSA 2018 Radar Congestion Study [2], which analyzes four basic vehicular scenarios in a congested radar environment and defines performance goals that vehicular systems must meet in the face of noise interference created typically by other vehicular systems in a congested road environment.
- The MOSARIM Project, a multiyear experimental and analytic effort undertaken by the European Union defining potential interferers, interfering scenarios, and performance goals [3]. MOSARIM represents perhaps the most ambitious effort to date in this area.
- ETSI standards relevant to vehicular radar systems which provide proscriptive performance criteria for radar systems [4] [5].

A summary of the key values resulting from this analysis is presented in Table 1. Our analysis demonstrates that the RPS MiRTLE system, even in worst-case scenarios, cannot interfere with vehicular radar systems with the installation restrictions cited above.

[1] “interfere” in points 1) and 2) refers to a Signal-to-Interference Ratio (SIR) of less than 10 dB, as proposed in the NHTSA radar congestion study [2], based on the expected minimum target signal level for that vehicular radar system (calculated in the NHTSA study).

Referenced Key Target	Target Limit	RPS Worst-case Calculation	Analysis Section
NHTSA Congestion Study – Minimum Signal-to-Interference Ratio (SIR)	10 dB (min.)	17 dB	§3
MOSARIM – Maximum Interference-to-Noise Ratio (INR)	0 to -10 dB (max.)	-20 dB	§4
ETSI Automotive Radar Standards – Maximum Unwanted Signal Level	55 mV/m (max.)	0.000135 mV/m	§5

Table 1: Summary of worst-case calculated values for the RPS MiRTLE unit from the analysis in this report, and the key target values taken from the referenced works

The reasons for the compatibility of the RPS MiRTLE system with vehicular radar lie within the physics of mm-wave transmission. Radio operation in the 70 to 80 GHz region suffers from high attenuation requiring high gain and concomitantly narrow beam antennas. Thus, unless antennas are placed in an environment where they operate coaxial to one another, significant attenuation between systems will occur. This is a widely acknowledged principle within this frequency range and, in fact, the FCC as well as other technical experts expect wide sharing of these bands among disparate systems through the use of spatial diversity created by these "pencil beams" of transmitted energy [6].

As we have discussed in past meetings with the FCC, our systems will be mounted typically at a height of 3-5m and angled down at a minimum angle of 3 degrees (see Figure 1). MiRTLE systems, as a result, will never be coaxial with vehicular systems that are mounted less than a meter off the ground and typically operate parallel to the plane of the earth. Furthermore, our analysis shows that when roadways are 21m or beyond from a MiRTLE installation, that regardless of antenna height, no impact on operation of vehicular systems is to be expected. When roadway surfaces are within 21m of a MiRTLE unit, RPS will commit to a minimum antenna height of 2.4m[2], the resulting geometry ensures there will be no degradation of the operation of vehicular radar systems.

[2] As we have noted, we expect typical installation height to be 3 to 5m.

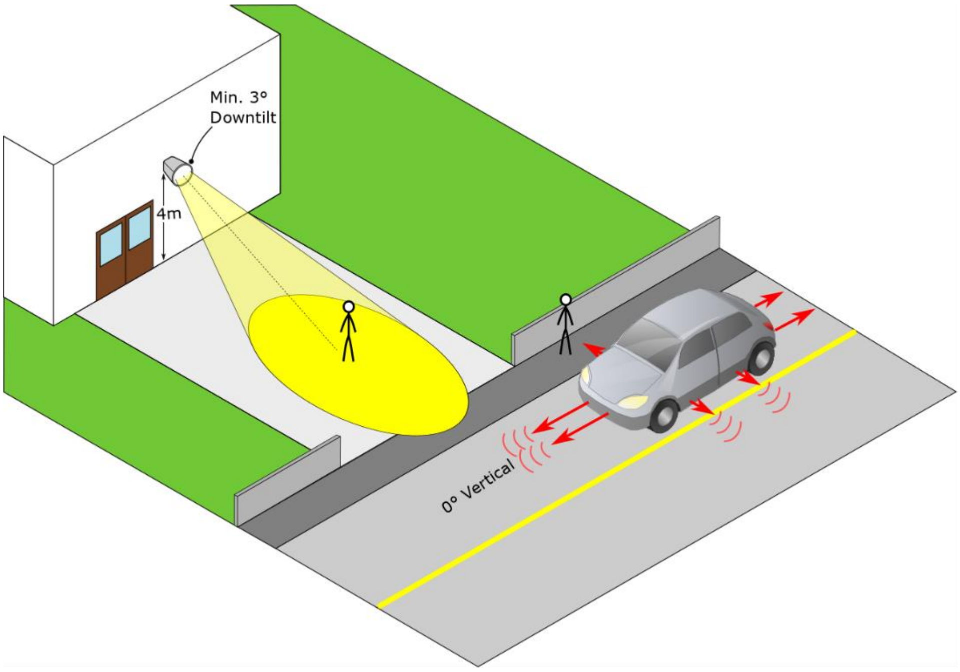

Figure 1: Typical installation geometry of an RPS MiRTLE unit with an adjacent roadway. MiRTLE unit is typically installed height of 3-5m, and operates with a maximum elevation of -3° from the horizontal. Vehicular radar will generally be operating near the ground and pointing parallel with the road surface. Additional clutter will generally be present such as walls, trees, parked cars etc.

Reviews of both the NHTSA study and the MOSARIM project make it readily apparent that the interfering scenarios of concern are those where the road infrastructure forces alignment of interfering sources with the victim receivers on a vehicle. As a result, the expected dominant interfering sources are other vehicles deploying similar radar systems that are geometrically constrained by road infrastructure, so they are aligned with the antennas of the victim receivers[3]. Our analysis, presented below, demonstrates that even when taking transient scenarios into account, RPS interfering signal levels are significantly (more than 10 dB) below levels that would interfere with the operation of vehicular systems as outlined within the references cited. This very conservative analysis does not take into consideration a real-world environment which would further mitigate any detrimental effects of the RPS MiRTLE signal. This conservative approach is necessary because of the difficulty in modelling those factors of real-world environments. Put simply, the MiRTLE system is not aligned with a road structure, as, for example, an interfering vehicle would be.

As noted in the NHTSA study, radar systems build a radar track of a target, eliminating spurious signals as noise which cannot be physically represented as a track. While we present data showing that

[3] MOSARIM also makes note of possible interference from point to point microwave utilizing roadway Right of Way (RoW) and therefore aligned with vehicular systems, though even in this situation, within the 70 GHz band, this was not viewed as overly significant.

MiRTLE signals are well below any credible interference level, even if that were not the case, movement of the victim car and scanning of the MiRTLE antenna would ensure that a radar track could not be formed. We also note that while we present “worst case” signals, they are transitory in nature and the movement of both the car and the scanning transmitter would guarantee less optimal configurations would prevail most of the time. We emphasize however that we have not taken these additional mitigating factors into our analysis, which follows.

3 Comparison to NHTSA Study Scenarios

The NHTSA “Radar Congestion Study” [2] provides an analysis of the likely levels of interference that can be expected to be seen as the number of vehicles on the roads utilising radar technology increases. This is done by constructing a number of scenarios where vehicular radar might interact between vehicles, and then applying stochastic modelling techniques to evaluate the likely level of interference seen by a victim vehicle[4] and the effect on the victim radar’s target tracking algorithms. This provides a good comparison for analysing the RPS device’s potential impact on vehicular radar.

The scenarios analysed in the NHTSA study are used by RPS as a framework for assessing the interference generated by the RPS device and its impact on vehicular radar. This is done by placing the RPS device into each scenario at a location representative of a real-world deployment scenario for the unit. In most cases, RPS believes that the MiRTLE system will be deployed away from roadways, so the setups used in each scenario represent a small number of potential worst-case deployments with respect to interfering with vehicular radar, and only a small subset of expected actual deployments.

This work builds upon the initial response to the NHTSA study that Radio Physics submitted in May 2020 [7], which covered a single scenario not directly linked to those in the NHTSA study (though representative of a possible interference situation). This work expands upon this initial submission by modelling the RPS MiRTLE unit in all four of the scenarios covered by the NHTSA study, using the scenario setups directly so that a direct comparison can be made. The parameters used for the victim radar in each scenario come from the representative values set out in Table 5 of the NHTSA study ([2] §5.1) and are based on NHTSA methodologies and assumptions as closely as is practical.

