# Passive Roadside Reflectors and Communications Systems for Improvement of Radar Reliability

**Krishna Vijayaraghavan**

**Alex Kossett**

**and**

**Rajesh Rajamani**

Department of Mechanical Engineering

University of Minnesota, Minneapolis, MN 55455

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## Abstract

The use of radar in automotive applications such as adaptive cruise control is limited to detecting target vehicles directly in front of the host vehicle. Vehicles around a curve on a highway and cross traffic vehicles at an intersection cannot be detected by current radar systems. This is primarily due to the limited beam width angle of the radar.

The first part of this report examines and evaluates the novel concept of using passive roadside reflectors (PRRs) to increase the utility of the radar system. PRRs on the shoulder and the median of a road are designed that would enable the radar system to pick up cross traffic at highway intersections. Both simulations and experiments demonstrate that this concept could be effectively used for cross traffic distance measurement. A limitation of this technology is that cross traffic cannot be detected when the radar equipped vehicle is very close to the intersection due to the lateral offset of the radar from the location of the PRR. However, the system is still valuable for providing future warning of cross traffic at rural intersections. A number of options are explored for the use of PRRs to improve radar measurements on highway curves. These include the use of tangential flat plate reflectors, skewed flat plate reflectors and convex reflectors. Algorithms for distance measurement with each of these options are derived and evaluated through simulations. The use of skewed flat plate reflectors is also evaluated experimentally and found to work effectively. The effective range of the radar on highway curves could be doubled by the use of the developed system.

The second part of this report describes the development of wireless sensors that can be embedded into the road and can detect the passing of a vehicle as well as the velocity of the vehicle. By embedding such sensors into the road the location of different vehicles on a curve can be estimated by the vehicle receiving wireless information from the embedded sensors. In

order to ensure that the developed sensors are maintenance-free, unique technology that enables the sensors to operate by harvesting energy from vibrations of the road has been developed. The developed sensors harvest energy using piezoelectric patches and then utilize this energy for wireless transmission. This ensures that the embedded sensors do not need power supply lines nor do they need batteries that require replacement. Experimental results show that the developed sensor can be embedded in the road and can reliably detect the passing of a vehicle. The design of the sensors and experimental results are presented in the report.

All the proposed tasks of the project have been completed. Details on the completed tasks are provided in the following pages.

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## Description of Task Completion

All the proposed tasks of the project have been completed. The following Table describes the tasks and their dates of completion.

| Task Number | Description | Initially proposed: | | Current: | |
|---|---|---|---|---|---|
| | | Start | End | Start | End |
| 1 | Preliminary experimental evaluation of passive radar reflectors for single lane applications. | April 23, 2004 | No end date specified | July 7, 2004 | Dec 31, 2004 |
| 2 | Development and refinement of algorithms for the use of passive radar reflectors for multi-lane highways. | April 23, 2004 | No end date specified | July 7, 2004 | March 30, 2005 |
| 3 | Implementation of system of passive reflectors for multi-lane applications. | April 23, 2004 | No end date specified | April 1, 2005 | Aug 29, 2005 |
| 4 | Development of vehicle location measurement system and roadside beacon system for addressing the radar reliability problems on curves. | April 23, 2004 | No end date specified | Mar 1, 2005 | Mar 15, 2006 |
| 5 | Experimental evaluation of radio beacons and location systems for various operational scenarios. | April 23, 2004 | No end date specified | April 1, 2005 | May 31, 2006 |
| 6 | Addressing of maintenance issues and maintenance free design of passive reflector mounts. | April 23, 2004 | No end date specified | April 1, 2006 | Jun 30, 2006 |
| 7 | Preparation of comprehensive report documenting the results of the two-year project. | April 23, 2004 | No end date specified | April 1, 2005 | Jun 30, 2006 |

The following paragraphs describe specific activities that were undertaken for each task and cite the sections of the report where detailed descriptions of these activities can be found:

1) **Task 1:** The use of radar reflectors was evaluated experimentally both for extending radar range on curves and for measuring distances to cross-traffic at intersections. Results show that the use of skewed reflectors can significantly extend radar range on curves.

Significantly, it was found that such reflectors could reliably detect cross-traffic at intersections and thus provide warning of potential collisions at intersection without traffic lights. Experimental results are described in sections 2 and 3 of this report.

2) **Task 2:** An algorithm was developed for determining both the radial and circumferential distance of the target vehicle by analyzing the radar reflections from the target using skewed reflectors. When the radial and circumferential distances are both known, the lane position and the range of the target vehicle can both be calculated. Thus the passive radar reflectors can be used for multi-lane applications. The algorithms are described in section 2 of this report.

3) **Task 3:** Experimental results describing the radial and circumferential measurements useful for multi-lane applications are described in section 3 of this report.

4) **Task 4:** A sensor system has been developed for detecting the location of vehicles on a curve and for transmitting this location information wirelessly to other vehicles in the neighborhood. Section 5 of this report describes the developed sensor system.

5) **Task 5:** The developed sensor system has been demonstrated experimentally. An experimental demonstration was provided to Caltrans on June 13$^{th}$, 2006. Experimental results documenting the performance of the system are shown in section 6 of this report.

6) **Task 6:** Significant effort has been expended on designing the systems developed in this project so that the required maintenance is minimal. The passive radar reflectors developed in the project require no power or wiring of any kind. Likewise, the wireless sensors developed for vehicle location measurement system are battery-less and require neither power

lines nor any wiring for obtaining signals. The design of the vehicle location measurement system so as to operate without batteries and without power lines is described in section 5 of this report.

7) **Task 7:** Task 7 involves writing a comprehensive report of the activities in the project. This report constitutes the deliverable from this task.

# 1. Introduction

There has been considerable progress towards driver assistance systems and partial automation systems to help improve driver convenience and aid in accident prevention on highways. Some of the systems that have been developed include Adaptive Cruise Control (ACC) systems, Collision Avoidance systems, lane keeping systems, lane departure warning systems, and automated highway systems (AHS) [1-9]. Of these systems, ACC, Collision Avoidance system and AHS utilize radar to determine the distance to other vehicles (targets) on the road. As the radar system is one of the critical systems in longitudinal vehicle automation it should be highly reliable and available at all times. Reliability of the radar can be compromised due to the occurrence of faults. Algorithms for monitoring the health of radar systems (fault detection) have been discussed in Rajamani et al (2002) ([10]). However, a more serious limitation of the radar is that its operation is almost completely restricted to a straight lane. The use of radar for curved lanes and for detecting cross traffic at intersections has not been previously addressed.

In an ideal world, it would be perfect if the vehicle was equipped with adequate radar systems to detect targets at any distance and with a full 360° range around the host vehicle (the vehicle equipped with the radar). However, due to the high cost of a radar system ($2,000 - $3,000), a regular passenger car is typically equipped with at most only one forward looking radar. Since the beam width angle of a radar is limited to only a few degrees, this effectively limits use of the radar to straight or very gently curving roads. Consequently, a radar system on its own is also essentially useless for detecting incoming cross traffic at intersections.

The purpose of this project is to check the feasibility of using passive roadside reflectors (PRRs) to increase the utility of automotive radar systems. PRRs can indirectly increase the beam width angle of the radar by redirecting the radar beams in a chosen direction. Properly placed PRRs could allow the radar to detect cross traffic at intersections, which would be particularly useful for collision avoidance at rural intersections. A different configuration of PRRs could be used to increase the effective range of the radar on curved sections of highway. It should be noted that PRRs are completely passive mechanical devices and need no power supply.

Section 2 of this report discusses the use of three possible configurations of PRRs at intersections. Sub-section 2.1 describes an idealistic setup of placing the flat reflector in the middle of the intersection. As this setup would not be feasible at real intersections, the primary purpose of this configuration was to evaluate the use of PRRs to detect targets. As a realizable design, this configuration can be modified by offsetting the flat reflector and placing it on the shoulder. Sub-section 2.2 evaluates this out-of-lane flat PRR setup. In sub-section 2.3, it is attempted to replace the flat out-of-lane reflector in sub-section 2.2 with a convex reflector.

Section 3 of this report addresses the use of PRRs to increase the range of the radar system on curved lanes. Sub-section 3.1 demonstrates the ineffectiveness of a simple curved reflector for this purpose. Sub-section 3.2 evaluates the use of skewed reflectors constructed using a series of flat reflectors along the curve. It is found that this PRR configuration is effective in increasing the effective range of the radar. Sub-section 3.3 discusses the extension of the PRR setup from sub-section 3.2 to multilane applications, sub-section 3.4 discusses the use of convex reflectors and sub-section 3.4 presents the results from experiments performed on a curved section of road.

The development of sensors that can be embedded in the road to measure vehicle position and speed is discussed in sections 5 and 6 of this report. Section 5 discusses the design of the sensor and of the electronic system for the sensor. Section 6 discusses the experimental results that were obtained using vehicle tests to evaluate the developed sensor.

## 2. Flat Reflectors for Cross Traffic Sensing at Intersections

The preamble of AASHTO Strategy No. 17, "Improving Design and Operation of Highway Intersections," states that one in every four fatal crashes occur at intersections. It is also estimated that 85% of intersection crashes were due to driver error [11]. Cross traffic sensing is particularly important at rural intersections, where many of the most severe accidents occur. For instance, in 2001, 61% of all fatal crashes occurred in rural areas [13]. Many of these accidents can be avoided by providing drivers with warning of cross traffic. It has been documented that with the installation of a traffic signal, the frequency of crashes can substantially increase while reductions in fatal crashes attributed to these installations are statistically insignificant [12]. Equipping the host vehicle with radar for this purpose would not solve the problem either, because the radar alone cannot detect cross traffic due to its limited beam width angle (Figure (1)). It is, however, possible to enhance the radar by using PRRs to redirect the radar beam to detect cross traffic. The following sub-sections examine various PRR configurations that can be used for this purpose.

### 2.1 In-lane Flat Reflectors for Cross Traffic Sensing at Intersections:

A rudimentary design for a PRR setup at the intersection involves placing the reflector at the intersection of the centerlines of the perpendicular lanes as shown in figure (2). This configuration cannot be implemented at a real intersection, however, as the reflector structure would stand in the path of oncoming traffic in both the lanes. Sub-section 2.2 discusses a modification of this setup, which makes the design realizable.

Despite the impracticality of the in-lane PRR setup, experiments were performed with this setup to evaluate the basic effectiveness of using radar in conjunction with a reflector to detect targets. The experiments also helped establish that the radar system would return the total optical distance to the target which, with the reflector, is the sum of the distances from the reflector to the radar and the distance from the target to the reflector. This is an important step since the operation of the offset reflector also depends on this principle.

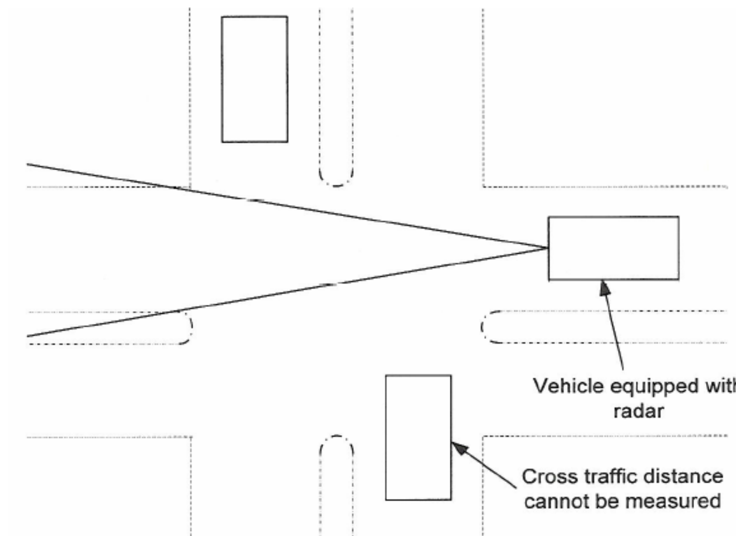


**Figure 1: Schematic of host vehicle approaching Intersection**

Figure (3) show shows the schematic of the experimental setup that involved placing a reflector at the intersection of the lane centerlines at a $45^0$ angle to each. A Dodge Caravan minivan served as the target. As the van was driven back and forth in one of the perpendicular lanes, the times at which a reference point on the van passed distinct equally spaced reference points on the lane was logged. The host vehicle was parked in the perpendicular lane and the output from the radar system was transferred to a computer through its serial port in RS232 format. A real-time C-program processed the serial data and stored the information sent by the radar into a file on the computer. The optical distance of the target surface calculated from the reference reading and distance of the target as returned by the radar were plotted on the same graph.

