REVISITING THE USE OF DRONE RADAR TO REDUCE SPEED IN WORK ZONES: SOUTH CAROLINA'S EXPERIENCE

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August 1, 2006

Word count: 7,494

ABSTRACT
Speeding through work zones is a major safety concern in South Carolina. The authors evaluated multiple traffic control devices aimed at reducing speeds in South Carolina work zones and found that the majority of these speed control measures, with the exception of drone radar, are often not practical for wide spread, cost-effective implementation. The drone radar device has been tested for more than twenty years although never in South Carolina. The focus of this research was to determine the effect of drone radar as a speed reduction measure in work zones on interstates and secondary highways during day and evening conditions for both passenger cars and tractor-trailers. One unique aspect of this study involves the use of a specialized radar detector *detector* to identify vehicles using radar detectors. Most documented research used visual inspection, which is not ideal for this determination, because many vehicles do not have their radar detectors in a visible location. The effectiveness of drone radar was evaluated based on the following factors: changes in mean speeds, 85^{th} percentile speeds, and percentage of vehicles exceeding the speed limit. Overall, the drone radar caused mean speed reductions of 2 mph for the entire traffic stream; however, individual vehicles equipped with radar detectors reduced speeds ranging from 5 to 8 mph. The drone radar also caused 85^{th} percentile speeds to decrease between 1 and 5 mph and a 20% speed reduction were shown in vehicles exceeding the speed limit.

INTRODUCTION

Across the nation between 2000 and 2003, approximately 1,000 traffic fatalities were recorded in work zone areas, with 10 percent of them occurring in South Carolina. The number of work zone fatalities in South Carolina is significantly higher than in the rest of the nation based on vehicle miles traveled and population. Driving too fast through work zones contributed to 2,609 crashes of all severity levels between the years of 2000 to 2004 in South Carolina, and excessive speeding was identified as the primary cause of these incidents. (1)

This problem of work zone safety is only going to get worse due to the many new projects and the vast number of roads that do not conform to current safety standards. In 1999, South Carolina proposed a plan that combined 27 years of construction into 7 years. During the 2004-2005 fiscal years, $243 million was spent on maintenance of highways and bridges. The magnitude of the situation is staggering. Almost one-third of South Carolina's interstate and primary highways are in poor condition, and at least half of the state's secondary roads fail to meet current safety standards. In addition, one in four bridges does not pass inspection. The condition of South Carolina's highways is undoubtedly one reason why it ranks eighth for the highest number of fatalities per million miles traveled. (2)

While some of the South Carolina work zones occur in congested areas causing long delays, many of the work zones occur in low volume rural areas where excess speed becomes a problem. To reduce work zone crashes, the South Carolina Department of Transportation (SCDOT) and Federal Highway Administration (FHWA) has held workshops throughout the state primarily focusing on measures to reduce speeding. One of the most effective ways to reduce speeds through work zones involves the presence of law enforcement; however, this method is often unavailable due to workforce limitations (3). This paper describes one of several other innovative treatments tested by Clemson University Researchers for the SCDOT.

PROBLEM STATEMENT

In order to address South Carolina's need for safer work zones, Clemson University was funded by the SCDOT to develop and experiment with various traffic control devices to reduce vehicle speeds on interstates and primary and secondary highways. While this study analyzed several traffic control devices, the research reported here considers the use of a small unmanned device, called drone radar. Drone radar simulates the presence of law enforcement by transmitting the same radar frequency, thus, activating the radar detector in use in either passenger vehicles or tractor-trailer trucks. The objectives of this research are as follows:

1. Assess quantitatively the impact of the drone radar on traffic based on the following measures of effectiveness:
   - Change in mean speed,
   - Change in 85th percentile speed,
   - Change in the percentage of vehicles exceeding the designated speed limit, and
   - Change in the mean speed of vehicles equipped with radar detectors.

2. Determine the proportion of vehicles with radar detectors in the traffic streams as well the monitoring of any CB radio transmissions pertaining to the drone radar.

3. Identify how different periods of the day, types of roads, and vehicular types affect speed reductions in radar detector equipped vehicles with the presence of drone radar.

4. Develop specifications for drone radar to achieve maximum detection during deployment.

BACKGROUND

Over the past twenty years, research conducted on radar devices has changed due a series of laws passed by the Federal Communications Commission (FCC). A United States Department of Transportation (USDOT) and National Highway Traffic Safety Administration (NHTSA) directive, authorizing the use of drone radar in August 1991, saying, "…the FCC has recently reconsidered its policy and will permit the use of unattended, continuously radiating radar, i.e. radar drones. The Commission continues to require that any radar units used in drone operation must be type accepted and licensed, by the Commission" (4).