The full detail of the modelling approach, calculations used, and setup and results for each scenario can be found in Appendix A – NHTSA Study Scenario Calculations.

Scenarios 1, 2 and 3 assess the impact on Long- and Medium-Range Radar (LRR and MRR, respectively), typically those used for Automatic Cruise Control (ACC) and emergency brake assist. Of these, as noted in our last meeting, scenario 1 provides the worst-case direct comparison for the RPS MiRTLE unit.

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[4] Termed ‘ego’ within the report.

The calculations show that the worst-performing setup in this instance (angled 30° towards the roadway, 20m back with victim MRR) gives an interference power level of -102 dBm (dB milli-Watts)[5] observed by the receiver. This results in a Signal-to-Interference Ratio (SIR) of 17 dB when compared to the minimum signal received back from the target vehicle in the NHTSA study. This means that the interference power from the RPS MiRTLE unit is a factor of -17 dB lower than the worst-case target signal being tracked by the victim radar, and a factor of -44 dB lower than the equivalent value calculated for the vehicular radar interferer in the NHTSA study.

Scenario 4 similarly assesses the effect of interference on a Short-Range Radar, in this case one used for assisting in backing up or reversing the vehicle. The calculations show that for this case the interference power presented by the RPS unit to the victim radar is below -96 dBm, giving an SIR of more than 28 dB. This means that the interference power resulting from the presence of the RPS unit is a factor of at least -28 dB lower than the lowest target signal being tracked by the victim radar (from the NHTSA study calculations), and a factor of -46 dB lower than the value calculated for interfering vehicular radar.

These results indicate strongly that not only will a deployed RPS device not cause interference with vehicular radar (as shown by the large SIR), but that the interference power levels are sufficiently low that any cumulative effect that an RPS unit adds to other interference sources is negligible.

The radar models presented in the NHTSA radar congestion study are also used to calculate minimum installation distances for the MiRTLE unit when being deployed in the vicinity of a roadway. These calculations are presented in Appendix A.7 – Calculation of Minimum Installation Distances, and show that an SIR of at least 10 dB is maintained in the worst-case for vehicles positioned 21 meters or further away from a MiRTLE unit. Additionally, it is concluded that for cases of a vehicle being within 21 meters of the unit, a minimum installation height of 2.4 meters ensures that the transmitter and receiver fields of view are misaligned sufficiently so as to keep the SIR well above 10 dB[6].

4 Comparison to MOSARIM Interference-to-Noise Levels

Following on from the analysis of the NHTSA scenarios, the equivalent Interference-to-Noise Ratios (INR) are calculated for each victim radar type from the worst-case interference power levels. These calculations are presented in Appendix A.6 – Interference-to-Noise Ratio (INR) Calculations.

The calculations show that in the case of the highest interference power level emanating from the RPS unit, the INR is -19.97 dB (i.e. ~20 dB below the noise floor of the victim receiver). At this level, the

[5] We note to avoid confusion that the NHTSA 2018 report cites power levels in both dBm and dBW. Within our presentation we consistently use the more common dBm for clarity.
[6] Misalignment of the MiRTLE unit transmit antenna and vehicular radar receive antenna means that the high antenna gains of each are not combined (the receiver does not "see" the transmitter), reducing the interference power level by a factor of 20 dB in the case of the Medium-Range Radar model.

effect that the RPS unit has on the noise floor of the victim receiver will be miniscule, and so there should be no discernible degradation of the receiver performance.

5 Comparison to ETSI Standard Unwanted Signal Levels

Although automotive manufacturers in the US market are not bound by ETSI standards, they provide an important reference point from which to analyse the signal levels produced by the RPS device, as they represent a European regulatory and industry consensus view on key performance characteristics for vehicular radar systems.

As discussed in the RPS Ex Parte submission in April 2020 [1], the ETSI automotive standards specify that receivers must be able to handle unwanted signals with a field strength of 55 mV/m at the device (for in-band signals).

Calculations originally submitted in [1] did not take into account path loss due to free space propagation, or the relative antenna geometry between the RPS device and a victim automotive radar. As both of these factors are important in determining the signal levels produced by the RPS device in any real-world, practical situation, these calculations have been updated to include them.

With the above factors taken into account, average transmit signal strength (over a dwell time of 1 second) from the RPS device incident on an automotive radar receiver at 20m is calculated to be 0.000135 mV/m. This represents a margin of -56 dB below the ETSI standard limit. Signal strength levels at additional distances are summarised in Table 2.

In the “instantaneous” case, with all time-averaged de-ratings excluded, the signal level at 20m is determined to be 0.0371 mV/m. This still represents a margin of -31.7 dB below the ETSI standard limit. This calculation is included as an additional reference point only, as instantaneous power levels are not a significant concern when considering interference with vehicular radar[7].

A full derivation of the factors included in these calculations is presented in Appendix B – Derivation of ETSI Unwanted Signal Level Calculations.

[7] Instantaneous or highly transitory interference is generally well rejected by vehicular radar receivers due to the various time-averaged techniques that are used to create and maintain target tracks, such as the use of CFAR, etc. Update periods for vehicular radar can be in the order of 10s of milli-seconds, and so the effect of very short period interference bursts gets heavily attenuated over these longer averaging periods.

Receiver Distance from Radio Physics Device, r (m)	Power Flux Density, S (W/m^2)	Electric Field Strength, E_{RPS} (mV/m)	ETSI Standard Limit, E_{LIM} (mV/m)	Ratio of Signal Level to Limit, E_{RPS}/E_{LIM} (dB)
10	8.074×10^{-16}	0.000552	55	-50.0
20	5.046×10^{-17}	0.000135	55	-56.0
30	9.968×10^{-18}	0.0000613	55	-59.5

Table 2: Calculated power flux density and electric field strength at multiple ranges, assuming a 1s dwell time

6 Conclusions

RPS has presented analysis of the interaction between the RPS MiRTLE system and vehicular radar, in the context of three of the major bodies of work that address interference between vehicular radar systems. Further, in this report, RPS has presented data regarding the effects of free space path loss and geometry on the potential for interference to vehicular radar. All of this analysis shows that the RPS MiRTLE system will not cause interference to vehicular radar.

The NHTSA 2018 Radar Congestion Study provides a set of scenarios and radar signal levels that were used as the basis for analysing how a deployed MiRTLE unit might interact with vehicular radar. The study also provides guidance of a target minimum Signal-to-Interference Ratio (SIR) of 10 dB that should be preserved in worst-case interference scenarios. After evaluating a modelled MiRTLE unit deployment in each of the scenarios explored by the study, RPS have presented calculations showing a worst-case SIR of 17 dB for a victim vehicular radar passing a MiRTLE installation.

The MOSARIM project was a large and extensive body of work covering many aspects of interference with vehicular radar. However, one key figure of merit presented in the project report was a maximum Interference-to-Noise Ratio (INR) of 0 to -10 dB to avoid degradation of victim receiver performance. RPS presented calculations based on the findings of the NHTSA study scenario analysis that determined maximum INR values resulting from the presence of the MiRTLE unit to be -20 dB, an additional 10 dB below the limit set by the MOSARIM project.

The ETSI standards for vehicular radar stipulate limits for unwanted (i.e. interference) signals that radar receivers must be able to handle without causing issues to the radar. For in-band interference, this signal level is defined as having an electric field strength of 55 mV/m. RPS have presented calculations that show the radiated power of the MiRTLE unit are equivalent to an electric field strength that is a factor of 56 dB lower than the ETSI limit.

Additional work based on the radar models utilised in the NHTSA radar congestion study has been presented that demonstrates that, even without factoring in practical relative geometries between the RPS MiRTLE unit and a vehicular radar receiver (as well as the dynamic nature of the real life scenarios), the RPS MiRTLE unit will not reduce the SIR of a vehicular radar below 10 dB at distances of 21 meters or greater. For distances less than 21 meters, RPS has established that a minimum installation height of 2.4 meters is sufficient to avoid reducing the SIR below 10 dB, and in almost all practical situations it will be significantly higher.

The above analyses demonstrate that in practical, real-world deployments, the RPS MiRTLE unit poses no threat of interfering with vehicular radar, and that the signal levels emitted by the unit are sufficiently low that the addition they make to any cumulative interference is negligible. We also note that the figures we have presented are conservative and, as we have described, do not include multiple other real-world mitigating factors that would further reduce the already negligible impact of the RPS MiRTLE system on vehicular radar systems. Based on our analysis, RPS proposes that MiRTLE units to be deployed within 21 meters of a roadway will be mounted at a minimum installation height of 2.4m, to remove any possibility of the RPS MiRTLE unit interfering with vehicular radar.