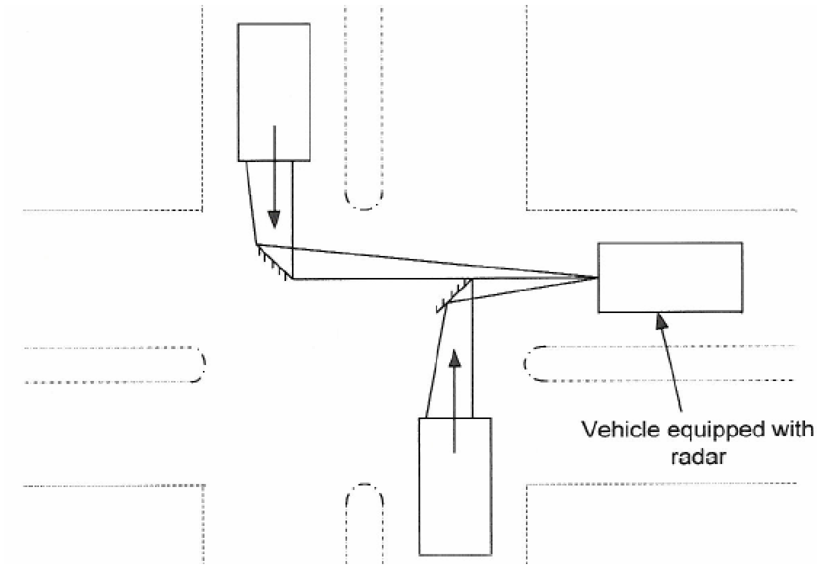


**Figure 2: Schematic of the In-Lane flat reflectors: Ideal but impractical**

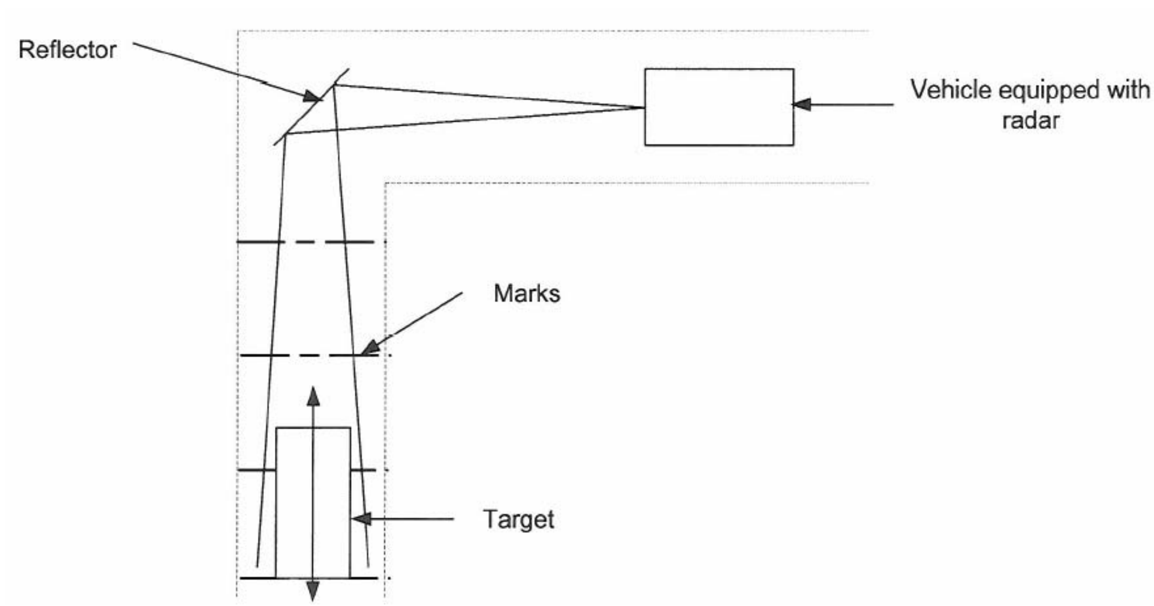


**Figure 3: Schematic of Experimental Set-Uup**

Figures 4 and 5 show representative data sets from the experiments. The reference data consists of linear interpolation of time and location information collected at discrete reference points on the lane of the target vehicle. The target id for the van for the most part is one, but occasionally it changes to two. This target id change can be explained as follows. The radar assigns target names based on distance. When a new, closer, target appears, for instance a pedestrian walking past the radar, it is assigned the id 1. This causes an apparent jump in the data corresponding to the first target, when in reality the van was assigned a different target id and all data was still recorded, and the radar indeed provides continuous data for a given target when using the PRRs. The basic principle was verified from these experiments, and the use of PRRs for radar applications was shown to work with high reliability and accuracy.

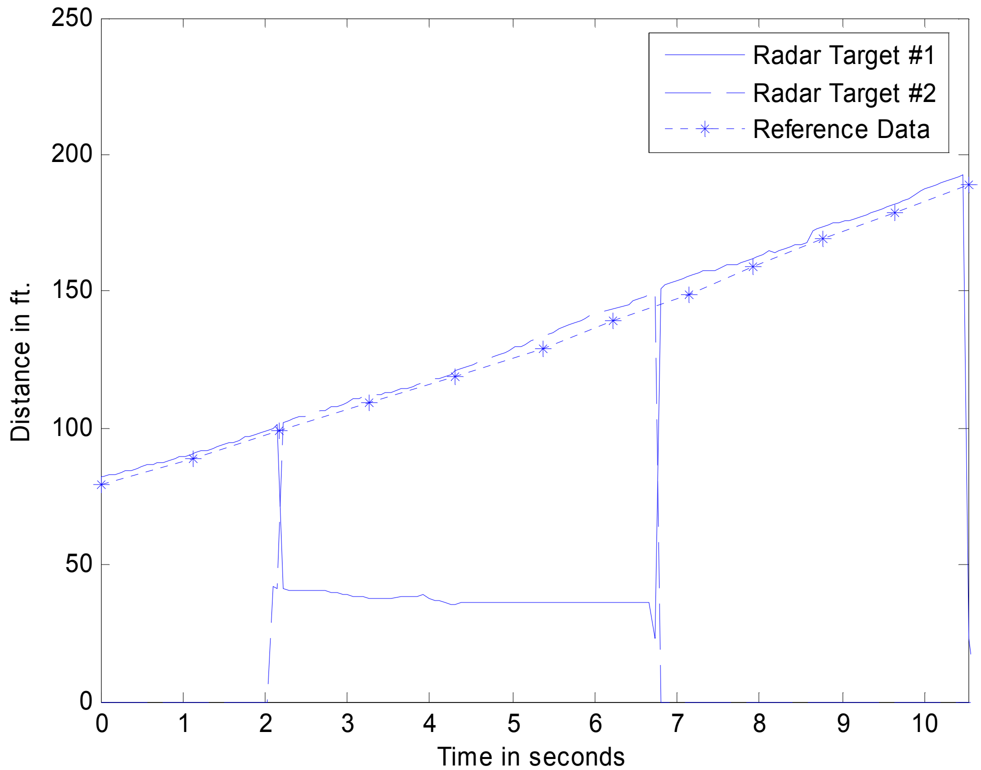


**Figure 4: In-lane reflector - departing target**

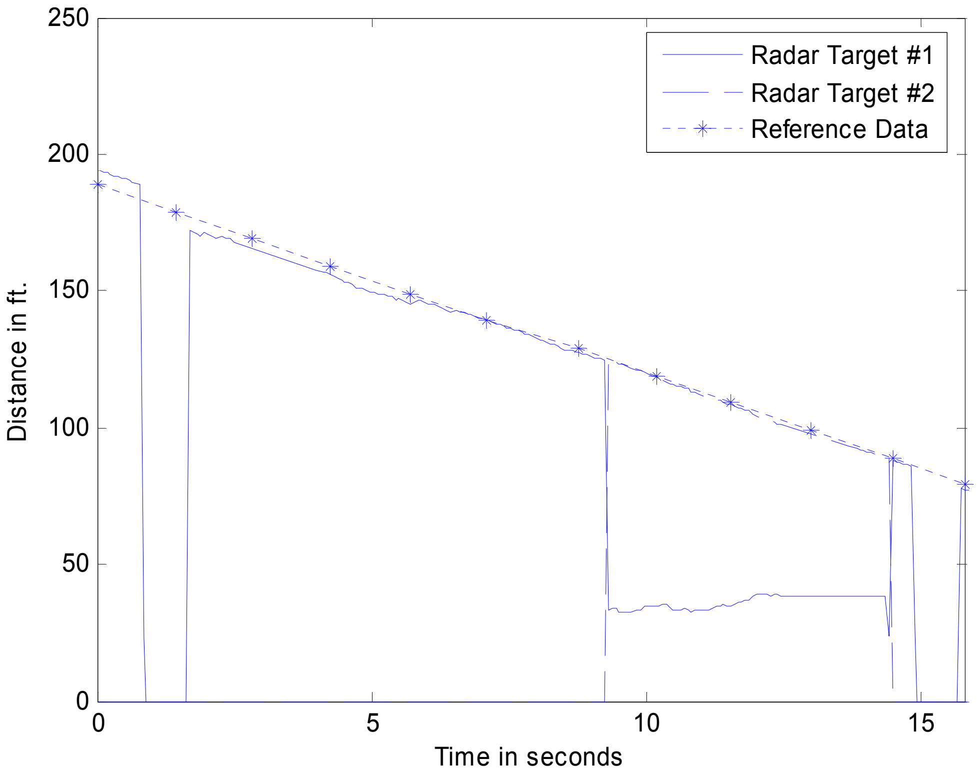


**Figure 5: In-lane reflector - approaching target**

## 2.2 Out of lane flat reflectors for Cross Traffic Sensing at Intersections:

A more realizable set up for the use of PRRs at intersections involves placing the reflector on either side of the lane, so that it does not block traffic. The schematic of the PRR setup can be seen in figure (6). In the figure (6) the rays originating from the "Vehicle equipped with Radar" represent the envelope of the original rays striking the reflector while the shaded region represents the span of the reflected rays. For maximum range, the PRR should be placed as close to the intersection as possible. However, for the PRRs to be effective, the host vehicle needs to be at least a distance of $Y_R = W\cot(\beta - \theta)$ away from the PRR - other target vehicles can be detected only when the host vehicle is at larger than this minimum distance from the intersection. Since the maximum beam width angle of the radar is constrained to $\beta = 3^0 - 5^0$ by the choice radar, there is a trade off in the choice of $\theta$ between decreasing this minimum distance and increasing the effective range. The ideal orientation of the reflector, the angle $\gamma$ with the centerline of the lane of the target (see figure 6 or 7) can be calculated from [14] as

$$\left[\frac{2W + Y_R\theta\cos\gamma}{Y_T + Y_R\theta\sin\gamma}\right] = \tan[2(\gamma-\beta)],\ Y_R = W\cot(\beta-\theta) \quad (1)$$

and the range up to which the radar detects targets is given by

$$Range = Y_T\ \tan[2(\gamma-\beta)+2\theta]-2W \quad (2)$$

where $W$ is the half width of the lane,

$Y_T$ is the distance of the PRR from the lane center

$\beta$ is the maximum beam width angle of the radar

$\theta$ is a design parameter chosen to have sufficient range.

Hence, for a typical intersection with the total width of target lane of 11m (three lane widths consisting of 2 lanes and a center divider), for $\beta = 3^0$ and for a choice of $\theta = 1^0$ the radar would be ineffective when the host vehicle is closer than 41.4m from the intersection [14]

The experimental setup, seen in figure (7), was identical to the previous setup with the exception of the location of the reflector, which is now offset from the intersection of the lane centerlines. As with the previous experiment the optical distance of the target surface calculated from the reference reading and distance of the target as returned by the radar were plotted on the same graph. Figures (8) and (9) show representative data sets from the experiments. It must be noted that with offset reflector the radar can only pick up target that are within a certain range of optical distances ( $D_{radar} + D_{target-\min}$ to $D_{radar} + D_{target-\max}$ in figure (7) ). The experiment was designed for the target to be detected when the optical distance of the target from the radar was between 120ft and 250ft. The sudden changes in the distance read by the radar in the first three seconds of the experiments arise from the target being located beyond this designed optical distance. When the target was located between 120ft and 250ft, the radar worked with high reliability and accuracy.