The effectiveness of the drone radar in reducing speeding depends on the number of radar detectors in a traffic stream. According to SPEEDLABS.com, approximately 12 percent of tractor-trailers still use the device even though radar detectors were banned in all commercial vehicles by all states in a USDOT directive in February 1995. Radar detector use in passenger cars is legal except in District of Columbia, state of Virginia, and US Military installations, according to the FCC. (4)

A second factor affecting the success of drone radar is the frequency used. The frequency bands assigned by the FCC for police enforcement include X, K, and Ka. The X-band frequency, used in police radar guns, is one of the older signals; however, the commission allows many other uses of this band, for example, automatic door openers, burglar alarms, and vehicle braking systems, creating many false alerts for the driver's radar detectors. The new technology in radar and radar detectors today has made X-band drone radars obsolete due to the new frequency emitted by police radar guns. Today 97 percent of all police radar units emit Ka or K-band. Of the fifty states, thirty-eight have contracts that mandate the use of the Ka-band. Only New Jersey still requires law enforcement applications to use X-band. (4)

Drone radars have the ability to emulate radar frequency up to one mile, when detected by in-vehicle radar detectors tricking drivers into thinking police enforcement is ahead. Drone radars can be located in vehicles and on roadside hardware to deceive drivers into believing there is police presence in work zones, ambulances, school buses, unoccupied police cars, agricultural tractors, school zones, and even in neighborhoods. (4)

The drone radar devices currently on the market range from basic K-band displaying on a radar detector to ones equipped with a safety warning system (SWS) that cause some detectors to voice words such as "Road Hazard Ahead" and/or "K-band". Studies performed with either the basic drone radar or SWS have contributed to a decrease in speeds within work zones. Past studies show varying results, potentially due to the fact that prior to 1995, radar detector use was legal in the entire United States for all types of vehicles, making the drone radar more effective due to the high number of detection devices in the traffic streams. (4)

Review of Past Drone Radar Research

Numerous research studies on the effectiveness of drone radar have been conducted over the last twenty years. The research indicates that drone radar has had a decreasing effect on speeds in work zones: with time and with technology. TABLE 1 provides a review of the drone radar experiments performed since 1985. As radar technology improved, the drone radar devices effectiveness seems to decrease. Results suggest that this ineffectiveness is due to the advancement in radar detector technology. Only three studies have taken place since the 1995 radar detector legislation.

Radar Detector Usage Studies

Before the introduction of the radar detector *detector* (RDD), the presence of a radar detector in a vehicle was determined through visual inspection. Visual inspection, though seemingly simple, can be complex, if not impossible, depending on the type and speed of a vehicle. Tractor-trailers have multiple devices hanging from their front windshields while radar detectors mounted in passenger cars windows can be blocked from view by window tint. Further, because radar detectors are illegal in tractor-trailers, truckers who use them usually do not place the detectors in plain view. Even by visually spotting a radar detector, one cannot be certain the device is activated. The study performed by Pigman et al. in 1985 observed radar detector densities in a rural section of Kentucky by visual inspection and found that 42 percent of tractor-trailers and 11 percent of passenger vehicles were equipped with the devices. At the time of this study; however, it was legal for a commercial vehicle to possess a radar detector (5). Today, on America's roads, 15 percent of passenger cars and 12 percent in tractor-trailers use radar detectors (4).

The first RDD, manufactured by Kustom Signals, Inc. in the early 1990's, operated using a VG-2 frequency searching for leakage around 11.55 GHz. The Insurance Institute of Highway Safety during this time developed a type of RDD based on the VG-2 frequency called the VG-2 Interceptor to determine the radar densities of commercial trucks. The institute's findings show that 56 percent of the tractor-trailers were equipped with radar detectors. Another study performed on four interstate sections in the states of Maryland and Virginia tested for radar detector densities, concluding that 5 percent of passenger cars and light trucks had radar detectors while 24 percent of tractor-trailers carried these devices. Again, these studies were conducted when radar detectors were legal in commercial vehicles. (6)