7 Appendices

Appendix A – NHTSA Study Scenario Calculations

Appendix A.1 – Modelling Approach and Calculations

The NHTSA study modelled interactions between vehicular radar in a number of scenarios. The authors constructed a fully statistical model to represent the interference caused by continuous streams of either opposing or passing traffic, and the effect this had on a victim radar attempting to track a target vehicle either in-front (scenarios 1-3) or travelling perpendicular (scenario 4) to it.

While this approach works well in the case where there is a steady stream of interferers (albeit a randomly distributed one), as one would expect with other vehicles, this approach is not directly applicable to the case of an RPS device installation. Firstly, the RPS device will be statically mounted (generally on a building), and so will not track with a vehicle (i.e. the vehicle will instead drive past the unit). Also, RPS units will generally not be mounted near roadways, and certainly not in great enough numbers to warrant representation in a similar manner (i.e. there will not be an RPS unit every 15-25m as with the NHTSA traffic model).

Therefore, the approach for constructing a similar model to the NHTSA study, but representative of a practical installation of an RPS device, instead places a single unit into each NHTSA scenario and moves the victim and target vehicles with respect to that unit. The unit is placed in a position representative of a realistic install location near a roadway and is assessed using the key performance parameters drawn from the NHTSA study.

The model then steps through the scenario (with the moving victim and target vehicles) in a number of sufficiently granular time steps (1 step = 200ms or approximately 5.5m of travel for a vehicle travelling at 100 km/h), in order to calculate the relative geometries of the victim/target vehicles and the RPS unit at each step and the resulting interference power presented by the unit.

The interference power observed by the victim radar receiver is calculated for each time step in the simulation as:

$$P_{RX} = \frac{P_{TX}G_{TX}G_{RX}D_F}{G_C FSPL(d)}$$

Where P_{TX} is the transmitted power from the RPS unit, G_{TX} is the RPS unit transmit antenna gain, G_{RX} is the victim receiver antenna gain, $FSPL(d)$ is the path loss due to free space propagation (as a function of distance).

G_C[8] is the receiver compression gain (equal to the number of range bins for each radar type). The compression gain is relevant due to the uncorrelated nature of the interference compared to the

[8] The value for G_C is obtained from the NHTSA report for the respective type of radar receiver, i.e. long-, medium- and short-range radar (LRR, MRR and SRR, respectively)

power received from a target. Both radar use FMCW modulation (as is also the case with the RPS device). This means that the power returned from the target is highly correlated with the victim transmitter used to illuminate it (as the transmitter is used to mix the received power down to baseband). Interference power from any other FMCW radar (vehicular or the RPS device), however, will not be correlated with the victim transmitter and as a result can be assumed to have the effect of adding white (gaussian) noise across all range bins of the receiver. This "spreading out" of the interference energy, while the correlated return from the target is confined largely to a small number of bins, provides a processing gain that is represented by G_C. This factor is applied within the NHTSA study to the interference power calculations for the same reasons outlined above.[9]

D_F is the duty factor, and is defined as:

$$D_F = D_{band} \times D_{frame} \times D_{rx}$$

Where D_{band} is the proportion of active transmit time that the RPS unit transmitter spends within the victim receiver operating band (0 to 1, varies according to radar type), D_{frame} is the RPS unit maximum duty cycle (25%), D_{rx} is the victim radar duty factor (0 to 1, varies according to radar type). See Appendix B.4 – Combined Duty Factors for a full breakdown of how these are calculated.

In each time step of the simulation, the relative geometries of the RPS unit transmitter and victim receiver are calculated and used to calculate an appropriate de-rating of the transmitter and receiver antenna gains. This is performed according to the angular displacement with respect to the transmitter or receiver antenna fields of view, with G_{TX} or G_{RX} being de-rated accordingly. This is an important factor in analysing the effect of the RPS device as a potential interferer, 1) because its high-gain antenna means that it is highly directive, and 2) the nature of its installation and operation (i.e. with implicit down-tilt) means that the transmit beam will generally not be co-axial with an automotive radar receiver.

G_{TX} also includes the antenna scan de-rating factor described in Appendix B.3 – Transmit Antenna Scan De-rating.

[9] Simply, we are following the NHTSA method of calculation.

Appendix A.2 – Scenario 1

Appendix A.2(i) – Setup

The NHTSA study scenario 1 ([2], §6.2) considered the effect of vehicles in the opposing lane on a victim vehicle with forward-looking radar gaining on a target vehicle. This scenario had the victim car travelling at 80 kph, with the target vehicle travelling at 20 kph. The interference from opposing traffic was modelled as a time-averaged power value based on a Poisson-distributed continuous flow of vehicles.

The RPS unit is statically installed at a fixed location, and so in order to provide a comparative model, the victim vehicle was instead modelled as driving towards and passing a fixed RPS unit installation a representative distance from the roadside (see Figure 2). This models a situation where the unit is covering a street entrance to a building, with a roadway running parallel to the building front. While not considered to be a common setup, this model represents the closest an RPS unit would get to the scenario 1 setup.

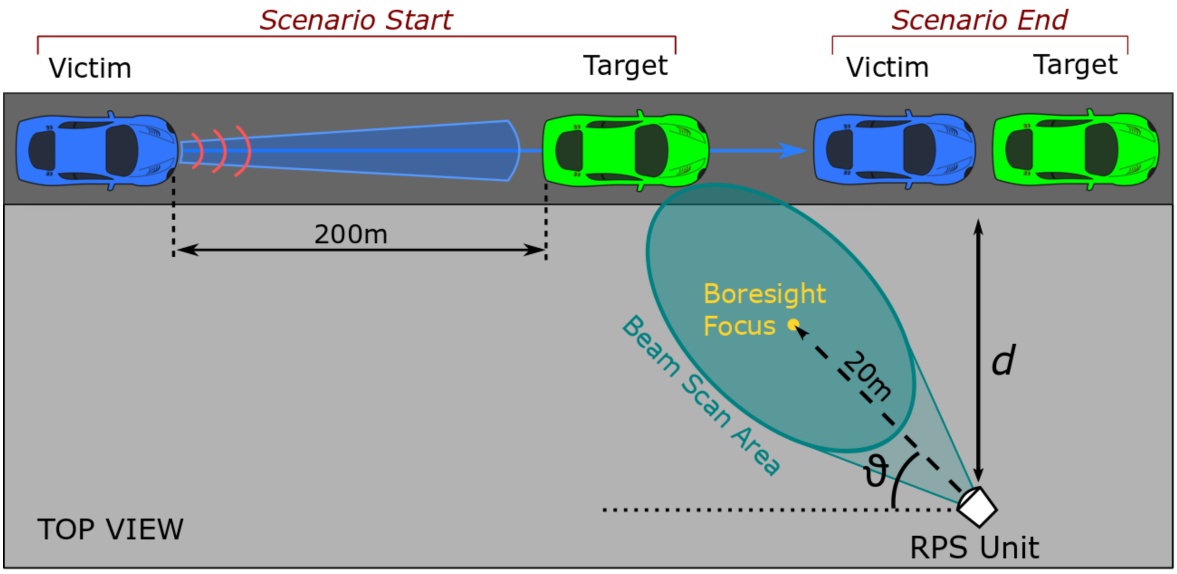

Figure 2: Top view of Scenario 1 model setup, showing start and end points of victim receiver. Target vehicle (green) represents the position of the target in the NHTSA model, and is not re-modelled for this analysis. d = 20m, 30m. θ = 30°, 45°, 60°

The scenario was set up with the following parameters:

- Scenario duration is 12 seconds – This matches the NHTSA study, and is time taken for the victim vehicle to collide with the target vehicle
    - Calculations were made at every 0.2s step within this duration
- Vehicles:
    - Victim / Ego vehicle (blue), 80 kph
        - The victim car's start position is so that after travelling for 12 seconds it draws level with the RPS unit (i.e. RPS unit was perpendicular to the victim receiver boresight). This equates to an initial distance of 267m at 80 kph

    - Target vehicle (green), 20 kph
- Radar
    - Forward-facing LRR and MRR on the victim vehicle (blue)
        - In both cases, the radar parameters are taken from the NHTSA study
- RPS Unit
    - Installation distance from the roadside, d = 20m, 30m
        - Two instances of the model were run for each radar type, one at 20m and one at 30m
    - Unit oriented at three different angles towards the road (ϑ(unit) = 30°, 45°, 60°)
        - All iterations were repeated with the unit at each angle

The speeds used were set to match the NHTSA study but have no particular effect on the incident power at each time step. That is, if the victim car were instead travelling at 40 kph (25 mph), the maximum incident power levels would not change (values averaged over the whole simulation would do, but this is not done in this analysis).