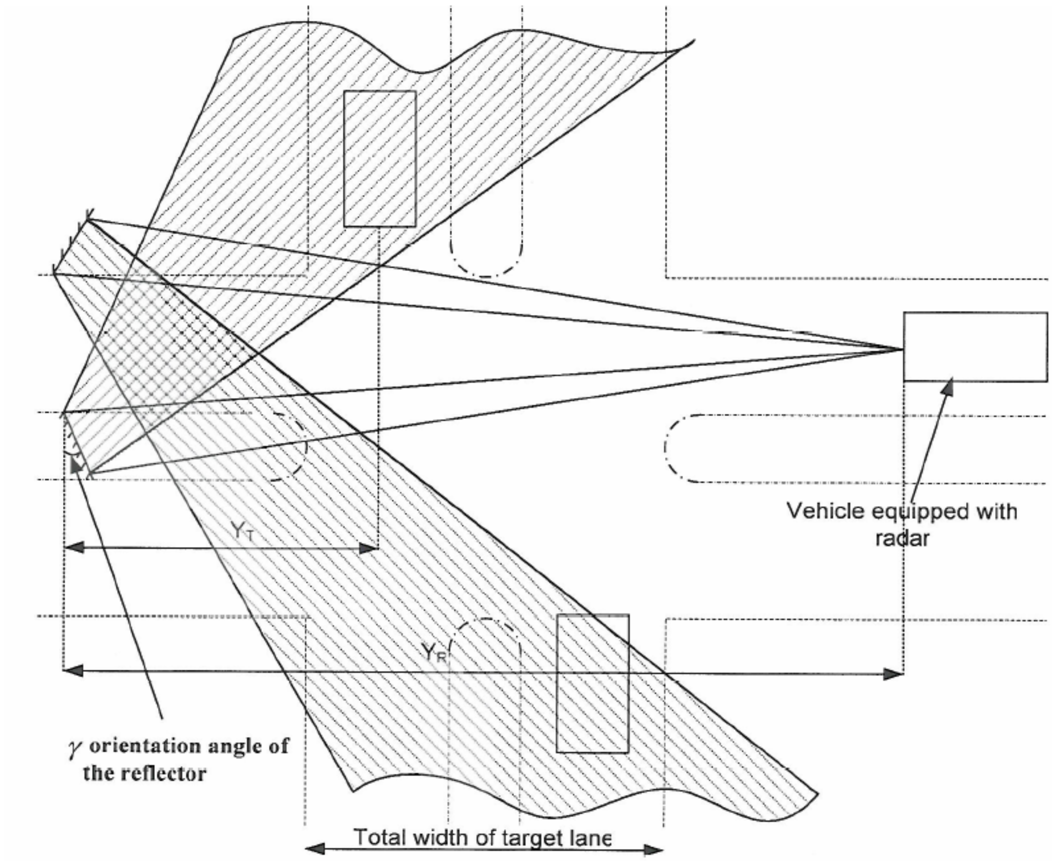


**Figure 6: Schematic of offset reflector set up**

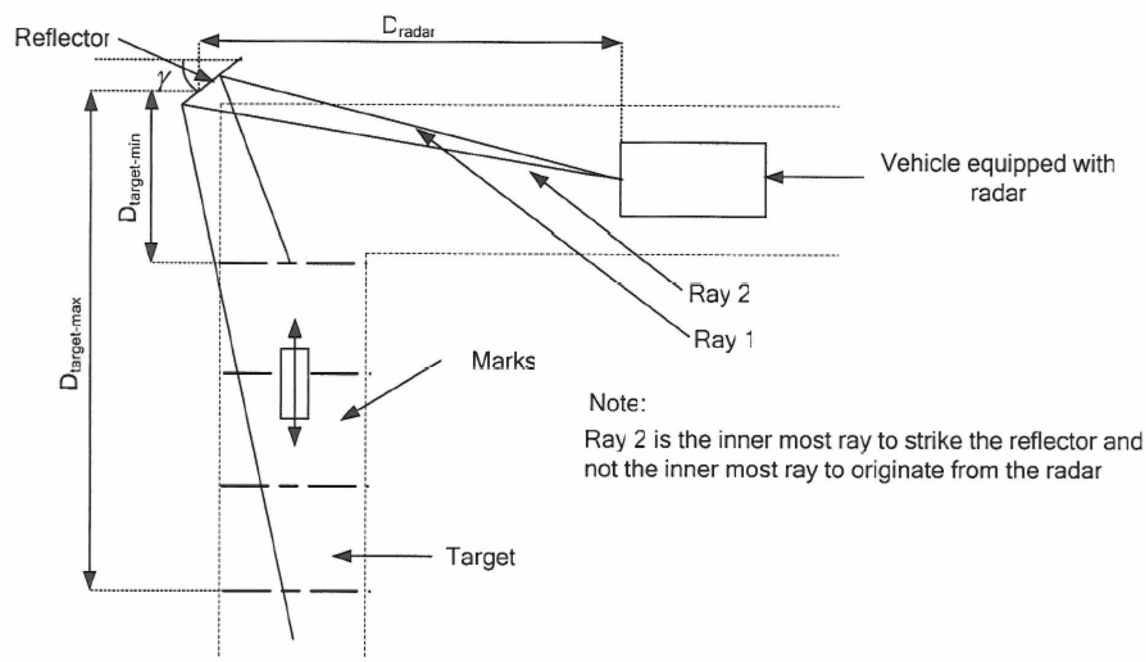


**Figure 7: Schematic of Experiment setup for offset reflector set up**

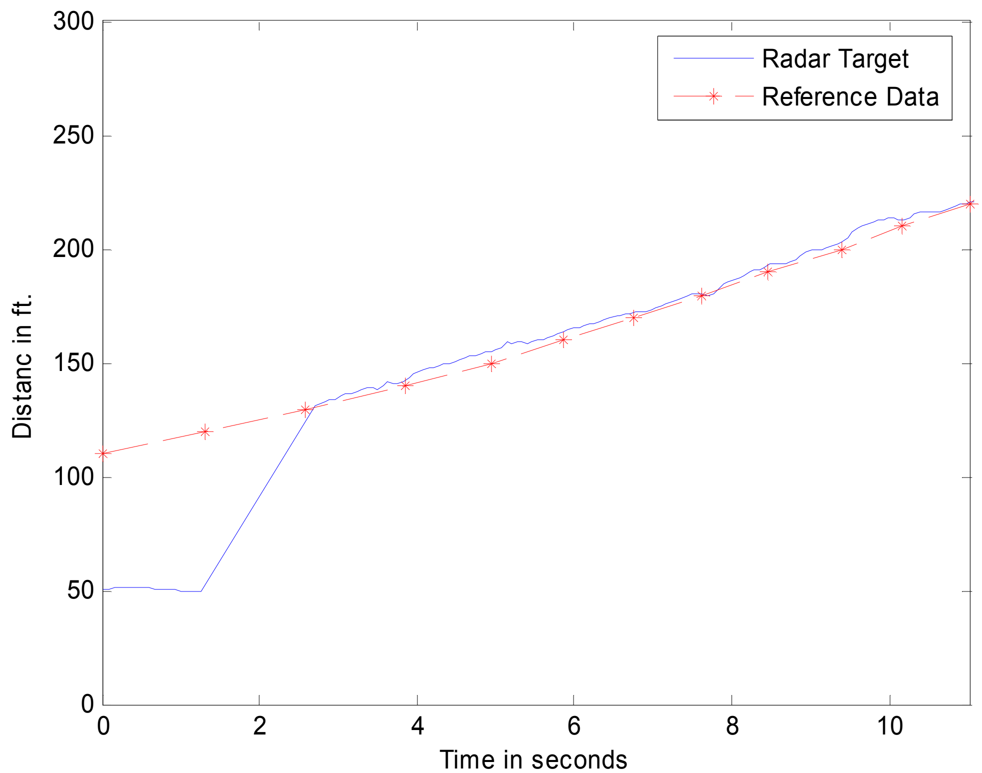


**Figure 8: Out of lane reflector - departing target**

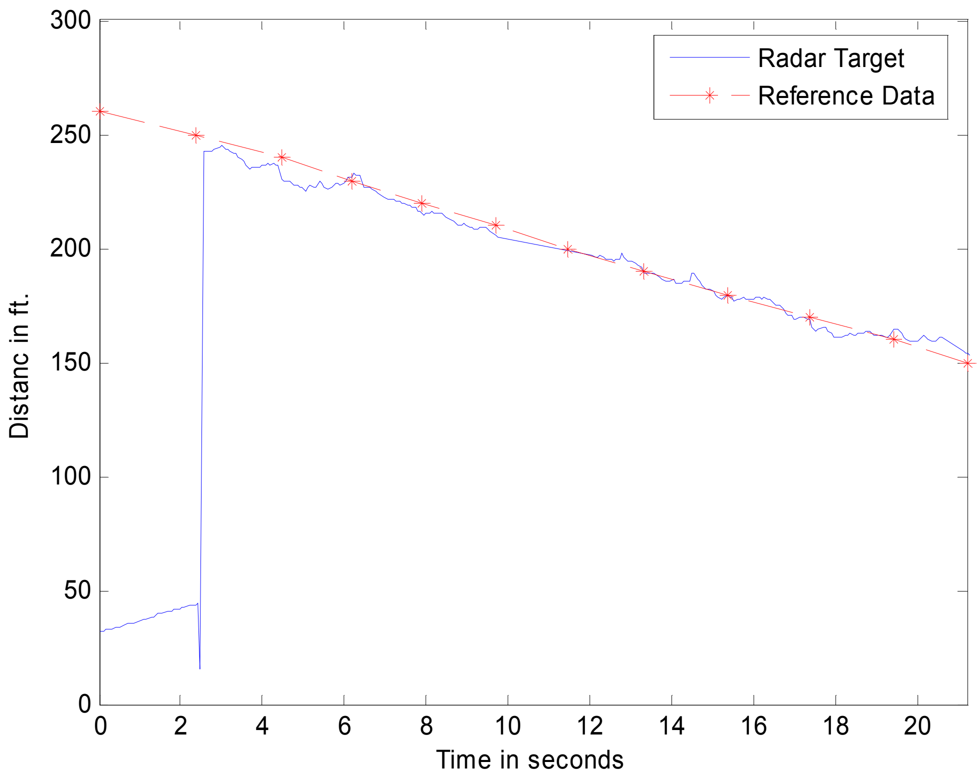


**Figure 9: Out of lane reflector - approaching target**

## 2.3 Use of convex reflector at intersection

When the flat out of lane reflectors are replaced by convex reflectors, due to the diverging action of the convex reflector, the reflected beam could almost completely span the lane perpendicular to the host vehicle as seen in figure (10), where as mentioned earlier the rays originating from the "Vehicle equipped with Radar" represent the envelope of the rays striking the reflector while the shaded region represents the span of the reflected rays. Hence it would be possible to move the reflector along the host axis (see figure (10)) away from the intersection without affecting the performance, such that the radar would detect targets even when the host vehicle is at the intersection.

Experiments were performed by replacing the flat reflector with a convex reflector. However, when the van was moved back and forth in its lane, no target was detected by the radar. The experiments were repeated for different reflector locations, but the radar was not able to pick up targets in any configuration. It was concluded that the radar cannot detect targets when the beams are reflected off a convex reflector. It is speculated that the divergence caused by the convex reflector diffuses the radar beam so much that the signal strength becomes too low for the radar to detect successfully the returning beam, thus making it impossible to detect any targets.

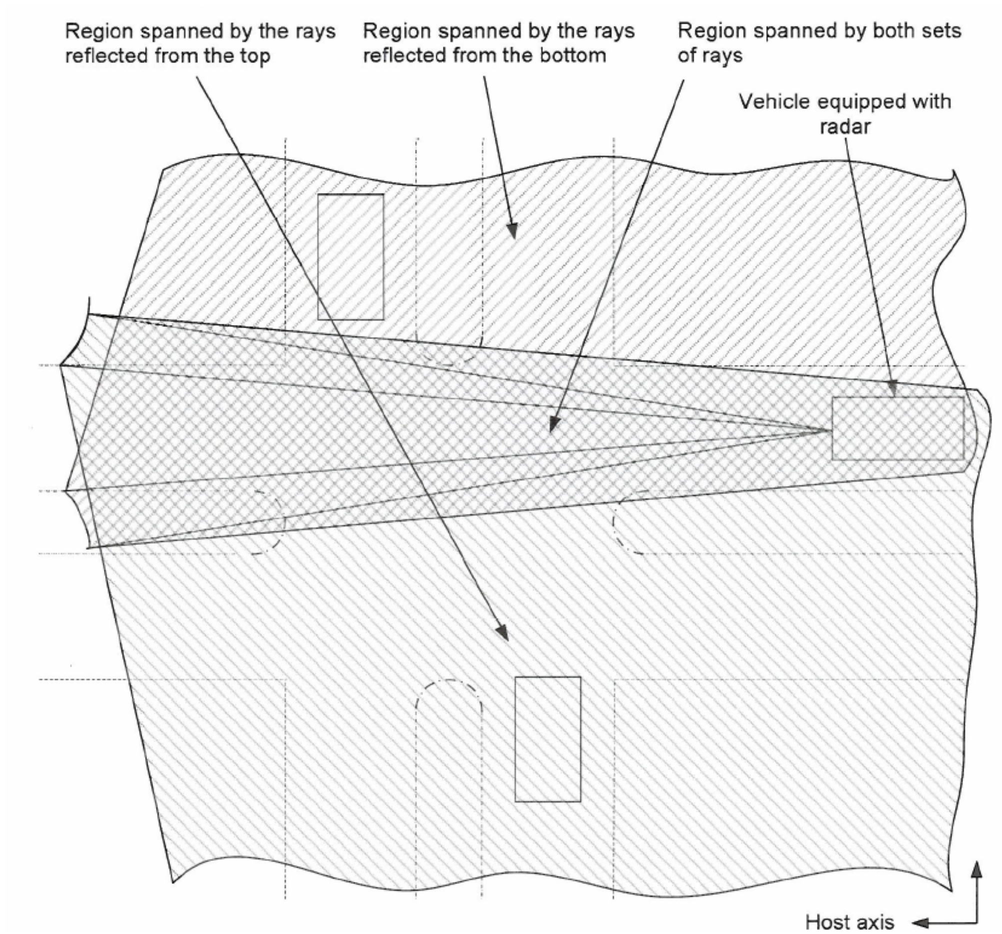


Figure (10): Schematic of a convex reflector setup

## 3. Passive Reflectors for Range Improvement on Curved Highway sections

It is very common for a vehicle traveling on a highway to encounter a curve. Since the radar beams are oriented to detect vehicles directly in front of the host vehicle, on a curved stretch the radar system would only detect targets within its beam width angle. It is evident from figure (11), that targets are not tracked beyond the horizon point, H, (the point on the lane where the extreme ray would cut the lane center). Mathematically, for a beam width spread of $2 \times \beta$ ($\beta$ expressed in radian), and a curve of radius $R_0$ the effective range is given by $2 \times R_o \times \beta$. Thus for typical values of $\beta = 3^\circ$ and $R_o = 300m$, the range works out to 31m. At highway speeds, this translates to roughly a 1.3 second warning at 55mph and 1 second warning at 70mph. It is thus desirable to increase the effective range of the radar to provide better warning time.

