Abstract—The Intelligent Transportation Institute at the University of Minnesota is developing an “Intersection Decision Support” (IDS) system for rural intersections. When deployed, the system will provide a driver stopped at a minor road information related to the safety of entering or crossing the mainline road traffic stream. The system uses surveillance sensors alongside the major road to determine the state of the intersection, and this state information is used to determine whether the gaps that exist are unsafe, thereby triggering a warning to a driver not to initiate the desired maneuver.

Low cost automotive radar forms the basis of the surveillance system. Found herein is a performance evaluation of an Eaton-Vorad EVT-300 Radar used as a fixed-base sensor for an IDS system. This evaluation includes documentation of the accuracy and resolution of sensor range, range rate, and azimuth measurements. High accuracy (5 cm) DGPS is used to validate all radar measurements.

Index Terms—Intelligent Intersection, Intersection Safety, Range Sensors, Radar, DGPS

I. INTRODUCTION

The Intelligent Transportation Institute at the University of Minnesota is developing an “Intersection Decision Support” (IDS) system for rural intersections. The system is designed to provide the safety benefits of a signalized intersection (fewer crashes, opportunities for all drivers to enter/cross the traffic stream, etc.) while minimizing the disadvantages (expense of installation, disruption of traffic flow, etc.) of such a signalized intersection.

The system uses sensors, communication (both wireless and wired), estimation algorithms, and driver interfaces to convey information to assist a driver with the decision to enter or cross the mainline of traffic from the minor road.

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“State” information includes the presence of vehicles, types of vehicles, the location of vehicles, the velocity of vehicles, acceleration/deceleration of vehicles, and the distance/time to the location where roads cross. State information is based on data acquired by roadside sensors and localized processors.

In May of 2004, the University of Minnesota and the Minnesota Department of Transportation will begin construction of a test intersection at the crossroads of US Highway 52 and Minnesota County-State Aid Highway 9 (CSAH 9) in Goodhue County, Minnesota, south of Cannon Falls. This intersection will be equipped with radar based surveillance sensors on the northbound and southbound high speed legs, Radar and Lidar based vehicle classification systems on the minor legs, and an infrared camera based system to compute and record the trajectories of vehicles entering or crossing the traffic stream from the minor roads. These sensors will be connected to the main intersection control/data acquisition system with both wireless and hardwired Ethernet. The results provided in this work have facilitated the design of an optimal surveillance sensor placement configuration for this test intersection.

The Eaton-Vorad EVT-300 radar unit was selected as the primary range sensor for the IDS system. This decision was based on a survey of presently available sensors and results obtained from other vehicle systems developed by the Intelligent Vehicles Laboratory at the University of Minnesota. In these previous projects ([1], [2], and [3]) however, the sensor was only used as a vehicle-based sensor. The results of tests conducted to determine the feasibility of the EVT-300 as a roadside-based sensor are presented herein.

Two distinct types of tests have been designed to evaluate the IDS surveillance system. The first type, a component test whose results are discussed in this paper, uses a high accuracy DGPS system and probe vehicles to document sensor performance. The design of the IDS mainline surveillance system is based on these performance results.
A large scaled test will also be conducted that will evaluate the accuracy of the system in actual traffic conditions, and this system is also described at the conclusion of this paper.

II. **HIGH ACCURACY EVT-300 RADAR SENSOR EVALUATION**

A. **Experimental Setup**

A single radar antenna unit was attached to a research grade mount equipped with a vernier turntable to adjust the radar orientation angle as shown in Picture 1. A riflescope was also rigidly mounted parallel to the antenna faceplate, so that it would rotate with the radar antenna. The riflescope was used to determine the radar yaw angle ($\theta_R$) with respect to North. A reference pole was placed 152m away from the radar station and the positions for both the pole and the radar unit were measured using a highly accurate DGPS system. The riflescope was then used to align the radar along the line-of-sight with the pole. With both positions known, the yaw angle with respect to North was determined ($\theta_R$ in Figure 1). With this measurement, the vernier turntable could be zeroed, and further changes in the radar yaw angle could be measured using the vernier dial reading.

![Picture 1. The EVT-300 Radar unit mounted on a Vernier Turntable.](image)

The EVT-300 radar antenna was connected to a computer that collected the radar data (range, range rate and azimuth) at 10Hz and processed the data to produce target position and velocity in state plane coordinates. This processed data was then sent to a data collection computer that added a timestamp before storing the data.

The probe vehicles (vehicles used as radar targets) were fitted with a high accuracy dual frequency, carrier phase DGPS receivers that provided position measurements with an accuracy of approximately 5cm at 10Hz [4]. A computer on a probe vehicle processed the DGPS data and then sent its position and velocity via wireless LAN to the data collection computer. A timestamp was added to each dataset to synchronize with the range sensor data.