Appendix A.2(ii) – Results

The results of the Scenario 1 simulation are shown in Table 3. The results list the maximum value for P_{RX} seen in any single time step during the simulation, in all twelve iterations of the test setup (LRR/MRR, 20m/30m, 30°, 45°, 60°). It should be noted that these values are not time-averaged across the duration of the simulation, as was the case for the power values determined in the NHTSA study[10].

The results show worst-case interference power observed at the victim receiver of -102.0 dBm, resulting in a minimum Signal-to-Interference Ratio (SIR) of 17.0 dB. In comparison to the interference power from other vehicular radar, as calculated in the NHTSA study, the worst-case interference power from the RPS unit is lower by a factor of -44 dB. Simply, the interference received from the MiRTLE system is more than 4 orders of magnitude less than interference from other vehicles as calculated in the NHTSA report.

It should be noted that the maximum received power from the RPS transmitter and the minimum target signal level have been aligned in this analysis, even though they did not necessarily occur at the same time in the simulation. In reality the events would not be synchronised, and so aligning them in this conservative manner presents the worst-case (i.e. minimum) SIR.

[10] Again, we note that we have purposely chosen to do a conservative analysis and that other mitigating factors such as power averaging add additional safety margins to our analysis

dB milli-Watts (dBm)	RPS unit horizontal angle towards road, ϑ(unit)	Interference power from RPS unit observed by victim receiver, P_{RX} (max.)		Minimum Target Signal Level, P_T (from [2] Table 8)	Interference Level from Equivalent Radar, P_I (from [2] Table 8)
		d = 20m	d = 30m		
Victim: LRR	45°	-123.41	-126.76	-77	-50
Victim: MRR	45°	-117.84	-121.20	-85	-58
Victim: LRR	30°	-126.00	-134.25	-77	-50
Victim: MRR	30°	**-102.00**	-123.78	-85	-58
Victim: LRR	60°	-122.58	-125.64	-77	-50
Victim: MRR	60°	-117.02	-120.08	-85	-58

Table 3[11]: Maximum incident power at victim receiver from RPS unit transmitter, for Long-Range Radar (LRR) and Medium-Range Radar (MRR) in Scenario 1 setup. For comparison, minimum power received from target, P_T, and interference power received from equivalent interfering radar (LRR to LRR, MRR to MRR), P_I, taken from [2], Table 8.

[11] Power levels in this table and quoted throughout this document are in terms of dBm (dB referenced to 1 milli-Watt). The NTIA study quotes power levels in terms of dBW (dB referenced to 1 Watt). NHTSA power levels referenced in this report have been converted to dBm. In addition, we have used the NHTSA power levels cited for the bandwidth of 76-81 GHz.

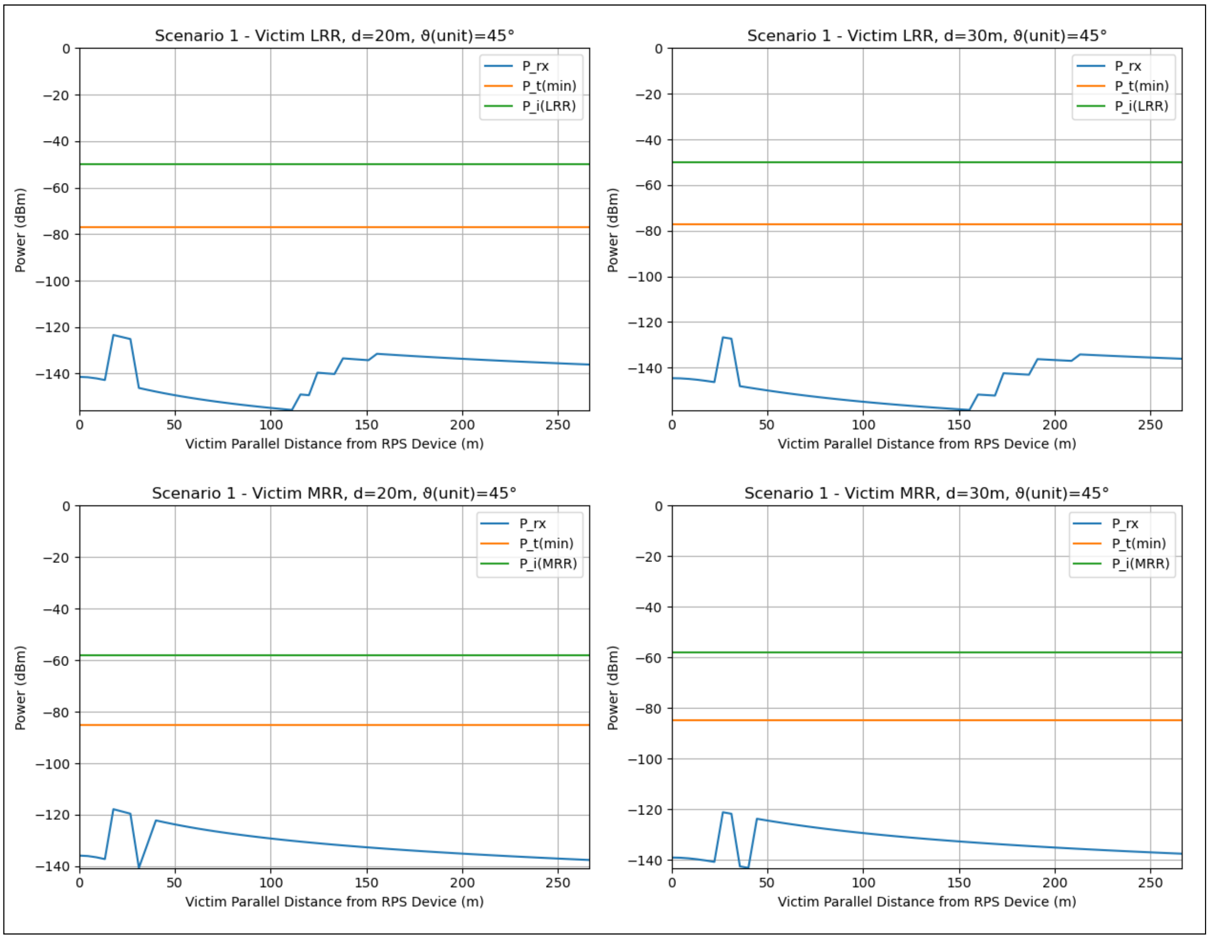

Figure 3: Interference power from the RPS unit at the victim receiver (P_{RX}) for unit oriented at 45° to the road at 20m and 30m back from the road, with LRR and MRR victims. Distance is measured along the road axis. Minimum target power (P_t) received at the victim and average interference power (P_i) for an equivalent vehicular radar (LRR/MRR), taken from [2], are shown on each sub-figure in orange and green, respectively.