The first radar detector use study performed after the banning of commercial use of radar detectors was conducted by the Georgia Tech Research Institute (GTRI) in 2000. The study used a modified VG-2 RDD to determine the radar detector use on Georgia highways. The researchers examined three sites in the Atlanta metro area, a rural two-lane road, a four-lane state route, and a six-lane interstate. This study found that only 2 percent of passenger cars and 5 percent of tractor-trailers were equipped with radar detectors. (7)

After radars detectors became illegal in commercial vehicles, radar detector companies began changing their leakage frequency to remain invisible from this VG-2 RDD. As a result of this change, in 2002 a new RDD made in Australia, called the Spectre III, is effective in detecting all radar detectors manufactured through 2004. Some radar detectors known as radar detector *detector detectors* have built-in sensors that shut off the device when a VG-2 is detected. Another RDD manufacturer from Hill County Research in Fredericksburg, TX developed a model, used in this research that operates with a VG-4 frequency. The state of Texas purchased 185 of these RDD for its commercial vehicle enforcement officers. (8)

TABLE 1 Review of Manned or Unmanned Radar Devices Studies Since 1986

Date	Study	Description	Setup or Strategy	Results
1986	Northern Kentucky (5)	Used X-band drone radar in 6-lane interstate work zones	Speed Collected at 2 locations for several days for both night and day	Radar Detectors (42% tractor-trailers and 11% cars) Mean and 85th percentile speed decreased
1990	Texas Transportation Institute (9)	Used low output radar transmissions in 8 interstate work zones	Station 1: 3000 ft upstream from work zone, Station 2: 1200 ft upstream from drone, Station 3: 2000 ft downstream of Station 2	Speeds decreased 2 mph and standard deviations increased
1992	South Dakota DOT (10)	Used 500 of Kustom Signal Pro 65 X-band drones	Drones were placed in 500 of the 602 state vehicles	21.1% decrease in statewide accidents
1992	Champagne, IL (11)	Used a radar gun which acts a drone on rural interstates, CB radio	Experiment 1: Immediate effect of drone, Experiment 2: Short term effect, Experiment 3: Use multiple radar guns	Experiment 1 (8 to 10 mph decrease), Experiment 2 (no effect), Experiment 3 (3 to 6 mph decrease)
1993	Maryland (12)	Used multiple police radar devices on interstates	Radar placed every few miles. Tested radar detector use by looking for braking and 5 mph speed reductions	Both Experiments showed police radar has short term effects on speed, radar detector usage was 30%
1994	Missouri (13)	Placed drones on pavement edge of roads of long term work zones	Station 1: 0.4 miles from work zone, Station 2: 0.2 to 0.8 miles in work zone, Station 3: 0.4 miles from drone	3.4 to 1.8 mph speed decreases (passenger cars), 3.6 to 2.0 mph decrease (tractor-trailers)
1995	New Mexico and Texas (10)	Placed drones on arrow boards and barrels	Monitored CB radio and collected speeds for 40 consecutive hours	3 to 4 mph decrease (tractor-trailers), 2 mph reduction in speeds (cars)
1995	University of Michigan (14)	Used drone radar and police enforcement in two major interstates	Station 1: Upstream from drone detection, Station 2: Detection distance from drone, Station 3: Downstream of drone	2 mph decrease in speeds, Radar detector usage days (5% cars), (19% tractor-trailers day, 28% night)
1997	Virginia Tech (15)	Used the drone radar Checkpoint Model 2A by PM Design Lab of NC	Station 1: Upstream into drone, Station 2: 500 to 1000 ft from drone detection	Mean speeds decreased 0.8 to 2.3 mph, standard deviations reduced in half with drone on
2001	Georgia Institute of Technology (16)	Tested Safety Warning System and basic drone radar on interstates	Station 1: Collected volume using road tubes, Station 2: Pictures of radar detector users, Station 3: Drone unit	No decrease in speeds, decelerated more with SWS in place
2002	Midwest Smart Work Zone Deployment Initiative (17)	Placed drone on either end of one mile segment of work zone	Speeds were collected 4 hours before drone deployment and 4 hours after	No significant changes in speeds, but may reduce 85th percentile speeds

Literature Review Summary

There have been numerous studies on drone radar effectiveness over the past 20 years but only few studies have occurred after the 1995 legislation prohibiting commercial vehicles from possessing radar detectors. Many of the past studies did not consider radar detector usage in the traffic stream. Some studies only used windshield surveys to identify radar detectors. A windshield survey cannot identify whether or not a detector is turned on. It is also difficult to correctly identify a radar detector visually. Some vehicles—e.g. tractor-trailers—intentionally try to conceal a radar detector from public view.