Figure 2 illustrates the probe vehicle experimental setup, and shows the experimental dataflow.

![Figure 2. The probe vehicle receives a differential correction from the base station and computes its position using high accuracy dual frequency, carrier phase DGPS. This position is transmitted to the data-collection computer at the radar station.](image)

Synchronization of the data was done by grouping records within 58ms of each other from the two data files. The 58ms threshold used for the synchronization also takes into account the wireless LAN transmission lag (about 15ms). The timing diagram, and jitter, is illustrated in Figure 4 below.
right-of-way regulations will result in a variety of sensor orientations. To determine the sensor sensitivity to orientation, yaw angles were varied to determine the effect on sensor accuracy and coverage.

The experiment was designed to determine, for each independent vehicle type, the following measures of performance. In each case, the radar sensor measurement is compared to that provided by the DGPS system.

**Lane Coverage:** This is the length of a lane that can be covered by a single sensor. Figure 5 shows the theoretical lane coverage for two lanes ($L_{1\text{Cor}}$ & $L_{2\text{Cor}}$). The theoretical lane coverage was calculated using the manufacturer specified beam width of 12 degrees and a measured maximum sensor range of 134m. Although the manufacturer specifies the maximum range to be 107m, the sensor consistently detects the test vehicles to a 134m range. The length of the line segment where the lane-center intersects with the edges of the theoretical radar beam is defined as the theoretical lane coverage. Lane coverage is essential to correctly determine the appropriate spacing between two radar stations placed along the road.

**Lane Classification Accuracy:** This is the ability of a vehicle position estimator to place the vehicle in the correct lane. Lane classification is dependent upon the error in the lateral position of the target as reported by the sensor (see Figure 6). For a standard sized lane (3.66m), a maximum lateral position error of $\pm 1.2m$ allows a vehicle to be correctly associated with its lane of travel.

**Lane Position Accuracy:** This is the accuracy of the longitudinal position of the vehicle in the lane reported by the sensor as compared to the position reported by the DGPS system.

**Speed Accuracy:** Speed accuracy is critical for the IDS project because the future position of a target currently being detected has to be accurately estimated using velocity and acceleration, in order to accurately predict its time to the intersection.

**C. Experiment Results**

Table 1 and Table 2 show the results of the experiments for the truck and sedan, respectively. DGPS data was not collected for the motorcycle. However, the lane coverage of the radar was determined for the motorcycle and was found to match that of the other two vehicles. The results described below also show that the accuracy of the sensor in terms of lane classification accuracy is better if the front of the vehicle is small. Furthermore, a longer vehicle produces a higher lane position (longitudinal) error. This means that for a motorcycle, the lane classification and lane position accuracy of the sensor should be higher than that for a passenger vehicle.
Theoretical lane coverage was determined by the geometry of the sensor orientation to the road and using a maximum sensor range of 134m. It is assumed that the target returns from the sensor correspond to the center of the front of the target vehicle. This assumption, as shown later, is likely invalid; at this point it is not possible to determine the exact point on the target from which a radar return is received.

Sensor orientation was varied between 0 and 9 degrees with intervals of 3 degrees for the truck. Similar experiments were conducted with the car, with an additional test at 16 degrees to determine the sensor sensitivity to the wide angle.

Two sets of data were collected for each condition and the tabular results are the average of the two data sets. The RMS values in Table 1 and Table 2 were calculated using
Each of the two data sets for each condition. The data used for RMS calculation covered the time the probe-vehicle was first seen by the sensor until the time at which the target moved out of the field of view of the sensor. An average of 47 data points were collected for the runs at 72 km/hr and 91 data points at 40 km/hr.

Table 2. Experiment results for the sedan

<table>
<thead>
<tr>
<th>No</th>
<th>Sensor Distance to Lane Center (m)</th>
<th>Orientation Angle w.r.t Lane (degrees)</th>
<th>Theoretical Lane Coverage (m)</th>
<th>Lane Coverage (m)</th>
<th>RMS Lane Classification Error (m)</th>
<th>RMS Lane Position Error (m)</th>
<th>RMS Speed Error (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>72 km/hr</td>
<td>Run 1 4.25</td>
<td>6</td>
<td>113</td>
<td>115</td>
<td>0.77</td>
<td>3.17</td>
<td>0.23</td>
</tr>
<tr>
<td>Run 2 7.9</td>
<td>6</td>
<td>94</td>
<td>111</td>
<td>0.96</td>
<td>3.94</td>
<td>0.48</td>
<td></td>
</tr>
<tr>
<td>Run 3 4.25</td>
<td>9</td>
<td>79</td>
<td>96</td>
<td>0.96</td>
<td>4.29</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Run 4 7.9</td>
<td>9</td>
<td>103</td>
<td>105</td>
<td>1.39</td>
<td>4.54</td>
<td>0.67</td>
<td></td>
</tr>
<tr>
<td>40 km/hr</td>
<td>Run 1 4.25</td>
<td>6</td>
<td>113</td>
<td>117</td>
<td>1.29</td>
<td>1.11</td>
<td>0.09</td>
</tr>
<tr>
<td>Run 2 7.9</td>
<td>6</td>
<td>94</td>
<td>105</td>
<td>1.3</td>
<td>2.4</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>Run 3 4.25</td>
<td>9</td>
<td>79</td>
<td>105</td>
<td>1.58</td>
<td>1.22</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Run 4 7.9</td>
<td>9</td>
<td>103</td>
<td>112</td>
<td>1.56</td>
<td>3.33</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>Run 5 7.9</td>
<td>16</td>
<td>27</td>
<td>43</td>
<td>3.8</td>
<td>1.83</td>
<td>0.81</td>
<td></td>
</tr>
<tr>
<td>Run 6 26.7</td>
<td>16</td>
<td>61</td>
<td>62</td>
<td>1.95</td>
<td>8.56</td>
<td>0.68</td>
<td></td>
</tr>
</tbody>
</table>