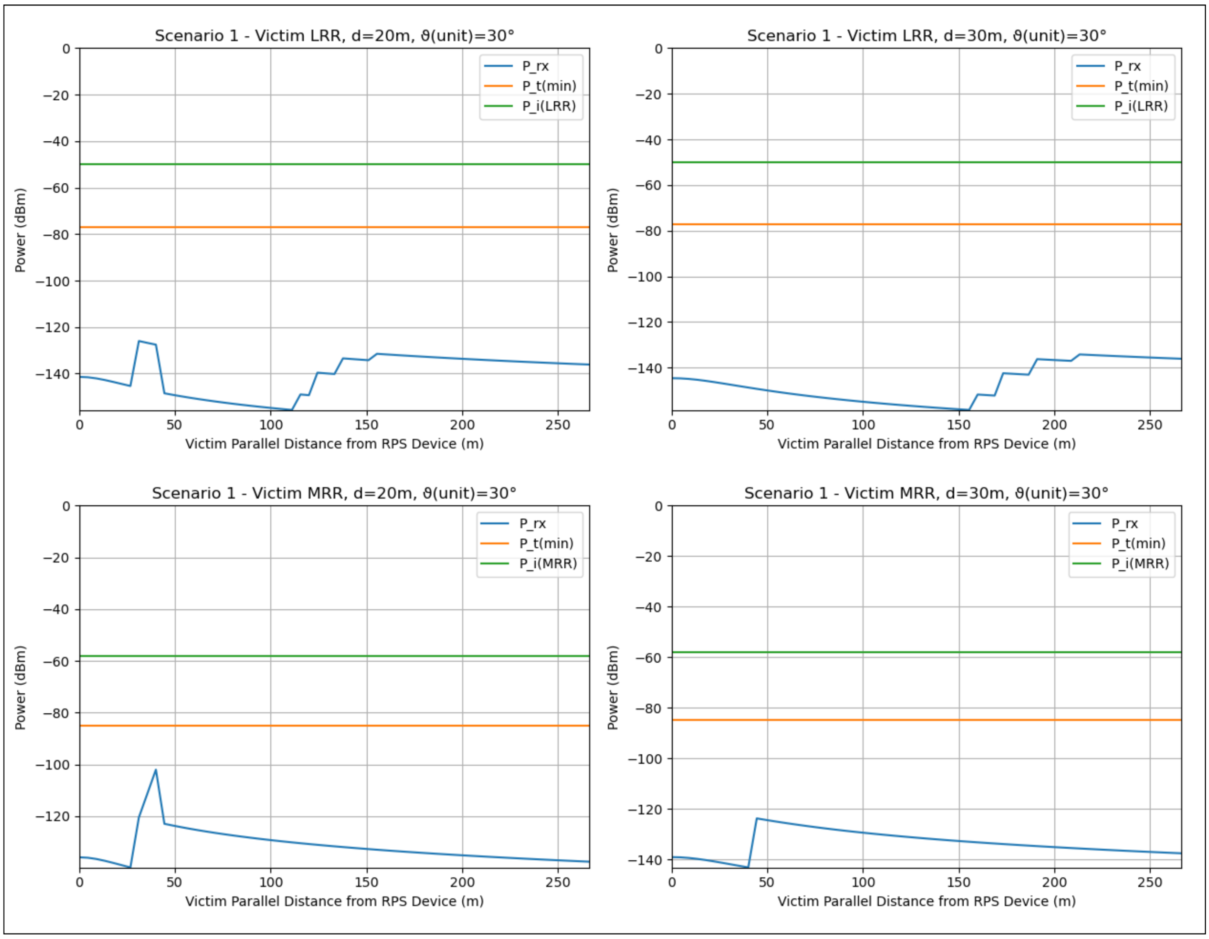

Figure 4: Interference power from the RPS unit at the victim receiver (P_{RX}) for unit oriented at 30° to the road at 20m and 30m back from the road, with LRR and MRR victims. Distance is measured along the road axis. Minimum target power (P_t) received at the victim and average interference power (P_i) for an equivalent vehicular radar (LRR/MRR), taken from [2], are shown on each sub-figure in orange and green, respectively.

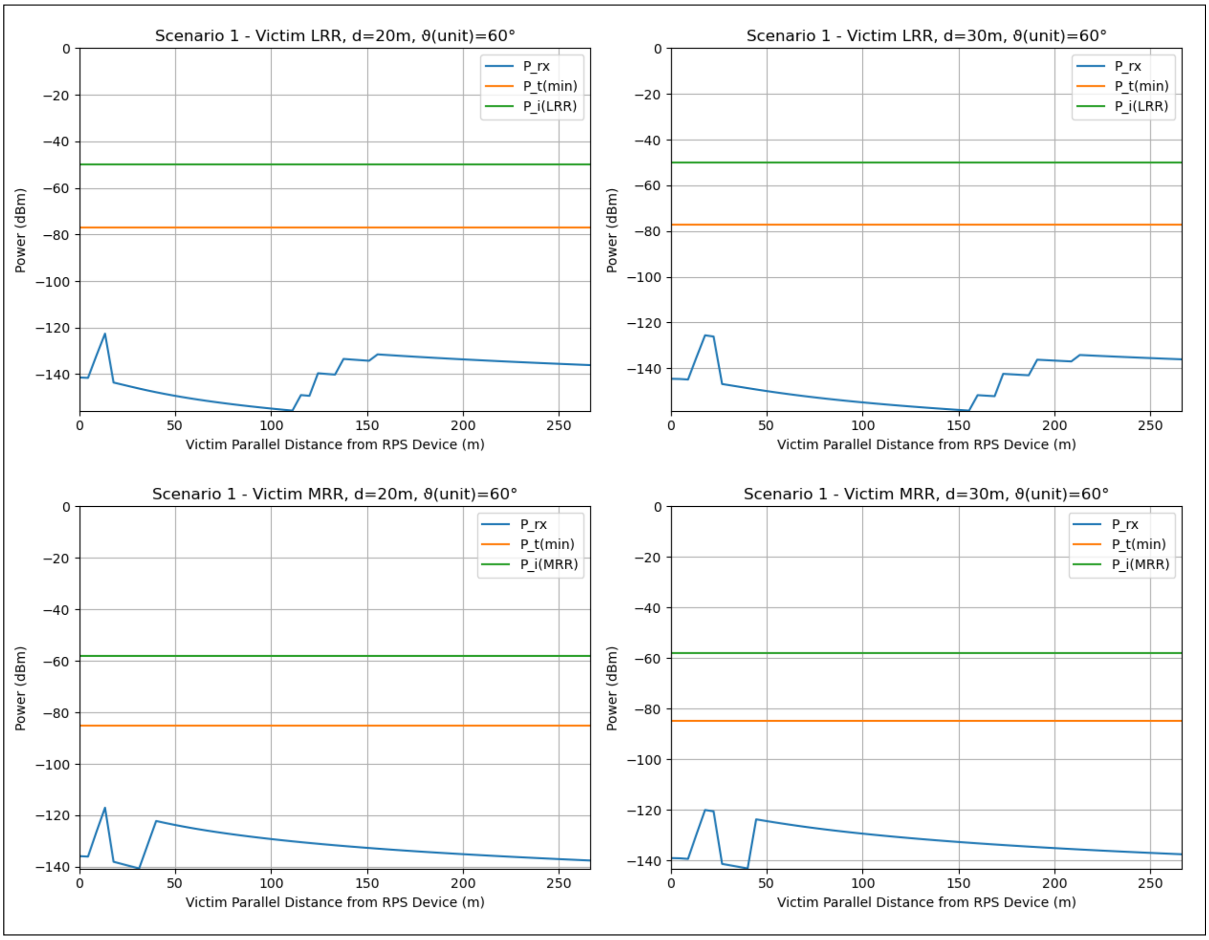

Figure 5: Interference power from the RPS unit at the victim receiver (P_{RX}) for unit oriented at 60° to the road at 20m and 30m back from the road, with LRR and MRR victims. Distance is measured along the road axis. Minimum target power (P_t) received at the victim and average interference power (P_i) for an equivalent vehicular radar (LRR/MRR), taken from [2], are shown on each sub-figure in orange and green, respectively.

Appendix A.3 – Scenario 2

The NHTSA study Scenario 2 ([2], §6.3) looks at interference from a stream of vehicles passing the victim vehicle, travelling in the same direction as the victim. This scenario is concerned primarily with interference power reflected from the target vehicle that the victim is attempting to track. As such, this scenario presents two ways in which the RPS unit might present interference power to the victim.

The first way is through direct illumination of the victim vehicle as it travels along the road (i.e. RPS unit facing towards the victim vehicle). This is identical to the setup in scenario 1 and the NHTSA interference levels are not directly comparable (no direct illumination), so this is not repeated here.

The second way in which interference power may be presented is as reflections off the rear of the target vehicle (i.e. RPS unit facing towards rear of target vehicle as it drives past and away from the unit). To get an idea of whether these levels may be of concern, a worst-case setup was analysed.