The literature review on drone radar made it evident that a more recent study, using RDD technology, was warranted to explore radar detector use. This usage needs to be broken down into vehicle types because of the 1995 legislation. Past studies indicated that the usage of radar detectors is variable on different types of roads; thus, the effectiveness of drone radar needs to be studied on both freeways and primary and secondary highways.

PREPARATION OF THE DRONE RADAR SYSTEM FOR FIELD APPLICATION

The primary purpose of this research involved the investigation of a drone radar device in multiple types of work zones under both day and night conditions to determine the potential successful scenarios for deployment. Research was conducted to identify various types of drone radar and radar detectors to be purchased for the study. The second step in the evaluation process included an investigation of the operating limitations of the drone radar to enable comparative test environments in the experimental tests. The third step included the development of a methodology for testing several qualitative and quantitative measures with the aid of a radar detector, a RDD, a laser and a radar speed gun, CB radio, and a communication device to relay messages between data collectors.

Drone radar research was performed to identify the various devices available for research purposes. Clemson University chose the Cobra XT 1000 Safety Alert Traffic Warning Systems drone radar, which emits K and KA-band. A series of tests were conducted to determine the optimal mounting specifications of the drones in the field. The tests included placement of the drones on different objects and in different terrains while using multiple brands of radar detectors to test the signal strength of the drones. The preliminary tests objective was to discern which radar detectors worked the best with the drone radar and to find placement locations (direction, mount, and terrain) where the drone signal transmitted the best.

The preliminary tests using the drone radar showed that it has limitations; it works best in flat areas where hills and other objects do not obstruct the signals; as well, it works best if elevated to avoid low-lying obstructions. Orientation of the drone radar also affects its performance. Based on these results, a simple mounting structure was developed to provide optimal signal detection length, as well as allow for quick installation of the drone. The complete apparatus, as shown in FIGURE 1, costs approximately $250. The drone is attached to the top of a steel post that is mounted with a rechargeable battery pack. The post and battery assembly is painted green to blend with surrounding vegetation in an attempt to make it difficult for drivers to identify the drones.

One serious limitation found in the preliminary tests was that not all radar detectors that are specified to detect K and KA-band detect the drone. This was found to be most apparent in low cost radar detectors. This was especially problematic for this study because there was no way to know whether or not a radar detector that is in use in a vehicle is actually sensing a drone.

FIGURE 1 Cobra XT 1000 Safety Alert Warning System Attached to Mounting Structure in the Field

Data Collection Methodology

Procedure

With the drone radar structure established, the researchers took the apparatus to the field to test its effectiveness as a speed reduction measure in both interstate and non-interstate work zones. At each study site, speed data was collected for two conditions, one with the drone radar activated and one with it off, in order to determine the effect of the drone on vehicle speed. Before and after spot speed data was collected during the same time interval (9:00 AM to 12:00 PM during the day and 7:00 PM to 10:00 PM during the evening) but on different weekdays. This was based on the assumption that a similar population of drivers would occupy the roadway at a given time each day. The study sampled all types of vehicles, separating them into passenger cars or tractor-trailer trucks. Samples chosen for the study consisted only of individual vehicles with headway greater than a few seconds or the lead vehicle in a platoon where traffic queuing existed. This methodology allowed samples to be collected where drivers were traveling at their desired speed, eliminating confounding variables that may affect the study.

The positioning of the observers varied based on the type of work zone. Ideally, the goal was to locate an observer at three stations inside a work zone spaced several thousand feet apart; however, many of the work zones contained rolling terrain, restricting the drone radar emission length necessitating multiple setups. The most important position in the setup was Station 1 because this location was placed in advance of the drone radar, outside of the signal range, but within the work zone signage area to obtain a normal work zone speed. The observer at Station 2 recorded speeds inside the detection zone of the drone radar. Since the radar gun was inside the range of the drone radar's range limit, it didn't matter whether vehicles detected the radar gun's signal. The data collected at Station 3, downstream of the drone radar and outside of the detection zone, provided researchers with data to determine if the vehicles returned to their normal speed after detecting the drone and failing to locate law enforcement. Some radar detectors may have detected the radar gun's signal at this station, but this was minimized due to the triggered mechanism of the gun.