This section describes the use of PRRs to improve radar performance on curved lanes. It is first shown through simulations that a PRR setup consisting of a simple curved mirror at the edge of the lane is ineffective in improving the radar performance. As an improvement a "skewed" reflector set up is proposed and evaluated. The use of radar for multilane applications is also discussed and experimental results are given.

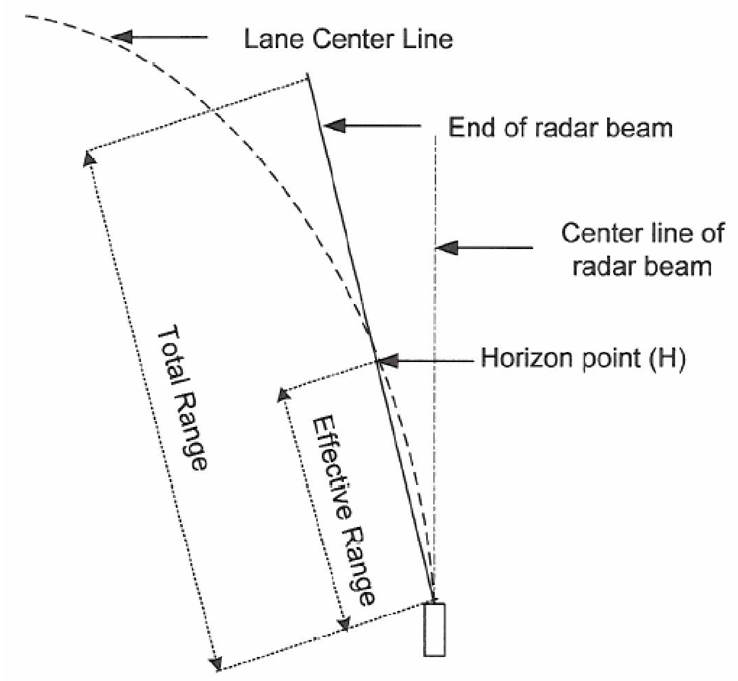


**Figure 11: Loss of Radar Range in curved lane**

## 3.1 Evaluation of a Simple Reflector

A simple curved reflector, either a sheet with appropriate curvature placed at the edge of the road or a series of flat reflectors beyond the shoulder, would be the simplest configuration to implement. Hence this set up was chosen as the first design. Figure (12) shows the simulation performed in Matlab for this setup. Though this simple reflector would enable the radar to pick up more targets further away, it would be ineffective in increasing the effective range of the radar due to the presence of a large blind spot just beyond the horizon point H.

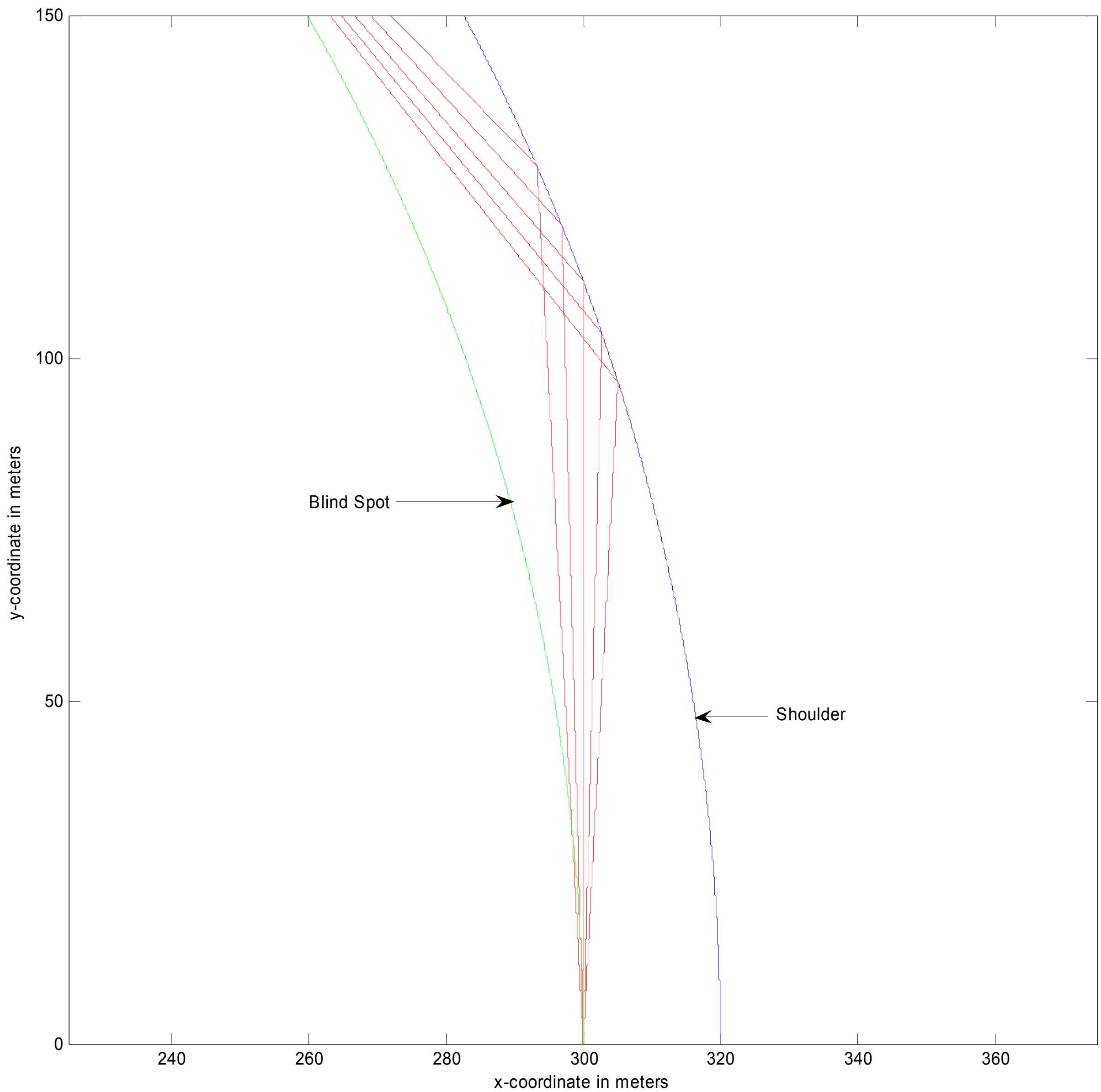


**Figure 12: Simulations for a simple curved reflector**

It can be shown [14] that the blind spot can be eliminated when

$$\frac{d}{R_o} = \sin\beta \tan 2\beta + \cos\beta - 1 \tag{3}$$

where

$\beta$ is the beam-width angle of the radar d is the distance to the shoulder from the current lane, and

$R_o$ is the current lane's radius of curvature.

For $\beta = 3^0$ and $\mathrm{d} = 20\,\mathrm{m}$, we get $R_o = 5\,\mathrm{km}$. Hence, this solution would not be effective except for an almost straight road.

### 3.2 Evaluation of a Skewed Reflector

It is evident from the previous subsection that a simple curved reflector is ineffective for increasing the range of the radar. By skewing the optical normal of the reflector the reflected rays can be redirected towards the blind spot. The blind spot is eliminated when the edge of the reflected ray passed through the horizon point H. Figure (13) shows the simulations for this reflector, for $R_0 = 300m$.

Given the radar output and the skew angle of the mirrors it is possible to identify the target location using elementary geometric formulae. If $D$ and $\theta$ are, respectively, the total distance to the target and the angle to the target as sensed by the radar, it can be shown [14] that distances to the target are given by

$$d_{radial} = R_0\left(\sqrt{\mu_1^2 + \mu_2^2 + \mu_1\mu_2 \sin(\theta - r)} - 1\right) \tag{4}$$

$$d_{circumference} = R_o\, a\tan\left(\frac{\mu_1 \cos\theta - \mu_2 \sin r}{\mu_1 \sin\theta + \mu_2 \cos r}\right) \tag{5}$$

where

$$\mu = \frac{d}{R_0}$$

and $d$ is the distance of the shoulder from the current lane

$$r = 2\left[\phi + a\sin\left(\frac{\mu_1 \cos\theta}{1+\mu}\right)\right] - \theta - \frac{\pi}{2} \tag{6}$$

$$\mu_1 = \sin\theta + \sqrt{\sin^2\theta + 2\mu + \mu^2} \tag{7}$$

$$\mu_2 = \frac{D}{R_0} - \mu_1 \tag{8}$$

$\phi$ is the skew angle of the reflector.

The skewing of the normal can be achieved by placing a series of flat mirrors such that they make the desired skew angle with the tangent to the curve at that point (as seen in figure 14). For this series of flat reflectors to model a skewed mirror accurately, it is desirable that the width of these mirrors be as small as possible. If the mirrors used are larger, then there would be abrupt change in the direction of the normal and analysis of such a problem is beyond the scope of this discussion. For manufacturing ease, the separate mirrors could be combined into a corrugated sheet that can be rolled in this shape using metal forming techniques and affixed to the guardrail in the road shoulder. The presence of series of flat reflector is equivalent to an uncertainty in the location of the center of the curve. Hence if $width\_of\_reflector/R_0 << \mu_1, \mu_2$, the series of flat reflectors would adequately approximate a skewed reflector.