Assuming a setup as shown in Figure 6, an RPS unit is mounted 20m back from a road, at a mounting height of 3m, and angled at 45° towards the road (note that the angle in this case is reversed so that the unit will illuminate the rear of vehicles driving past on the near-side). The unit down-tilt is set so that the boresight covers an area 20m from the base of the unit. The worst-case positioning of the target vehicle in this case would be as shown in the figure, diagonally in-line with the transmit boresight (from a top-down perspective, the transmitter is pointing into the ground). This provides some overlap of the transmit beam onto the rear of the vehicle, with incident power on the target, P_T, as follows:

$$\begin{aligned} P_T &= \frac{P_{TX} G_{TX} \sigma_T}{FSPL(31m)} \\ &= 7\ dBm + 20.2035 + 10 - 100.16 \\ &= -62.9565\ dBm \end{aligned}$$

Where σ_T is the Radar Cross-Section of the target vehicle (as in the NHTSA study, this was taken to be 10 m^2 as determined in [8]), and the other symbols are as used in Appendix A.1 – Modelling Approach and Calculations. Path loss was determined at 31m, as being the distance from unit to target vehicle.

The power then actually received at the victim receiver would then be subject to additional attenuation factors, to give the receive power from the RPS unit, P_{RX}, as:

$$P_{RX} = \frac{P_T G_{RX} D_F}{FSPL(d_T)}$$

This will give different power levels at the victim receiver depending on how far the victim vehicle is behind the target vehicle. Using the distance that gives the minimum signal level received from the target used in the NHTSA study (100m), gives a value of P_{RX} in the order of -170 dBm. Assuming the victim vehicle is much closer to reduce the path loss (10m behind the target) gives a value of P_{RX} of approximately -150 dBm. However, in this instance the minimum signal level from the target vehicle would be considerably higher at the victim.

The minimum signal level received back from the target for this scenario in the NHTSA study was -85 dBm. This would give an SIR of between 65 and 85 dB depending on which distance was used. In either case, the worst-case power in the reflected setup is many orders of magnitude below the level of concern (and the power levels from the direct case in scenario 1), and so is not modelled further.

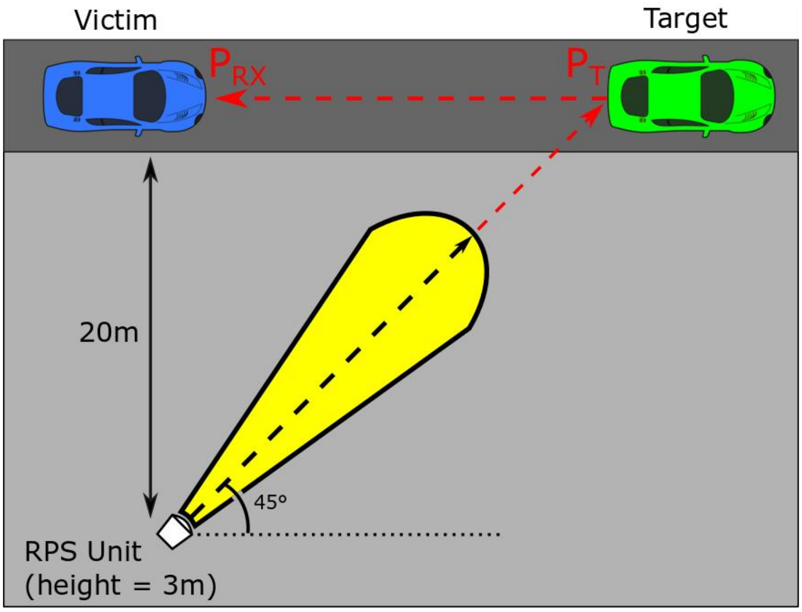

Figure 6: RPS unit setup for scenario 2 reflected case. Target vehicle is placed in worst-case position with respect to RPS device transmit beam, with victim vehicle following some distance (10-100m) behind the target

Appendix A.4 – Scenario 3

Scenario 3 is very similar to scenario 2 from the perspective of the RPS MiRTLE unit, and so for the same reasons as outlined above the scenario 3 setup is not modelled[12].

[12] The calculated reflected power levels from the target and resulting SIR are identical as for the worst-case situation calculated in Appendix A.4 – Scenario 3

Appendix A.5 – Scenario 4

Appendix A.5(i) – Setup

Scenario 4 of the NHTSA study ([2] §6.5) considers the effect of passing traffic on the ability of a Short-Range Radar (SRR) to detect a target vehicle when the victim vehicle is reversing out from a parking space. This scenario differs from the others in that it focuses on a victim SRR receiver. Additionally, the victim vehicle is modelled as being stationary, with both target and interferer vehicles moving perpendicularly to it instead. As the movement of the victim vehicle (and change in respective field of view geometries for the transmit and receive antenna) is the relevant characteristic for the RPS calculations, this scenario will be calculated using a static geometry (i.e. the victim will not move with respect to the RPS unit as with the other scenarios). However, the calculation will still be performed over the same time step as the other scenarios (0.2s).

The setup for the RPS calculation for scenario 4 is shown in Figure 7. This shows an RPS device deployed across the road from the victim vehicle, with the antenna boresight directly in-line with the victim receiver (though not aimed directly at it)[13]. The unit is placed 30m back from the road edge (30m is selected because the unit is perpendicular to the road), with the unit boresight focused at the ground 20m horizontally from the base of the unit.

[13] Since this is a static scenario and unlike the other analysis presented, we performed this analysis at only a single angle, the worst case, with the RPS MiRTLE antenna boresight directly in-line with the victim receiver.

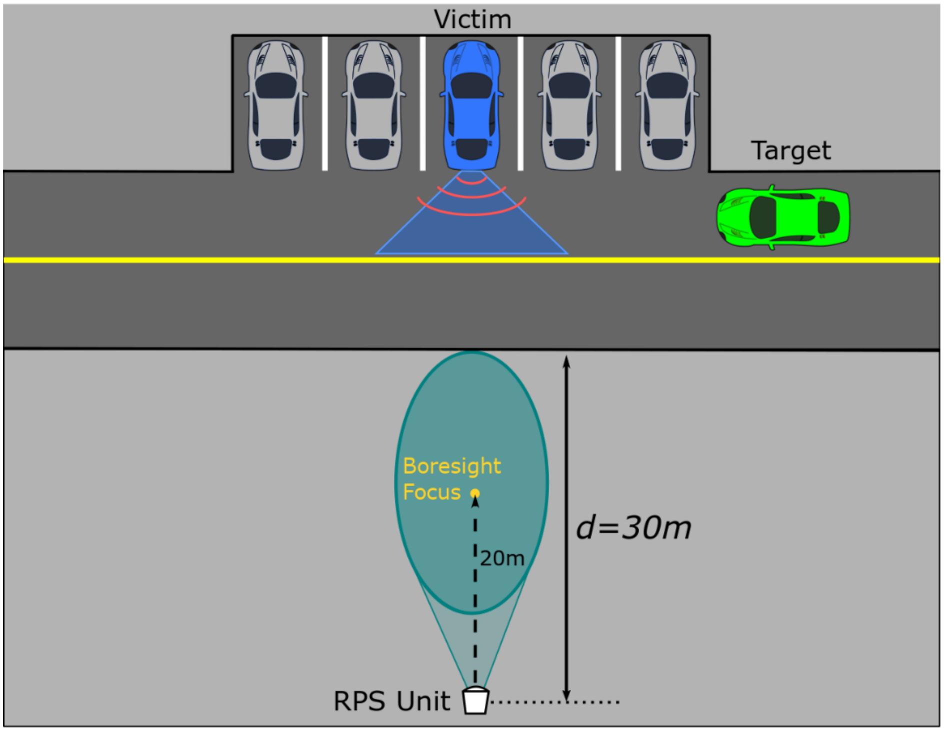

Figure 7: Top view of scenario 4 model setup. Scenario was modelled with a static geometry, as victim vehicle remained stationary in the NHTSA model. Target vehicle used in NHTSA scenario shown for reference but was not re-modelled in this analysis.

Appendix A.5(ii) – Results

As stated in the setup, this scenario is to be calculated from a static model, and so the calculation can be provided in full. The interference power observed by the victim receiver, P_{RX}, is calculated as follows:

$$P_{RX} = \frac{P_{TX} G_{TX} G_{RX} D_F}{G_C FSPL(d)}$$

Or for values in dB:

$$P_{RX} = P_{TX} + G_{TX} + G_{RX} + D_F - G_C - FSPL(d)$$

Where the symbols are as defined in Appendix A.1 – Modelling Approach and Calculations.

As with all cases, G_{TX} and G_{RX} depend on the relative geometries of the unit transmitter and victim receiver. In the setup defined above, it is determined that both the transmitter and receiver would be within the main lobe FOV of each other, and as such the full gain values are used. G_{TX} is still de-rated as per Appendix B.3 – Transmit Antenna Scan De-rating.