Other methods to verify the effect of drone radar included the monitoring of the number of radar detectors, CB radio users, and the volume of both passenger cars and tractor-trailers in the traffic stream to stratify the results among the various locations. Radar detectors were identified using a VG-4 frequency RDD at Station 1. This RDD was placed perpendicular to traffic flow and made a beeping noise when a radar detector was identified. Using visual inspection, the researcher then separated the vehicles into passenger car or tractor-trailer. CB radio transmissions provided the researchers with any communications that may confound the results of the study. Specifically, the researchers listened for any messages about police enforcement, the identification of the drone, or a data collector being spotted. Several vehicles reported on CB radio that possible police enforcement was in the area. All vehicular volume was recorded for both passenger cars and tractor-trailers.

At Station 1, speeds were recorded using a triggered type laser gun while a triggered type radar gun was used at Station's 2 and 3. The use of the laser gun at Station 1 was important because researchers did not want vehicles reacting to the radar prior to the detection of the drone. Vehicles were tracked going away from the laser gun to minimize the chance that a vehicle equipped with a laser/radar detector would detect the laser as well. Individual speeds of those vehicles equipped with radar detectors were also recorded to see if they decreased their speeds when encountering the drone radar's signal. After the RDD identified a vehicle at Station 1 containing a radar detector, the speed was recorded and a description of the vehicle was radioed to Station 2. The speed of the same vehicle at Station 2 was noted for further analysis. Ideally, using Hi-Star Nu-metrics speed detection instruments would have increased the accuracy of the data, but due to time and cost restraints, this technology was not used.

Sample Size

Sufficient data was collected to ensure a confidence level of 95 percent. The minimum sample size can be determined for a desired degree of statistical accuracy by using the following equation (18):

$$N = \left(S * \frac{K}{E}\right)^2 \qquad (1)$$

where

N = minimum number of measured speeds
S = estimated sample standard deviation, mph
K = constant corresponding to the desired confidence level
E = permitted error in the average speed estimate, mph

Previous speed studies under similar conditions indicated the value of the standard deviation was approximately 5.0. For this study, a value of 5.0 for *S* was used and from preliminary data collection, an average standard deviation of 4.2 supports this as a safe assumption. This estimate proved correct throughout the entire project. For a 95 percent confidence level, *K* equals 1.96. *E,* which reflects the precision of the observed speeds, is the maximum tolerance for errors in the data collection process. For the speed study technique used in this study, a value of 1.0 mph was assumed for *E*. Thus, the minimum sample size at the 95 percent confidence level based on the above equation is as follows:

$$N = [5.0 * \frac{1.96}{1.0}]^2 = 96.04 \quad (1)$$

Site Selection Considerations

The intent of the project was to collect data to analyze a wide range of roadway conditions and work zone types including both rural two-lane roads and interstates maintenance and construction activities operating at a high level-of-service. Early testing on rural roads indicated a low percentage of radar detectors and tractor-trailers within the stream of traffic, making interstates a more attractive option for future drone radar studies. Interstates provided a larger sample size for both passenger cars and tractor-trailers as well as allowing for more radar detectors and communication on CB radio. Summary descriptions for each site can be found in TABLE 2.

TABLE 2 Work Zone Site Summary

Location (County)	Route	Type of Work Zone	Length (miles)	Speed Limit (mph)	Observed Volume (veh/hr)	Dates of Data Collection	Date Work Began
Laurens	SC72	Widening, 2 to 4 Lanes with median	10 miles	55	149 - 215	Oct. 20, 27 2005	Mar. 04
Greenville	I-385	Relocate frontage rd, replace bridges	1 mile	65	804 – 908 (Day) 428 – 679 (Night)	Nov. 7, 14 2005 (Day) Jan. 26 Mar. 2 2006 (Night)	Feb. 2004
Spartanburg	I-85	Modifying Interchange	2 miles	60	2020 - 2340	Nov. 10 2005 Jan. 19 2006	Oct. 2004
Oconee	S-488	Widening, 2 to 5 Lanes	1 mile	35	191 - 271	Jan. 31 Feb. 7 2006	Apr. 2003
Spartanburg	I-585	Widening, 4 to 6 Lanes	2 miles	45	276 – 429 (Day) 202 – 429 (Night)	Feb 2, 16 2006 (Day) Feb. 21 Mar. 9 2006 (Night)	Jun. 2003

DATA ANALYSIS

Upon completion of the data collection for this project, statistical analysis was conducted to examine the following:

- To examine for the differences in the change in mean speed and change in percent of vehicles exceeding the speed limit (for 5+ and 10+ mph) for each of the three data collection stations and the types of vehicles under the control (drone radar off) and treatment (drone radar on) conditions

- To estimate the change in 85th percentile speeds between the control and treatment conditions.