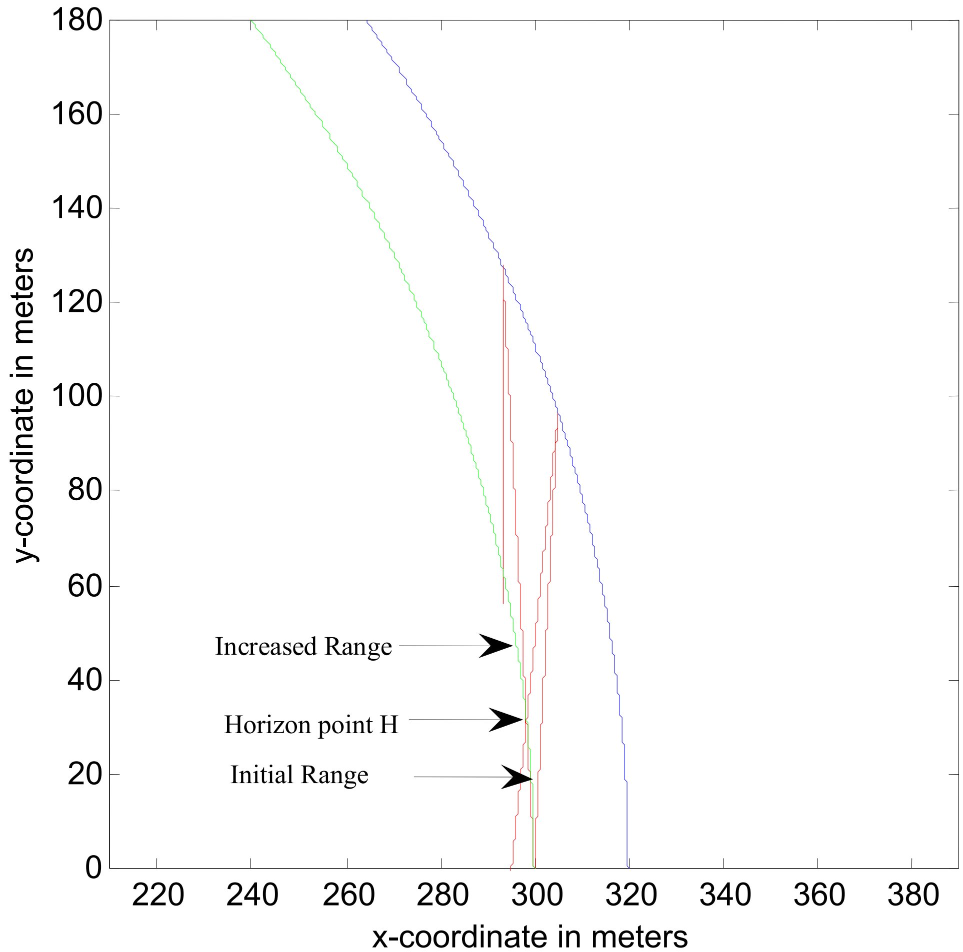


**Figure 13: Simulations for a skewed curved reflector**

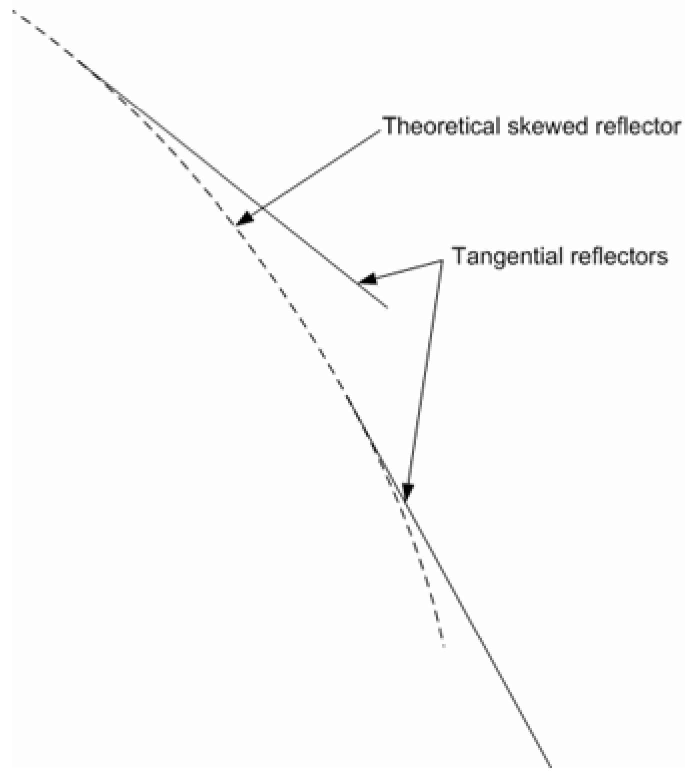


**Figure 14: Simulations for a skewed curved reflector**

### 3.3 Extension of Skewed PRR to Multi-Lane

For multilane applications, it is not only necessary to find the distance of the target along the circumference, but it also desirable to calculate the distance of the target in the radial direction in order to determine its lane. Since the formulae presented in sub-section 3.2 calculate both these distances it is possible to identify the location of the target over multiple lanes. For multilane applications, however, there is an additional challenge of the radar identifying targets in adjacent lanes as seen in figure (15). It can be calculated that the range of the incident ray is $2\beta R_0$. The optical distance to any target picked up by the reflected ray would be greater than $R_0\sqrt{2+2\mu+\mu^2}$ . Hence by denoting targets within $2\beta R_0$ as targets in the current lane and by processing targets at distance greater than $R_0\sqrt{2+2\mu+\mu^2}$ using the formulae, it would be possible to use the PRR in multilane

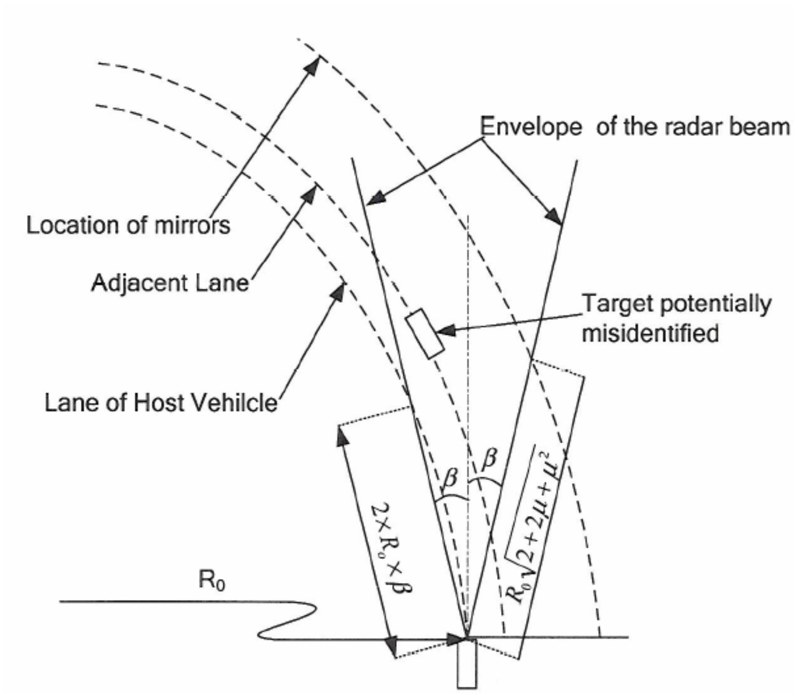


**Figure 15: Potential misidentification of target lane**

## 3.4 The Use of Convex Reflectors

The skewed reflector redirects the entire radar beam towards the horizon point. Hence the use of a skewed PRR doubles the effective range of the radar when compared to inherent range. However, the range of the radar is still smaller than the range on a straight section.

It is possible to have the reflected radar beam sweep the lane of the host vehicle, there by increasing the effective range of the radar. This can be achieved by replacing the series of flat reflectors with a series of convex reflectors. The diverging action of the convex reflector would enable a larger area to be spanned compared to the flat reflector. As the vehicle moves along the curved section, different segments of the radar would sweep the lane of the host vehicle as seen in Figure 16. Thus all targets in the lane could be detected.

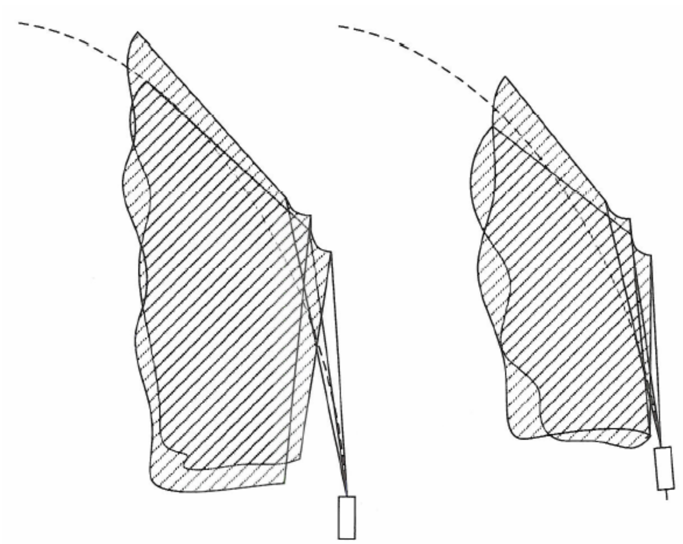

**Figure16: Schematic of series of convex reflectors**

When trial experiments were performed using a convex reflector, as in subsection 2.3, no targets could be detected. This is likely due to divergence of the beams after reflection from the convex reflector which diffuses the radar beam so that the return signal strength becomes too low for the radar to detect returning beams. As it might be possible to detect targets if a more powerful radar was available, the formulae for calculating the target position from the data returned by the radar is presented below. The derivation of these formulae can be found in Vijayaraghavan et al [14].

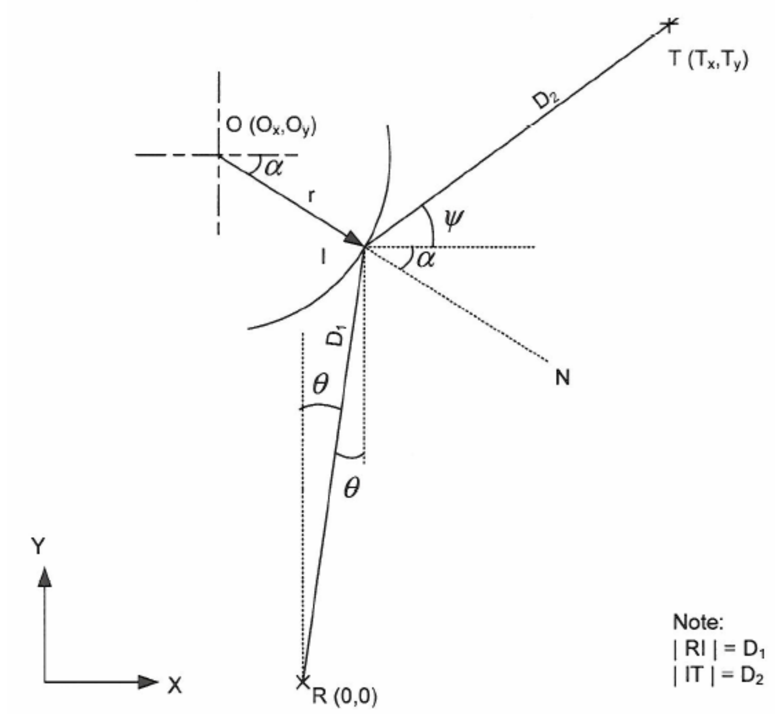


Figure17: Target location determination for target identified with a single convex reflector

Consider a single reflector as in Figure 17 with the origin of coordinates at the radar. Let O, be the center of the reflector. It is assumed that we have a priori knowledge of the radius of the reflector as well as the relative position of the reflector with respect to the radar. Hence $r$, $O_x$ and $O_y$ are known. Let $D_1$ and $D_2$ be the distances from the radar to the point of reflection on the reflector and from the reflector to the target respectively. Let $\theta$ be the target-angle data provided by the radar and let $\psi$ be the orientation of the reflected ray as shown in Figure 17. Then the location of the target is given by

$$T = \left(D_1 \sin\theta + D_2 \cos\psi, D_1 \cos\theta + D_2 \sin\psi\right) \tag{9}$$

where

$$D_1 = \min\left[\left(O_x \sin\theta + O_y \cos\theta\right) \pm \sqrt{r^2 - \left(O_x \cos\theta - O_y \sin\theta\right)^2}\right] \tag{10}$$

$$\psi = \theta + \frac{\pi}{2} - 2\ a\tan\left(\frac{D_1 \cos\theta - O_y}{D_1 \sin\theta - O_x}\right) \tag{11}$$

$D_2$ can be obtained for the target-distance data from the radar ( $D$ ) using

$$D_2 = D - D_1 \tag{12}$$

### 3.5 Experimental results

As with the previous experiments the data from the radar was logged into a file and, as reference data, the time instants when the target passed reference marks in its lane were logged separately. To simulate multilane operation, the host vehicle was stationary in the middle of one lane of radius 78ft (23.77m) and the target was moved along a lane of radius 68ft (20.73m). The data from the radar was processed to translate linear distance to circular distance. Figure (18) shows the Matlab® plots from representative data sets of the experiments carried out with the target moving away from the host while Figure (19) shows the experimental results for the target moving toward the host. The processed radar readings were in reasonable agreement with the reference data. The experiments reveal that the targets can be tracked with a margin of error of roughly 5ft (1.52m) along the circumference and roughly 3ft (0.91m) in the radial direction. The use of wide reflectors for these experiments and the uneven motion of the target may have partly contributed to the error. These effects can be greatly minimized on a section with a higher radius of curvature.