D_F is re-calculated using the parameters used for SRR in the NHTSA study ([2] §5.1, Table 5): this gives operating bandwidth of 500 MHz and a receiver duty factor (D_{RX}) of 1. These values give an overall D_F = -21.25 dB. Receiver compression gain, G_C, is used as given (18 dB).

Path loss due to free space propagation ($FSPL(d)$) is calculated using a unit to victim distance of 37.48m[14].

Combining these values into the equation above gives the following for the receiver interference power from the RPS unit:

$$P_{RX} = 7 + 20.20 + 17 + (-21.25) - 18 - 101.82$$
$$= -96.86\ dBm$$

This value is shown, alongside a summary of the findings from the NHTSA study, in Table 4. These results show a worst-case Signal-to-Interference Ratio (SIR) of greater than 28 dB for the minimum received target signal level, and indicate that the interference levels from the RPS unit are a factor of -46 dB below the interference levels from other vehicular radar modelled in the NHTSA study.

dB milli-Watts (dBm)	**Minimum Target Signal Level, P_T (from [2] Table 11)**	**Received Power from Interferer Radar, P_I (from [2] Table 11)**	**RPS Unit Interference Power Observed by Victim Receiver, P_{RX} (max)**
Victim: SRR	-68	-46 (LRR) / -50 (MRR)	-96.86

Table 4: Calculated interference power levels from RPS unit for scenario 4, as compared to minimum target signal levels and vehicular interferer power levels from the NHTSA study ([2] §6.5)

Appendix A.6 – Interference-to-Noise Ratio (INR) Calculations

The MOSARIM project [3] establishes a maximum target Interference-to-Noise Ratio (INR) of 0 to -10 dB for vehicular radar, meaning that any interference observed at the receiver from external sources should be no higher than the noise floor of the receiver (ideally 10 dB below).

The worst-case INR values can be calculated from the above scenarios by first calculating the thermal noise floor of the receiver:

$$P_{NT} = 10 \log_{10}\left(\frac{k.B.T}{1mW}\right)$$

Where T is the temperature in Kelvin (assumed 290 K), B is the bandwidth in Hz of the receiver, and k is Boltzmann's constant (1.38064852 x10^{-23}).

The noise floor of the receiver, P_N , is then a combination of the thermal noise, P_{NT}, with the Noise Figure (NF) of the receiver. For the radar models used in the NHTSA calculations above, this gives the noise floor values listed in Table 5.

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[14] While we have chosen 37.48m as a "typical" distance, we also calculate below the minimum distance at which an RPS MiRTLE system could operate with negligible impact on a vehicular short-range radar system. SeeAppendix A.7 – Calculation of Minimum Installation Distances.

Radar Type	Receiver thermal noise, P_{NT} (dBm)	Receiver Noise Figure, NF (dB, from [2])	Receiver noise floor, P_N (dBm)
LRR	-90.97	10	-80.97
MRR	-87.96	10	-77.96
SRR	-86.99	10	-76.99

Table 5: Calculated noise floor values for three radar models used in the NHTSA study

The maximum interference levels from the RPS unit can then be used to calculate the worst-case INR for each radar type, based on the NHTSA scenarios analysed above. The results of this are shown in Table 6. The largest INR in the scenarios that were analysed was from scenario 4, with the SRR victim receiver. In this case, the INR is -19.97 dB – this is far below the target 0 to -10 dB INR stipulated in the MOSARIM report, and indicates that the RPS device would not have a noticeable effect on the noise floor of the receiver (i.e. no degradation of victim radar signal-to-noise ratio).

Radar Type	Maximum interference power from RPS unit, P_{RX} (max.) (dBm)	Receiver noise floor, P_N (dBm)	Interference-to-Noise Ratio, INR (dB)
LRR	-122.58	-80.97	-41.62
MRR	-102.00	-77.96	-24.05
SRR	-96.86	-76.99	-19.97

Table 6: Calculated worst-case INR values for each radar type

Appendix A.7 – Calculation of Minimum Installation Distances

In addition to the modelling of practical scenarios taken from the NHTSA study, minimum installation distances from roadways (horizontal and vertical) can also be determined that will eliminate the chance of the RPS MiRTLE device interfering with vehicular radar.

In order to do this, first the horizontal case is considered. For this, a MiRTLE unit is assumed to be positioned at the same height as a vehicular radar receiver, and angled horizontal to the ground so that the transmitter boresight directly illuminates the boresight of the victim receiver[15].

Assuming the vehicular radar receiver has, in turn, the characteristics of each of the three radar types used in the NHTSA study, the distance is calculated at which the Signal-to-Interference Ratio (SIR) drops to 10 dB. That is, the minimum distance at which the target margin established by the NHTSA

[15] It should be noted again that this is a purely theoretical setup for the purposes of determining an absolute minimum distance to avoid interference.

study is maintained for each radar type. The calculations used are as described in Appendix A.1 – Modelling Approach and Calculations, except in this case the transmit and receiver antenna gains, G_{TX} and G_{RX}, are not de-rated according to geometry as alignment to each antenna boresight is assumed.

The distance between the two devices starts at 30m and is decreased in steps of 1m until the SIR falls below 10 dB. The ratio of interference from the MiRTLE device to the noise floor of the receiver (INR) is also calculated for this minimum distance, but is not determined to be the gating factor on minimum distance (values for INR are always below 0 dB at the minimum distance to maintain 10 dB SIR). The results of these calculations are given in Table 7.

Radar Type	Minimum distance to maintain 10 dB SIR[16], d_{min} (m)	Signal-to-Interference Ratio at d_{min}, SIR_{dmin} (dB)	Interference-to-Noise Ratio at d_{min}, INR_{dmin} (dB)
SRR	5	11.4	-2.4
MRR	21	10.3	-17.3
LRR	12	10.7	-6.7

Table 7: Calculated minimum distances to maintain 10 dB Signal-to-Interference Ratio (SIR), for each radar model listed in the NHTSA congestion study ([2] §5.1, Table 5). Signal values are taken from the minimum signal level returned from the tracked target vehicle in the study scenarios ([2] §6.2, Table 8 for LRR, MRR and §6.4, Table 10 for SRR). INR is calculated as per Appendix A.6 – Interference-to-Noise Ratio (INR) Calculations, using the same noise floor calculated for each rdar type.

As can be observed from the calculation results, the Medium-Range Radar (MRR) presents the worst-case. Therefore, a minimum height is required to ensure that the MiRTLE transmitter main lobe and MRR receiver FOV do not intersect if the vehicle is within 21m of the unit. Trigonometry gives that a minimum height difference of 1.84m between the vehicular radar and the MiRTLE unit will ensure that the MiRTLE unit transmitter is outside the FOV of the MRR receiver[17]. Assuming a maximum mounting height of 0.5m, as with the earlier scenario calculations, gives a minimum installation height of 2.34m, which is rounded up to 2.4m.

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[16] Minimum distance to granularity of 1m, rounding up

[17] This calculation is still very conservative as it assumed full receiver antenna gain up to the full limit of its FOV – in reality, this will usually be defined by the 3 dB (half power) angle, so the gain has already dropped off by this point.

Appendix B – Derivation of ETSI Unwanted Signal Level Calculations

Appendix B.1 - Setup

The calculation of the RPS device signal level incident on an automotive radar receiver as an "unwanted" signal is based on the setup as shown in Figure 8.