Statistical Testing

Speed data collected from a moving traffic stream in stable flow generally follows the normal distribution. The accurate assumption of each data collection period to be normally distributed allows for parametric hypothesis testing for equal means and the change in the percentage of vehicles exceeding the speed limit (19).

Testing for Equal Means: The Two-Sample t-Test

Testing for equal means requires a t-test which assesses whether two independent samples are statistically different from each other. For this particular study, the effect of the drone radar on mean speeds at each of the three stations is of concern to the research team; therefore, the mean speeds for the control condition (drone radar off) were compared with the mean speeds for the treatment conditions (drone radar on) at the 95 percent confidence level assuming unequal variances. The t-statistic value is computed as follows (20):

$$t = \frac{Y_1 - Y_2}{\sqrt{\frac{s_1^{\ 2}}{N_1} + \frac{s_2^{\ 2}}{N_2}}} \qquad (2)$$

where

Y_1, Y_2 = Mean speed for the control and treatment conditions,
s_1,s_2 = Sample variance for control and treatment conditions, and
N_1, N_2 = Sample size for control and treatment conditions

Change in Percent of Vehicles Exceeding the Speed Limit

Based on minimal mean speed reductions from previous research, a statistical analysis was conducted to determine if the drone radar generated a significant reduction in the proportion of vehicles exceeding the speed limit. In this research, all sites contained a different posted speed limit ranging from 35 to 65 mph. This statistical test measured the speeds of vehicles exceeding the speed limit by 5 mph and 10 mph. The z-statistic for comparing proportions taken from two independent samples was calculated using following equation:

$$Z = \frac{(P_1 - P_2)}{\left\{\frac{P_1 \times (1 - P_1) + P_2 \times (1 - P_2)}{N}\right\}^{0.5}} \qquad (3)$$

where

P_1 = Proportion of traffic exceeding speed limit with drone off,
P_2 = Proportion of traffic exceeding speed limit with drone on, and
n = sample size.

Changes in 85th Percentile Speeds

The 85th percentile speed, as indicated from previous research, should demonstrate the largest speed reductions; however, under a normal distribution, 85th percentile speeds are more than one standard deviation from the mean speed. Since the 85th percentile speed is not a parameter that defines the normal distribution, a parametric hypothesis test could not be conducted. Nonparametric tests can be performed when a value other than the mean is of interest; however, additional assumptions must be made about the distribution, decreasing the accuracy of the test, making this statistical theory not generally accepted.

RESULTS

In general, results from this study show a 2 mph decrease in mean speeds of all highway vehicles and a 6 mph decrease with those equipped with radar detectors as indicated in TABLE 3. This table combines all the sites mean speed reductions for both non-interstate and interstate roadways for the entire traffic stream. As expected, tractor-trailers had a higher reduction in mean speeds on interstates because non-interstate primary and secondary highways have lower speed limits than interstate facilities.

TABLE 3 Summary of Mean Speed Reductions By Road and Vehicle Type

Roadway Type	Speed Limit Range (mph)	Passenger Car (mph)	Tractor-Trailers (mph)	Radar Detector Users (mph)
Non-Interstate Highways	35 to 55	1.86	1.42	6.1
Interstates	45 to 65	1.34	2.06	5.4

TABLE 4 displays ranges of speed reduction, with the results, in many cases, indicating that the drone radar caused minor reductions in the mean speed, the 85th percentile speed, and the percentage of vehicles exceeding the speed limit in the overall traffic stream. Individual vehicles equipped with radar detectors exhibited larger reductions in mean speed. Although the sample size for these types of vehicles was insufficient to run a statistical test, observation and the consistency in their speed reduction indicate a significant change. This study also separately analyzed both passenger cars and tractor-trailers, finding that passenger cars with radar detectors show greater reductions in speed. The research only tested the short term impact of drone radar, indicating that the drone radar can result in significant reductions in vehicle speed over a three-hour period in vehicles with radar detectors. During those three hours of data collection, there was no indication that speed reductions differed between the first and third hours.