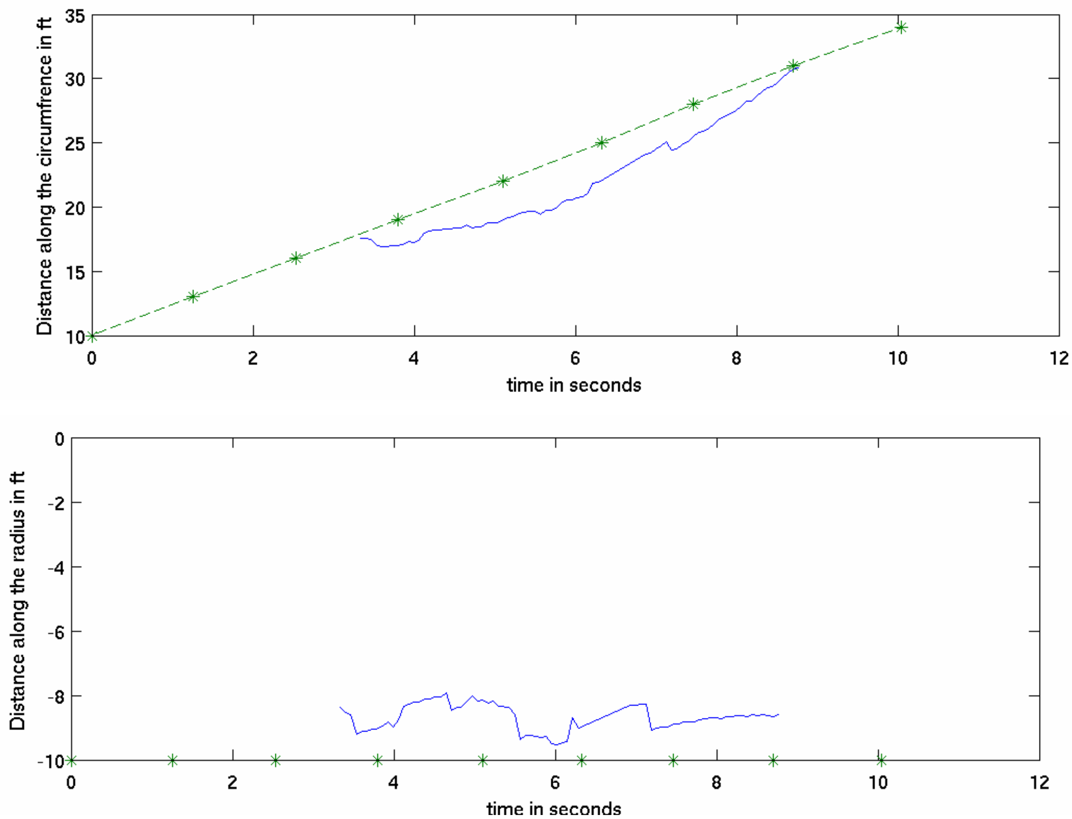


**Figure 18: Experimental plot (1) -- for departing target**

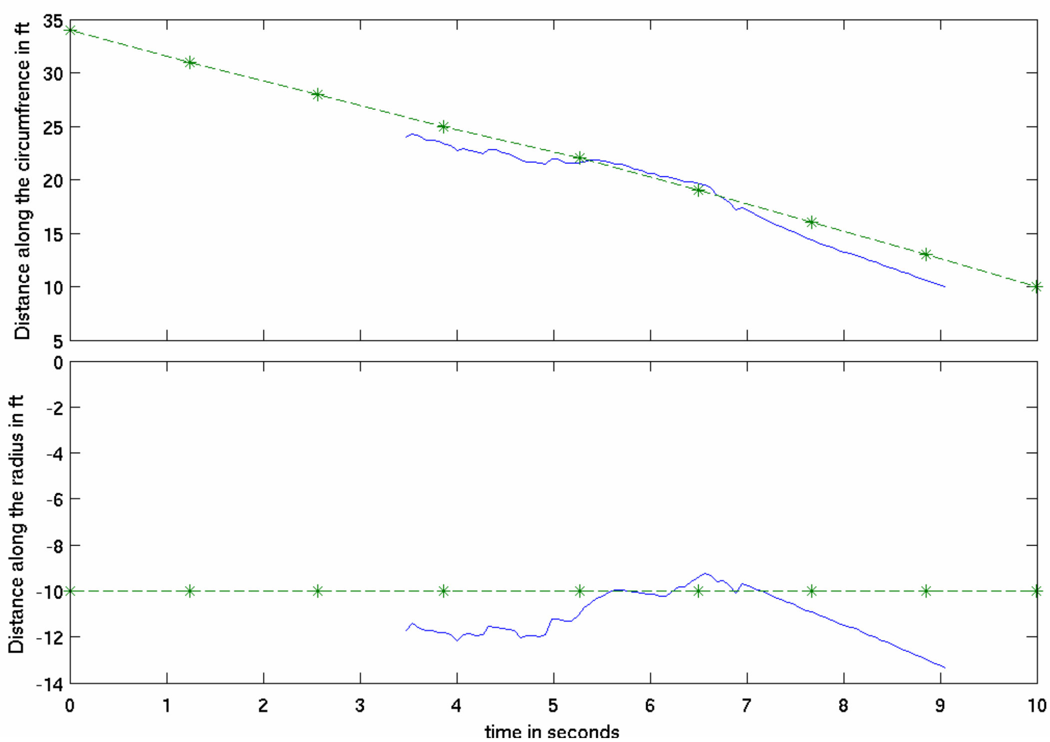


**Figure 19: Experimental plot (2) -- for approaching target**

### 3.6 Optimal Skew angle

It is obvious the design parameter $\phi$ (skew angle; 0° would be tangent to the curve, 90° would be normal) needs to be chosen with caution. This parameter $\phi$ represents the angle by which the optical normal of the mirror has to be skewed relative to the geometric normal. As explained in section (3.2) the skewing can be obtained by using a series of flat mirrors. If the skewing is not sufficient then the blind spot would not be eliminated, while if the skew angle is too large, the increase in range would be limited. Hence, we desire that the skew angle be such that all but the lower envelope of the reflected radar rays pass beyond the horizon point, H, and the lower envelope of the reflected radar rays passes through the horizon point so that the blind spot is just eliminated.

The optimal skew angle is given by [14]

$$\phi_{optiimal} = \frac{\pi}{4} + \frac{1}{2}\tan^{-1}\left[\frac{(1+\mu)\sin(\delta_1) - \sin(2\beta)}{(1+\mu)\cos(\delta_1) - \cos(2\beta)}\right] + \frac{\beta}{2} - a\cos\left(\frac{\cos(\beta)}{1+\mu}\right) \tag{13}$$

and new range of the radar is given by [14]

$$Range = R_0\left\{a\sin[(1+\mu)\sin(\delta_2 - \alpha_2)] + \alpha_2\right\} \tag{13}$$

where

$$\delta_1 = a\cos\left(\frac{\cos\beta}{1+\mu}\right) - \beta$$

$$\alpha_2 = 2(\gamma + \delta_2) - \frac{\pi}{2} - \beta$$

$$\delta_2 = a\cos\left(\frac{\cos\beta}{1+\mu}\right) + \beta$$

Figure (20) shows the variation of the optimal skew angle with the non-dimensional radius $R_0 / d$ for different values of $\beta$. The $\gamma_{optiimal}$ for $d = 20m$ and $R_0 = 300m$, i.e. $R_0 / d = 15$ is $\phi_{optiimal} = 68^0$. For this optimal value of $\phi$, it can be shown that the effective range of the radar is doubled. It can be noticed that for the same $R_0/d$ the skew angle is larger for smaller $\beta$. This can be explained by the fact for smaller $\beta$, the horizon point 'H' would move closer to the host vehicle and hence a larger skew is needed to eliminate the blind spot discussed in section 3.2. Figure (21) show the change in the range of the radar obtained by using PRR obtained from equation (13).

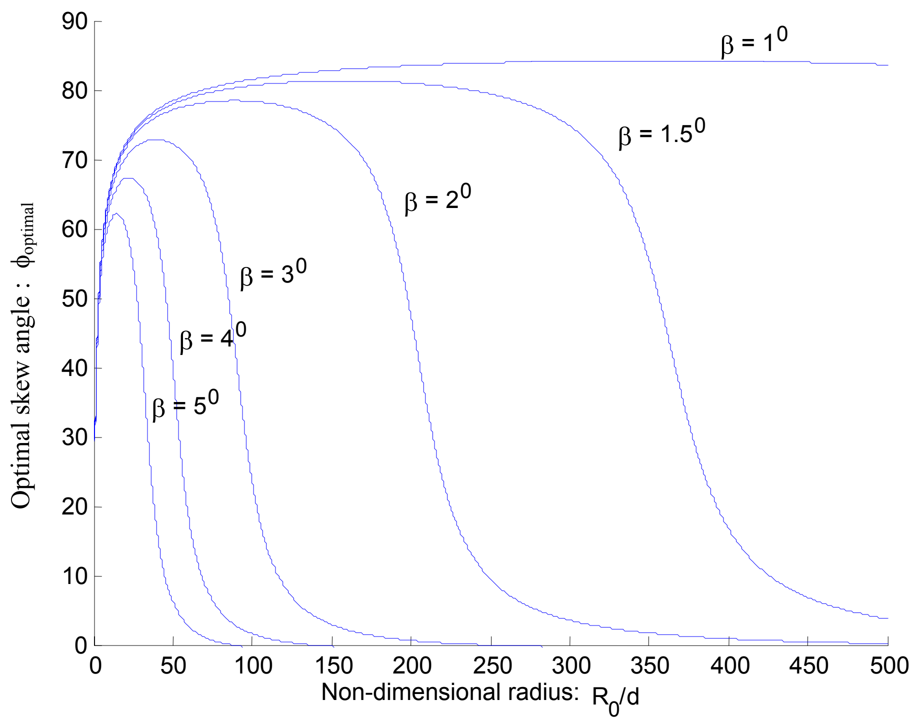


**Figure 20: Variation of optimal skew angle**

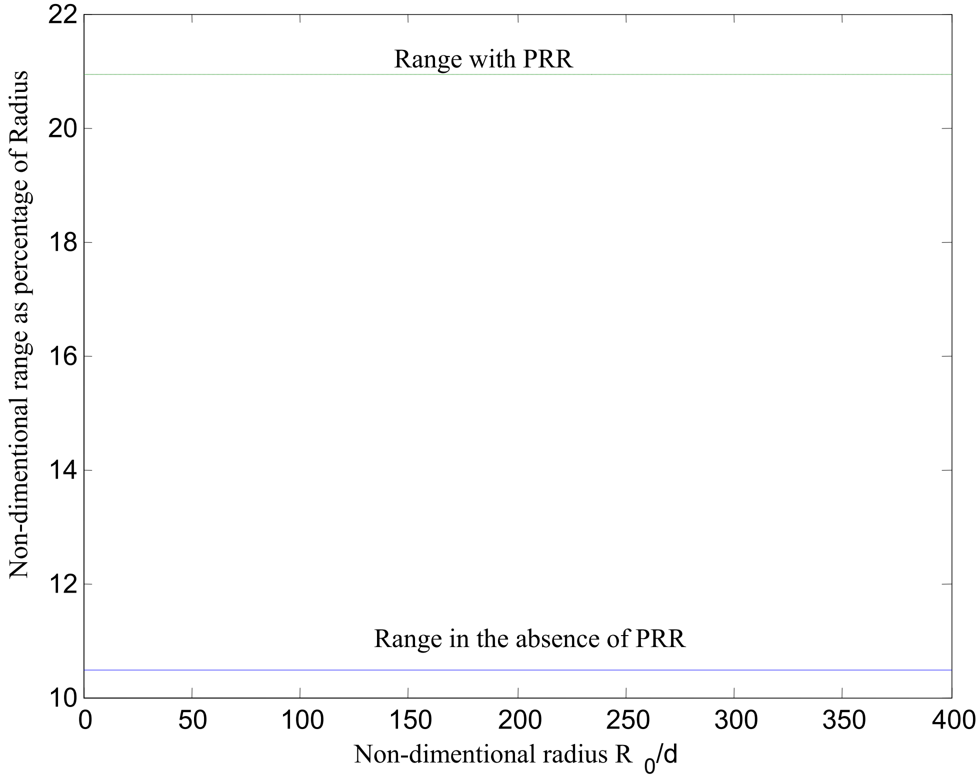


**Figure 21: Change in range of Radar for introduction of PRR for $\beta = 3^0$**

## 4. Conclusions on Performance of Passive Radar Reflectors

Current automotive radars, owing to their limited beam width angle, do not have the necessary reliability to aid drivers adequately for target detection in several scenarios. It has been demonstrated that the use of PRRs in curved sections of highways can essentially double the effective range of the radar. It was also shown that a PRR setup can be used at intersections in order to provide an early collision warning system. Though the use of convex reflectors would enable the radar to detect targets when the host vehicle is closer to the intersection, experiments revealed that the radar does not detect targets with beams reflected by a convex surface

Some limitations in the use of PRRs should be mentioned. With the use of PRRs in multi-lane curved lanes, vehicles in adjacent lanes of the highway may block the path of either the incident or the reflected radar beam, preventing the PRR-radar system from identifying crucial targets. Hence, the effectiveness of PRRs may be limited to light traffic or to two-lane highways. A PRR would help identify cross traffic only when the host vehicle is at a sufficient distance from the intersection. For PRRs to be effective in curved lanes, they need to be deployed throughout the length of the curved section.

# 5. Development of a Wireless Sensor for Vehicle Location Measurement

After consideration of the desirable properties for a vehicle location measurement system and the types of technologies available for the same, it was decided that a vehicle location measurement system that utilized battery-less wireless measurements would be most suitable for this application. Once embedded in the road, such a sensor system would not need external power (no wiring needed and no power supply needed). Also, there would never be a need to change batteries for this device. The disadvantage of battery-less wireless type of technologies is their limited telemetry distance. However, for the present application, the required telemetry distance is small and therefore acceptable.

## 5.1 Sensor Design

A battery-less wireless sensing system that depends on the use of a piezoelectric sensor embedded in the road has been developed. The passing of a vehicle over the piezoelectric sensor is used both to harvest energy for wireless operation and to detect the passing of the vehicle and its speed.