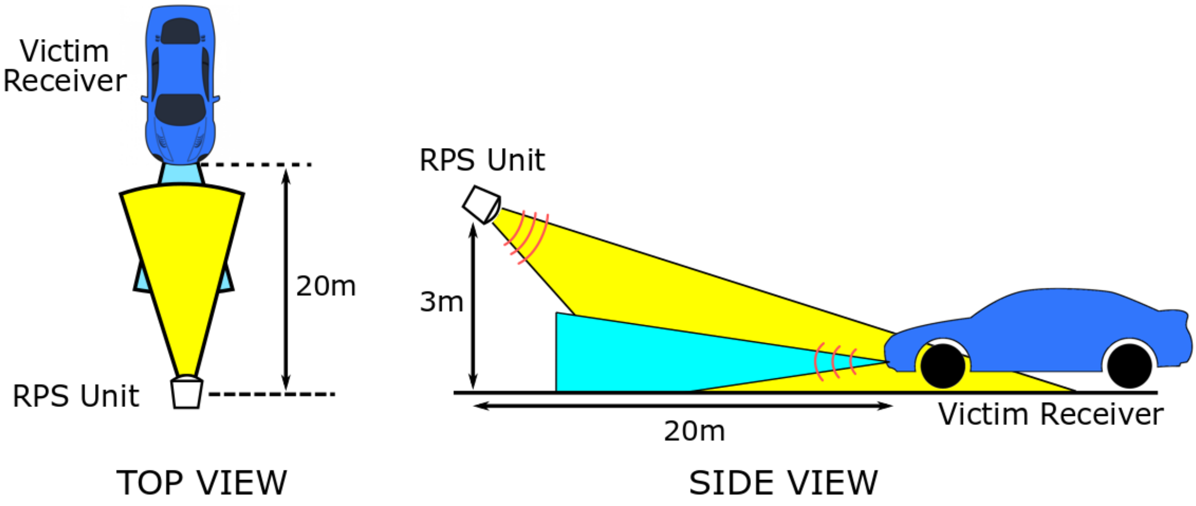

Figure 8: Assumed setup of RPS MiRTLE unit and victim receiver for calculation of interference levels versus ETSI standard limits

The following assumptions are made for the purpose of performing the calculation:

- Dwell time: 1 second
  - This is the time period over which the modelled "measurement" is calculated. This was chosen to match the test methods listed in the ETSI standards from which the signal level limits are taken.
- Receiver Characteristics
  - Bandwidth: 200 MHz
  - Duty Factor: 0.67
- Path loss due to free space propagation
- Transmit to receive antenna misalignment
  - Due to the relative geometries of the vehicle-mounted receiver radar and an RPS unit mounted at 3m, the transmitter and receiver antennae will not be co-axial. This has been included as a de-rating of the receiver antenna gain

Note that the instantaneous calculation excludes the factors resulting from the 1 second dwell time, and assumes an instant where:

- The RPS device is actively transmitting and the beam is directly incident on the receiver
- The sweep frequency is within the receiver bandwidth
- The receiver is within the active part of its duty cycle

Free space path loss and antenna misalignment are still assumed as above.

Appendix B.2 - Calculations

The power received at the radar receiver is calculated as:

$$P_{RX} = \frac{P_{TX} G_{TX} G_{RX} D_f}{FSPL(d)}$$

Or, taking values in dB:

$$P_{RX} = P_{TX} + G_{TX} + G_{RX} + D_F - FSPL(d)$$

Where:

- The transmit power of the RPS unit, $P_{TX} = 7dBm$ ($5mW$)
- The transmit antenna gain, $G_{TX} = 20.2035\ dBi$ (see Appendix B.3 – Transmit Antenna Scan De-rating)
- The receive antenna gain, $G_{RX} = 0\ dBi$ (due to antenna misalignment)
- The combined duty factors, $D_F = -26.968\ dB$ (see Appendix B.4 – Combined Duty Factors)
- The path loss due to free space propagation, $FSPL(20m) = 96.3598\ dB$

Combining the above gives:

$$\begin{aligned} P_{RX} &= P_{TX} + G_{TX} + G_{RX} + D_F - FSPL(d) \\ &= (7) + (20.2035) + (0) + (-26.968) - (96.3598) \\ &= -96.1346\ dBm \end{aligned}$$

The equivalent power in Watts is then given by:

$$\begin{aligned} P_{RX}(W) &= 10^{\left(\frac{P_{RX}-30}{10}\right)} \\ &= 2.44 \times 10^{-13} W \end{aligned}$$

This power value is then used to compute the Power Flux Density (PFD, in W/m^2) at a given distance from the transmitter as follows:

$$\begin{aligned} \text{PFD}, S(r) &= \frac{EIRP(W)}{4\pi r^2} \\ &= \frac{P_{RX}(W)}{4\pi r^2} \\ &= 2.573 \times 10^{-17}\ W/m^2 \end{aligned}$$

The Electric Field Strength (in V/m) at the same distance is then determined using:

$$E = \sqrt{Z_0 S}$$

Where Z_0 is the characteristic impedance of a vacuum, ~377Ω, giving:

$$\begin{aligned} E &= \sqrt{377 \cdot S(r)} \\ &= 0.0001353\ mV/m \end{aligned}$$

When compared to the ETSI standard limit of 55 mV/m this gives a ratio of 1/406570, or -56.1 dB.

Appendix B.3 – Transmit Antenna Scan De-rating

The RPS device transmit beam is mechanically steered using an internally mounted reflector and steering mechanism (not related to the device gimbal). This steers the beam over a continuous helical path that reciprocates multiple times per second. This provides a larger circular area of coverage of the beam without having to operate the gimbal mechanism.

As shown in Figure 9, this expands the beam angle from 0.65° (axial about the transmitter boresight) to 8°. This has the effect of de-rating the gain (directivity) of the antenna when viewed over time.

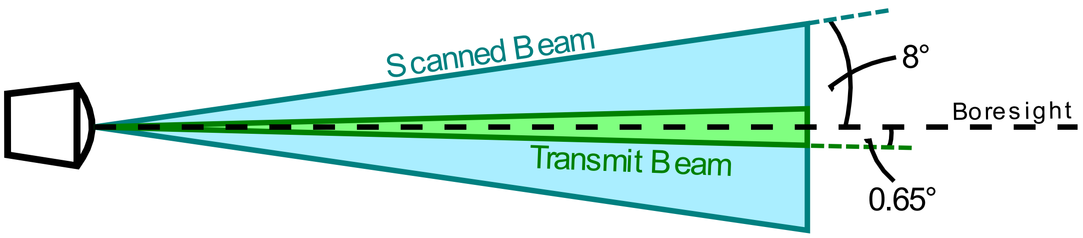

Figure 9: Effect of the antenna scanning on the effective transmitter angular beam width

This de-rating factor is determined using the ratio between the solid angles of the antenna beam and the scanned beam:

$$d_{scan} = \frac{\Omega_{beam}}{\Omega_{scan}}$$

$\Omega_x$is the solid angle, defined in general terms as:

$$\Omega_x = 2\pi(1 - \cos\theta)$$

Where θ refers to the beam angle ($\theta_{beam} = 0.65°$) and scan angle ($\theta_{scan} = 8°$), respectively. Substituting these in gives the solid angles:

$$\Omega_{beam} = 2\pi(1 - \cos\theta_{beam}) = 0.0004$$

$$\Omega_{scan} = 2\pi(1 - \cos\theta_{scan}) = 0.0611$$

The de-rating factor in dB, D_{scan}, is then calculated as:

$$D_{scan} = 10\log_{10}\left(\frac{\Omega_{beam}}{\Omega_{scan}}\right)$$
$$= -21.7965\ dB$$

This is combined with the base transmit antenna gain of 42 dBi to give $G_{TX} = 20.2035\ dBi$.

Appendix B.4 – Combined Duty Factors

The combined duty factor, D_F, takes into account a number of duty cycles that are operating concurrently both in the RPS device and at the receiver.

The first of these, D_{BW} , represents the amount of time that the transmitter is actually transmitting in the same band as the receiver. The RPS device transmitter sweeps across a 15 GHz bandwidth (71 – 86 GHz), and so will only overlap with the receiver bandwidth for some proportion of the total transmit time. This is calculated using the time in the 5 GHz automotive band and the proportion of the receiver bandwidth within this band, as follows:

$$\begin{aligned} D_{BW} &= 10\log_{10}\left(\frac{BW_{RX}}{BW_{76-81GHz}} \cdot \frac{t_{sweep(76-81GHz)}}{t_{sweep(71-86GHz)}}\right) \\ &= 10\log_{10}\left(\frac{200\ MHz}{5\ GHz} \cdot \frac{33us}{110us}\right) \\ &= -19.2082\ dB \end{aligned}$$

The second factor, D_{proc}, represents the maximum duty cycle of the RPS device (25% - see [1], §4):

$$D_{proc} = 10\log_{10}(0.25) = -6.021\ dB$$

The third factor, D_{RX}, is the duty factor of the receiver radar:

$$D_{RX} = 10\log_{10}(0.67) = -1.7393\ dB$$

These are then combined to give the duty factor, D_F:

$$\begin{aligned} D_F &= D_{proc} + D_{BW} + D_{RX} \\ &= -26.968\ dB \end{aligned}$$