TABLE 4 Summary of Overall Speed Reductions

Measure of Effectiveness	Speed Reduction Range for Entire Traffic Stream	Speed Reduction Range for Passenger Cars	Speed Reduction Range for Tractor-Trailers
Mean Speed	0.3 – 3.5 mph	0.2 – 3.4 mph	1.2 - 2.7 mph
Mean Speed of Radar Detector Users	4.6 -7.9 mph	4.6 -7.9 mph	4.6 -7.9 mph
85th Percentile Speed	1.0 – 5.2 mph	0.4 – 6.0 mph	1.0 - 3.0 mph
% of Vehicles Exceeding Speed Limit by 5 mph	0.0 – 20.7%	2.8 – 23.0%	5.3 – 5.5%
% of Vehicles Exceeding Speed Limit by 10 mph	0.7 – 6.0%	0.5 – 6.3%	0.0%

The results at all five sites for all vehicles in the traffic stream are summarized in TABLE 5. As this table indicates, on average, mean speeds decreased as a result of drone radar up to 2.5 mph. The 85th percentile speed had reductions that reached a maximum of 5.2 mph. As a whole, the results from the research show relatively minor decreases in speed for all categories of the statistical analysis.

TABLE 5 Summary of Entire Traffic Stream by Site

Location (County)	Time of Day	% Tractor-Trailer	% Radar Detector	Mean Speed Reduction (mph)	85th Percentile Reduction (mph)	% Exceeding Speed Limit by 5 mph	% Exceeding Speed Limit by 10 mph
Laurens SC -72	AM	6.0-16.0	2.0-8.0	0.30-0.90	No Reduction	0.0-0.5	No Reduction
Greenville I-385	AM	10.0-15.0	3.0	0.90-1.50	1.0-2.0	5.3-16.3	2.5-3.1
	PM	11.0	2.0-5.0	1.1-2.5	3.3-5.2	14.9-20.7	4.6-5.4
Spartanburg I-85	AM	16.0-27.0	2.0-4.0	1.1-1.9	1.0-2.0	2.1-13.4	1.4-2.4
Oconee S-488	AM	2.0-5.0	1.0-4.0	1.4-3.5	2.0-3.0	6.4-11.9	0.7-1.3
Spartanburg I-585	AM	7.0-9.0	4.0-8.0	2.2-2.3	2.0	11.6-14.2	3.7-6.6
	PM	2.0-6.0	2.0-8.0	No Reduction	No Reduction	No Reduction	No Reduction

The percentage ranges of radar detector use for the various types of roadways and vehicles in this research are on average, slightly higher than the findings of Georgia as reported in a Georgia Tech study (2000) shown in TABLE 6. It is noteworthy that the RDD used in the Georgia Tech Study has been found to be less reliable than the RDD used in this study because of its frequency used (7). The percentage of radar detector usage found for the routes in South

Carolina may vary depending on the time of day. Georgia Tech's radar detector use study lasted over a period of nine consecutive days. The low radar detector use in South Carolina verifies the results shown in mean speed reductions for the various types of work zones. Overall, the drone radar is very effective when looking at the mean speeds of only those equipped with radar detectors, with speed reductions ranging from 4.6 to 7.9 mph.

TABLE 6 Comparison of Radar Detector Use Between South Carolina and Georgia

Roadway Type	Passenger Cars with Radar Detector %		Tractor-Trailers with Radar Detector %	
	SC	GA	SC	GA
Rural Route Site	2.2%	1.5%	7.1%	2.0%
State Route Site	5.0%	1.6%	N/A	0.0%
Interstate Site	3.1%	2.7%	7.5%	5.4%

A comparison, shown in TABLE 7, between mean speeds of the entire traffic stream and those equipped with radar detectors demonstrates a major difference between the two groups with the drone radar off. Radar detectors users are traveling much faster; however, when the drone is activated, the opposite trend occurs.

TABLE 7 Comparison of Mean Speeds Between Entire Traffic Stream and Radar Detector Users With Drone Radar Off and On

Location (County)	Time of Day	Speed Limit (mph)	Mean Speed with Drone Off (mph)		Mean Speed with Drone On (mph)	
			Entire Traffic Stream	Radar Detector Users	Entire Traffic Stream	Radar Detector Users
Laurens SC -72	AM	55	56.1	N/A	54.7	N/A
Greenville I-385	AM	65	68.6	N/A	68.3	N/A
	PM	65	65.8	71.0	65.8	63.1
Spartanburg I-85	AM	60	62.3	64.3	63.3	59.9
Oconee S-488	AM	35	34.8	39.3	36.7	33.2
Spartanburg I-585	AM	45	54.9	55.6	49.8	50.4
	PM	45	45.5	54.8	47.3	48.8

While the overall decreases in mean speed are relatively low in most of the sites studied, the ease of installation and relatively inexpensive cost of the drone radar make it a justifiable investment and should be considered for a widespread deployment in SCDOT work zone vehicles. TABLE 8 displays the costs of other technological speed control techniques used in work zones.