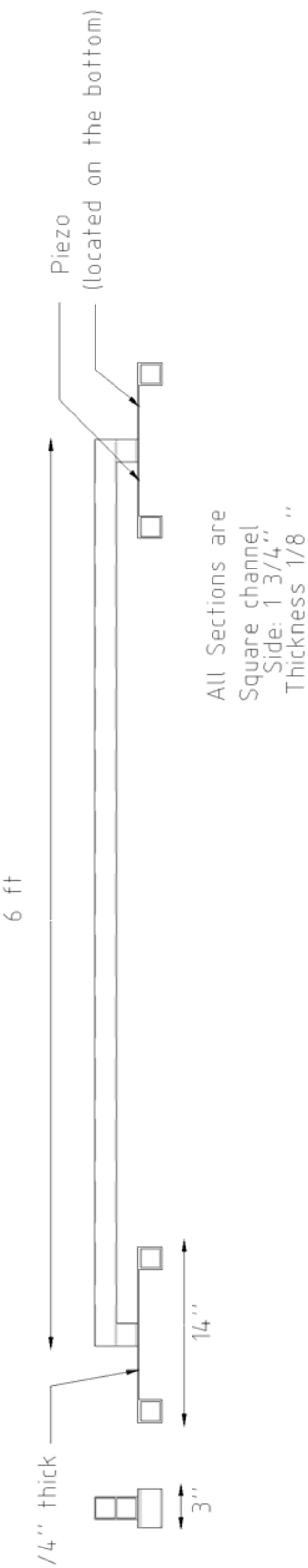


**Figure 22: Side view of mechanical drawing of sensor system**

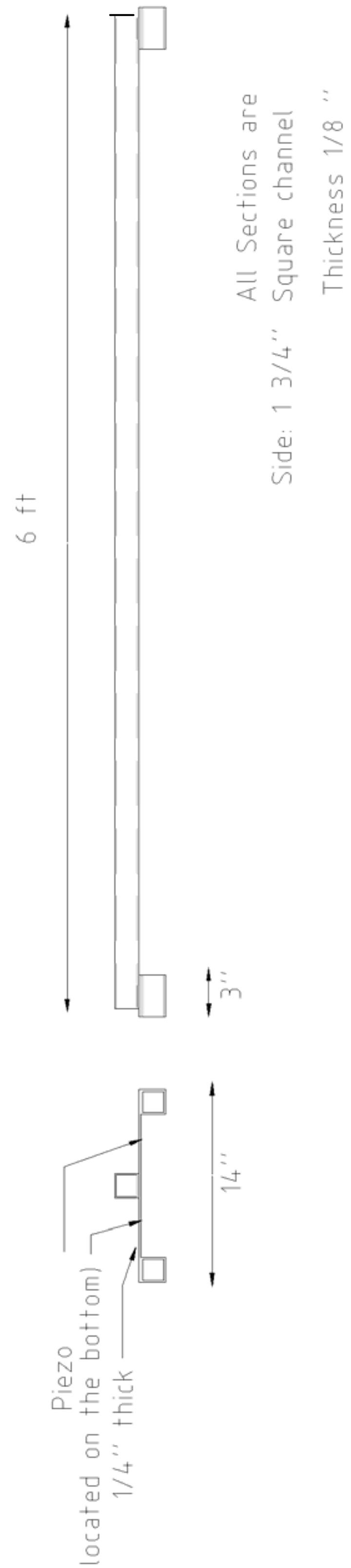


**Figure 23: Side view of sensor system in different configuration**

Figure 22 shows a mechanical drawing of the developed sensor system. The eventual sensor could be much smaller than the one shown in Figure 22.

As shown in Figure 22, the setup has a long (6 ft) beam, that ensures that no matter where the vehicle is in its lane, exactly one set of wheels (either the right or the left set of wheels) will pass over the beam. The load from the long beam is transmitted to the smaller end beam and the ¼'' plate is subjected to bending load. The piezos located on ¼'' are subjected to a strain and they generate a voltage. When the wheel is closer to the left end of the long beam, the piezo on the left support beam reads a higher voltage. Similarly when the wheel is closer to the right end of the long beam, the piezo on the right support beam reads a higher voltage. However the average voltage of the piezo depends only on the total load applied on the long beam. Hence all the piezos have been electrically connected in parallel so that the energy harvesting circuit sees the same voltage regardless of where the vehicle is in the lane. This is demonstrated in Figure 27, which shows the data collected when a person stepped on different locations on the long beam. The voltage generated is nearly the same in all cases.

In the proposed setup, the whole beam would be buried, under the asphalt. The beam has been designed to have a maximum deflection of 5mm (1/5'') under a load of 500 Kgs. This would ensure that the deformation of the sensor does not adversely affect the road structure.

The setup does not require any external power source. The transmission distance is determined predominantly by the choice of transmitter and distances greater than 3000ft are possible (using, for example, the Linx technologies LR series transmitter)

## 5.2 Electronic System Design

A diagram of the circuit that is used to harvest vibration energy from a piezoelectric element power an RF transmitter is shown in Figure 24 below.

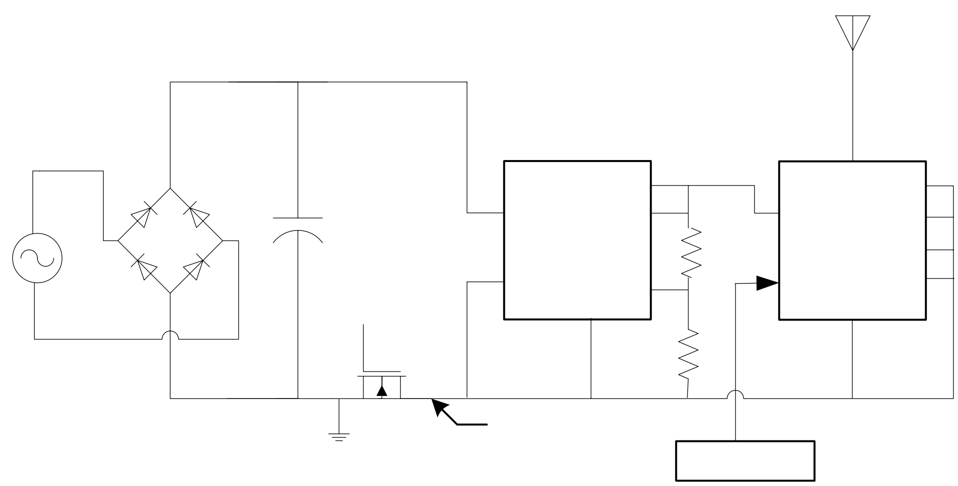

**Figure 24: Energy Harvesting Circuit Layout**

The sinusoidal electrical signal is rectified and used to charge the capacitor $C_1$. After the capacitor has been adequately charged, the voltage across the capacitor can be connected to the MAX 666 chip and LYNX transmitter with a MOSFET as the connecting switch.

The control voltage for the MOSFET needs to be supplied in such a way that a high voltage (e.g. 5 V) is required across the capacitor to close the switch and a lower voltage (e.g. 2 V) is required to open it. A diagram of the circuit to generate this control voltage is shown in Figure 25. In this case the threshold values of the control voltage are determined by the Zener diode breakdown voltage and the resistances used.

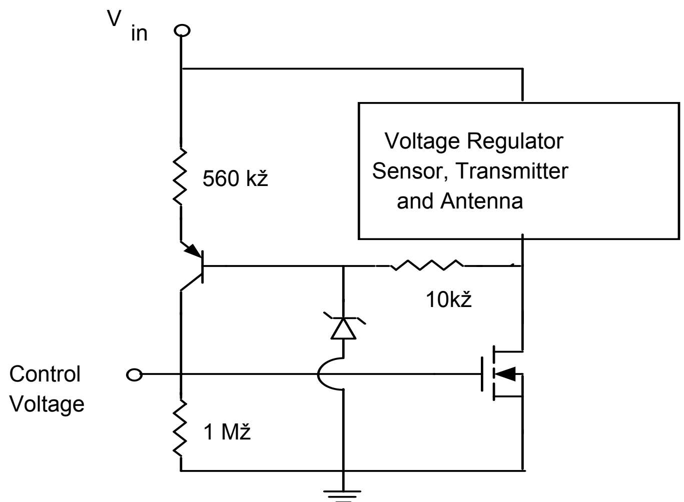


**Figure 25: Control voltage generation circuit.**

## 5.3 Printed Circuit Board

A printed circuit board was developed by implementing the energy harvesting circuit of Figure 24 and the control voltage generation circuit of Figure 25.

Figure 26 shows photographs of the printed circuit board developed for the sensor system. The upper part of the figure (the first photograph) incorporates the circuits shown in Figure 24 and Figure 25. The lower part of the figure (the second photograph) shows the size of the circuit. It can be seen that the printed circuit board is approximately the size of a credit card.

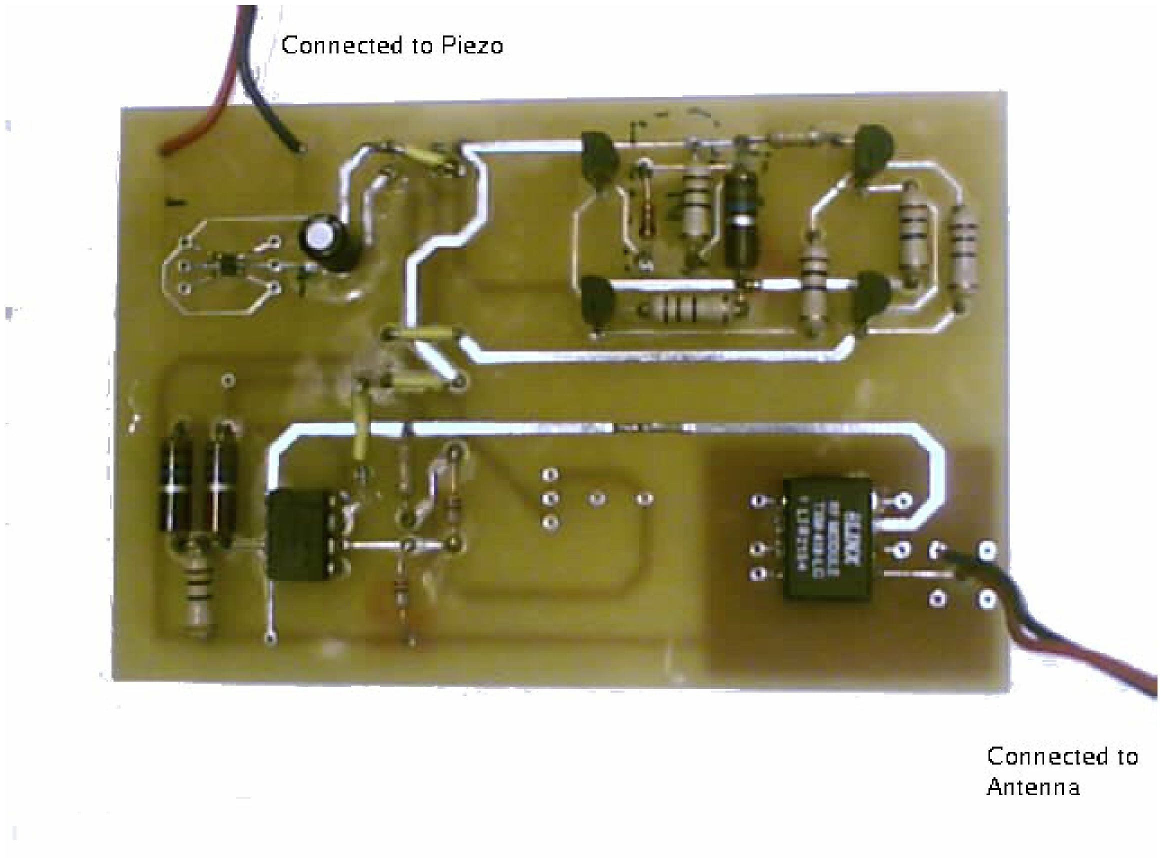
Connected to Piezo
Connected to Antenna


**Figure 26: Photograph of the printed circuit board developed for the sensor system**

# 6. Experimental Results on Vehicle Location Measurement Using Wireless Sensors

## 6.1 Vehicle Tests and Wireless Transmission

Figure 27 shows measurement data from the vehicle location sensor. The upper part of the figure shows the voltage signal received by wireless transmission at the receiver end of the system. Two pulses are received at the receiver end, one each corresponding to each axle of the vehicle. This data was obtained by using a Dodge Caravan test vehicle. Data was recorded as the test vehicle passed over the embedded sensor system.