TABLE 8 Comparison of Speed Control Strategies

Speed Control Technique	Change in Mean Speed	Approximate Cost
Changeable Message Signs	3.0 - 7.0 mph	$15,000
Speed Monitoring Displays	4.0 - 5.0 mph	$10,000
Changeable Message Signs with Radar	4.0 - 8.0 mph	$20,000
Drone Radar with Mounting Structure	0.3 – 3.5 mph *4.6 -7.9 mph *vehicles with radar detectors	$250

CONCLUSIONS

This research determined the optimal deployment conditions for drone radar and evaluated its effectiveness as a speed control device in five South Carolina work zones. Overall, the drone radar caused minor reductions in mean speeds, 85^{th} percentile speeds, and percentage of vehicles exceeding the speed limit; however, this technology caused significant decreases in the mean speed of isolated vehicles equipped with radar detectors which indicates the effectiveness of drone radar is dependant on the number of radar detectors in the traffic stream. South Carolina's radar detector statistics were comparable to the ranges noted by the research in Georgia, both being too low to show large significant changes in mean speed for an entire traffic stream. One of the findings when developing specifications for the drone radar was the discovery of a radar detector that failed to detect the signal of the drone. This inexpensive radar detector model purchased at a large department store may be one of many models that fail to detect drone radar.

If the SCDOT does decide to install drone radars in their vehicles, it is important that the drones are oriented properly for maximum detection by radar detectors. In addition, research needs to be conducted to determine what percentage of vehicles will possess radar detectors in the future before the SCDOT adopts this new change in work zone setup. The drone radar studied in this research satisfied the objective provided by SCDOT for an affordable and easy-to-implement technology to reduce speeds in work zones. The $250 cost of drone radar is much more affordable than other traffic control devices ranging from $10,000 to $20,000. This research has showed that the implementation of drone radars in work zones can have a positive impact on lowering vehicle speeds, especially with those vehicles equipped with radar detectors. One side benefit of the drone radar includes is the possibility of alerting fatigued drivers as they drive through work zones. Work zone safety increases with slower vehicle speeds; therefore, this cost-effective technology can benefit both highway workers and drivers, increasing the safety of the nation's highways.

RECOMMENDATIONS

This research suggests that the drone radar device has the potential to lower vehicle speeds in work zones, in several scenarios. The drone radar should not be limited to work zone conditions because the low cost of this technology potentially allows their use for non-work zone applications. The long-term effects of drone radar as a speed reduction measure were not evaluated in this study because of the lack of labor and time. Previous research suggests that its effectiveness decreases with time; however, this conclusion could not be verified in this research. Ideally, the drone radar targets those driving at unsafe speeds indicated in TABLE 7. Radar detector user's means speeds are significantly higher than those without these devices. The drone radar also decreases speeds of vehicle platoons if a radar detector user is at the front.

As a result of this study and previous research, the SCDOT can better understand the effectiveness of drone radar in South Carolina work zones. The following recommendations can be made to improve the effectiveness of drone radar as a speed reduction measure in work zones:

- The highest consideration for the use of the drone radar should be given to short-term evening work zones on interstate highways with an on-site inspector. It is much more difficult to detect the presence of a drone or lack of law enforcement at night. Further, previous research has shown that drones lose their effectiveness in long-term use.
- A single drone should not be used for work zones longer than a mile because drivers may speed up after the detection no longer exists.
- The drone radar should be elevated to avoid lower obstructions and faced in the proper direction to optimize transmission distance.
- Multiple drones should be placed in work zones consisting of rolling terrain to maintain a longer detection period.
- The drone radar should be placed in advance of the work zone activity to slow vehicles prior to entering a heavy work area.
- The drone radar should be turned off during non-operation hours of the work zone to maintain effectiveness for those using the road daily.

ACKNOWLEGEMENTS

This research was made possible with the sponsorship and guidance of the South Carolina Department of Transportation (SCDOT). The authors would also like to thank Abhijit Kenale, Yashu Rastogi, Hiram Shah, and Sunil Jahkadi who spent countless hours in collecting data to make this research possible.

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