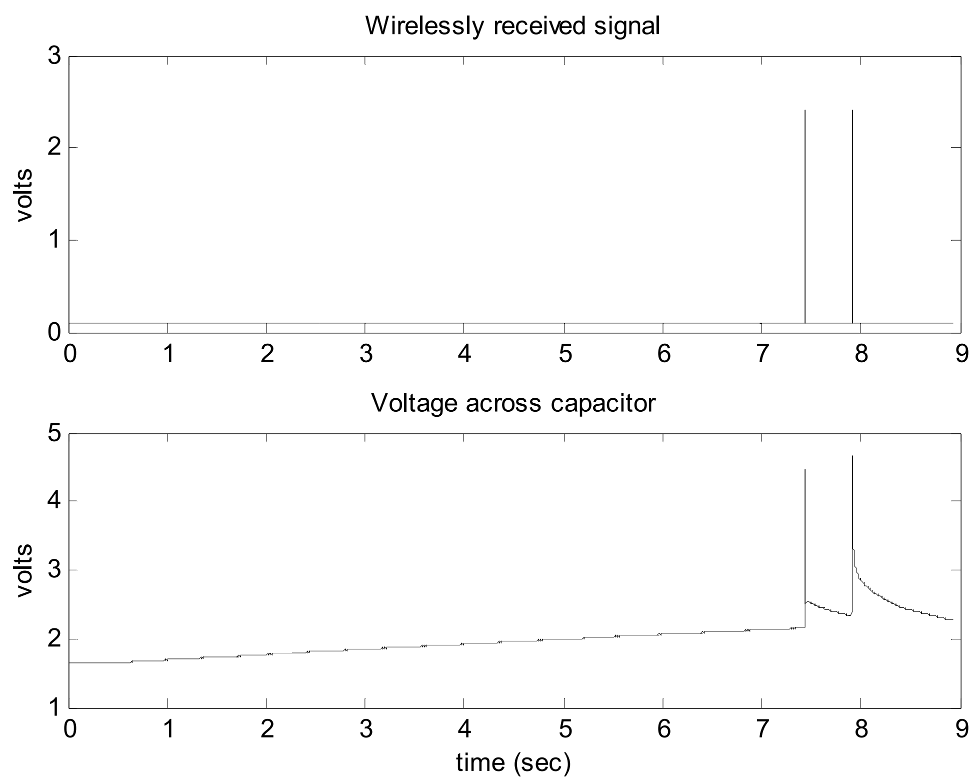


**Figure 27: Voltage across storage capacitor and wirelessly transmitted signal**

The lower part of the figure shows the voltage across the storage capacitor at the transmitter end of the sensor system. As seen in the figure, the voltage across the storage capacitor builds up during the vibration induced by the passing of each axle of the vehicle. Figure 28 shows a close-up of the voltage build up in the capacitor. As seen in the figure, the voltage builds up to a value of 4.5 volts for each axle. When the 4.5 volt threshold is reached, the switch connecting the capacitor to the transmitter is closed. The voltage across the storage capacitor then drains rapidly as the transmitter draws power in order to wirelessly transmit the signal. When the voltage across the capacitor drains to 2.5 volts, the switch is opened again. The wireless transmission then stops and no more power is drained from the capacitor. The whole cycle repeats for the second axle of the vehicle.

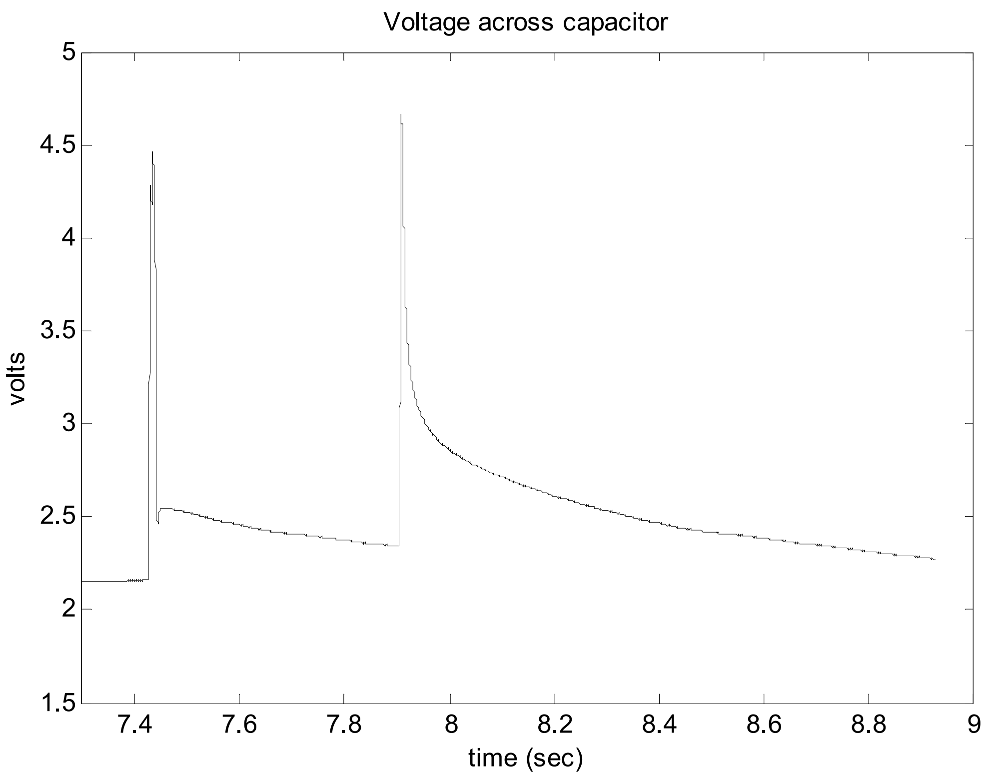


**Figure 28: Close-up of voltage across storage capacitor**

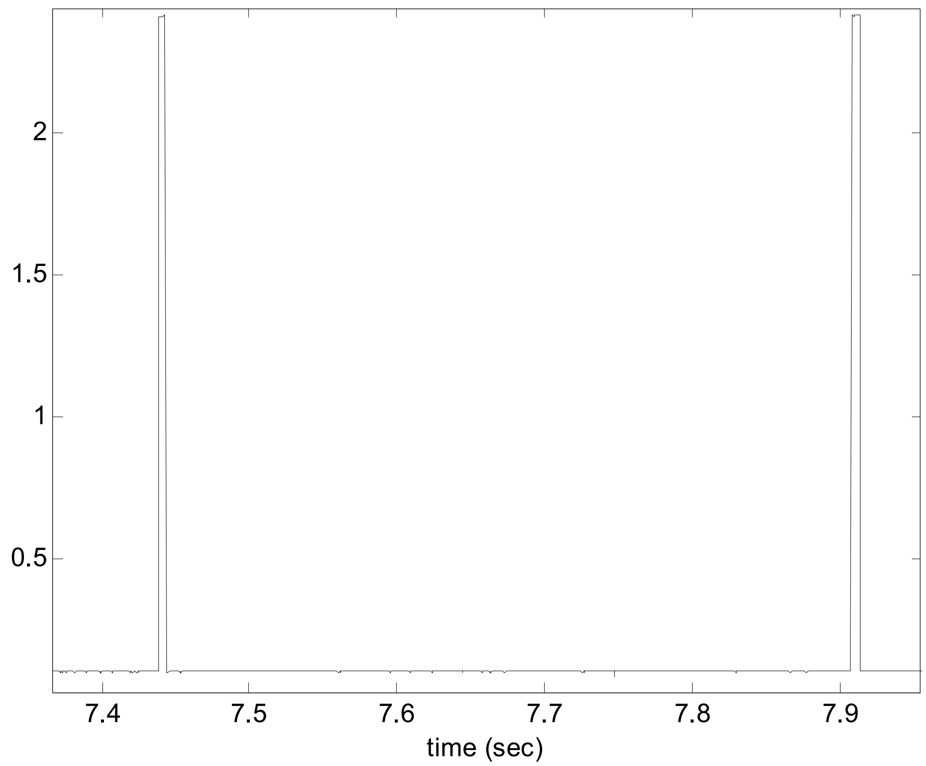


**Figure 29: Close-up of voltage across storage capacitor**

The speed of the passing vehicle can also be measured by the developed sensor system, in addition to measurement of vehicle location. The speed is obtained by measurement of the time gap between two consecutive signals received wirelessly. Figure 29 shows the time difference observed between two wireless signals generated from a vehicle moving at approximately 12 miles per hour. The time difference is seen to be 0.47 seconds. Knowing the distance to be 2.5 meters, the speed is calculated to be (2.5/0.47) = 5.32 m/s or 11.97 miles per hour.

## 6.2 Tests on Influence of Load Location

It was demonstrated experimentally that the sensor system was able to generate the same voltage across the capacitor no matter where the load was applied on the sensor beam. Thus, the vehicle could pass over any portion of the beam and this would not change the voltage generated. This helps the sensor to provide reliable measurements that do not change with vehicle lateral location inside the lane. Figure 30 shows the voltage measured across the storage capacitor for three different load locations. These load locations were in the middle, near the left edge and near the right edge of the beam. For all three load locations, the voltage across the storage capacitor remains essentially the same.

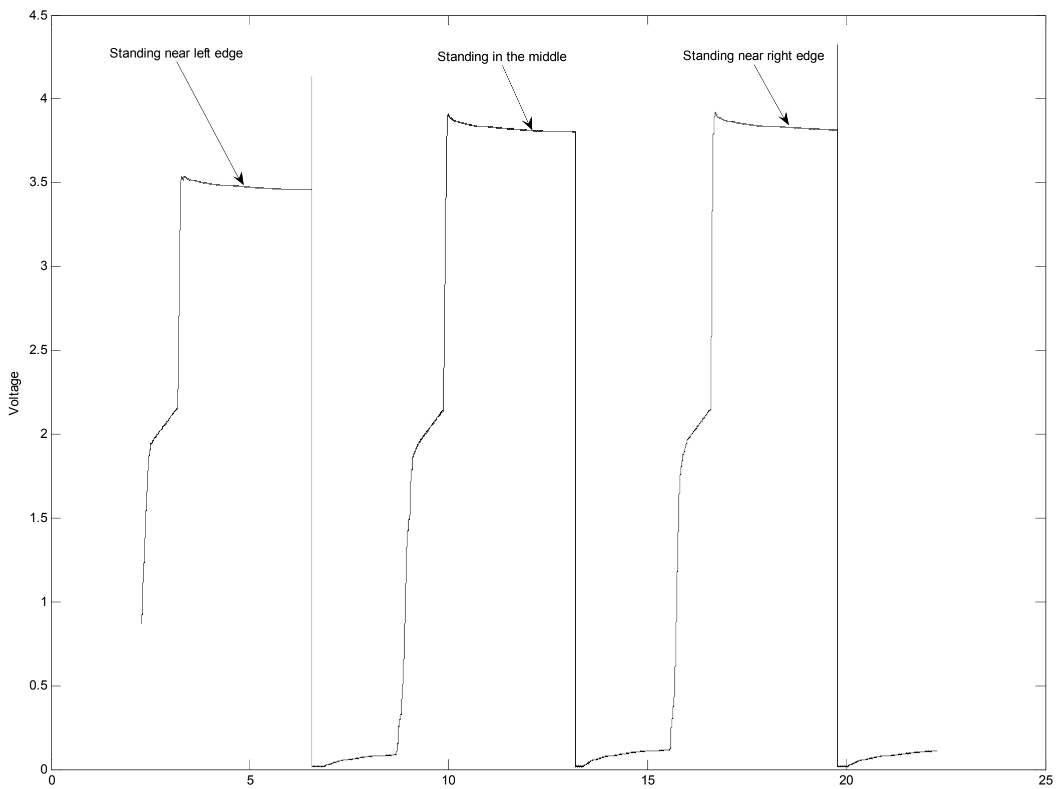


**Figure 30: Voltage measured across the capacitor for various positions of load**

As discussed earlier in section 5.1, the uniformity of the voltage generated (no mater where the load is applied on the sensor) is ensured directly by the mechanical design of the sensor. The interested reader should read section 5.1 for an explanation of the design.

# 7. Conclusions

The limitations of current use of radar in automotive applications were pointed out. In applications such as adaptive cruise control the radar can only be used for detecting target vehicles directly in front of the host vehicle. Vehicles around a curve on a highway and cross traffic vehicles at an intersection cannot be detected by current radar systems. This is primarily due to the limited beam width angle of the radar.

The first part of the project studied and evaluated the novel concept of using passive roadside reflectors (PRRs) to increase the utility of the radar system. PRRs on the shoulder and the median of a road were designed that would enable the radar system to pick up cross traffic at highway intersections. Both simulations and experiments demonstrated that this concept could be effectively used for cross traffic distance measurement. A limitation of this technology is that cross traffic cannot be detected when the radar equipped vehicle is very close to the intersection due to the lateral offset of the radar from the location of the PRR. However, the system is still valuable for providing future warning of cross traffic at rural intersections. A number of options were explored for the use of PRRs to improve radar measurements on highway curves. These included the use of tangential flat plate reflectors, skewed flat plate reflectors and convex reflectors. Algorithms for distance measurement with each of these options were derived and evaluated through simulations. The use of skewed flat plate reflectors was also evaluated experimentally and found to work effectively. The effective range of the radar on highway curves could be doubled by the use of the developed system.

The second part of the project focused on the development of wireless sensors that can be embedded into the road and can detect the passing of a vehicle as well as the velocity of the vehicle. By embedding such sensors into the road the location of different vehicles on a curve can be estimated by the vehicle receiving wireless information from the embedded sensors. In order to ensure that the developed sensors are maintenance-free, unique technology that enables the sensors to operate by harvesting energy from vibrations of the road has been developed. The developed sensors harvest energy using piezoelectric patches and then utilize this energy for wireless transmission. This ensures that the embedded sensors do not need power supply lines nor do they need batteries that require replacement. Experimental results showed that the developed sensor can be embedded in the road and can reliably detect the passing of a vehicle. The design of the sensors and experimental results were presented in the report.

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