The following can be concluded from the data:

a. The actual coverage is consistently larger or matches the theoretical lane coverage (see Figure 7). The length of the line segment where the lane-center intersects with the edges of the theoretical radar beam was considered as the theoretical lane coverage (See \( L_{1Cov} \) & \( L_{2Cov} \) in Figure 5). Because the actual coverage matches the theoretical coverage, the theoretical coverage can be used to determine sensor locations for an actual intersection.

The results for the sedan (Table 2) show that the lane coverage is similar to that for the truck. The maximum lane coverage for both lanes occurs when the sensor orientation angle is between 3 and 6 degrees.

b. Lane classification accuracy decreases as the orientation angle (\( \alpha \) in Figure 5) relative to the road increases. Lane classification accuracy also decreases for increasing sensor distance from the lane (Figure 8). In all the data sets except one, the RMS error was well under 1.2m, the requirement for accurate lane classification. At a distance of 8m from the lane center and at an orientation angle of 9 degrees, the lane classification error was larger than the 1.2m threshold; this arrangement should be avoided.

The results for the sedan show that the lane classification error is slightly lower than that for the truck. This is likely due to a more narrow vehicle cross section.

c. Lane position accuracy also decreases with increase in orientation angle and sensor distance to the lane. A substantial difference exists in the lane position accuracy for the different vehicles. The truck produced a significantly larger lane position error than did the sedan. This can be attributed to the fact that the truck is longer than the sedan. As the orientation angle increases and the distance from the sensor to the lane increases, more of the side of the vehicle is visible to the sensor; so the target is likely detected at the sides. Lane position error was also higher at 72km/hr than it was at 40 km/hr. This may be attributed to an internal radar-processing lag.

d. The speed accuracy of the radar was found to be very good. However, as shown in Figure 9, this error also increases with increase in both radar orientation angle and distance to the lane center. For the IDS project, because the position of a target presently detected has to be projected to determine its time to reach the intersection, it is critical that the speed accuracy be
high so that an accurate estimate of the target position can be made. Hence the orientation angle and distance to lane must be kept as low as possible.

e. The effect of vehicle size on the accuracies was negligible. The only significant error difference was in the longitudinal position (lane position accuracy). As mentioned earlier, this could have been caused due to radar beams hitting the sides of the vehicle.

Figure 9. Speed Error at various sensor orientations for two different lanes (Truck at 72 km/hr)

III. VISION BASED SYSTEM EVALUATION

In order to validate the vehicle position estimation process in actual traffic conditions, a vision-based system will be used. The system will consist of a camera placed approximately 9m above the road surface. The camera will look straight down at the two lanes of the section of road being monitored.

Each time a vehicle passes by the pre-defined region of interest of the camera, an image-processing program will detect and record the vehicle as well as the lane in which the vehicle is traveling. This would then be compared to the range sensor reported position of the vehicle. The time difference would be recorded as the position estimator error. False reported targets would be counted and logged as ‘false targets’ and targets that are not reported by the range sensor would be counted as ‘missed targets’.

This system is presently under evaluation, and will be deployed at the IDS test intersection when the intersection is brought “on-line” in June 2004.

IV. CONCLUSION

The results from the tests conducted with the EVT-300 verify the fact that the sensor can be used as a roadside range sensor. The next step in the IDS system design is the fusion of data from other intersection sensors to determine the real-time state of the intersection.

A Kalman filter-based estimator is being developed to fuse this sensor data and to provide a system-wide representation of vehicles at the intersection. The estimator will track vehicle trajectories along the main high-speed legs as well as the low-speed legs, and will estimate both the size and velocity of the gaps as well as the time of arrival of a gap at the intersection. Radar and lidar based vehicle classification systems are also being developed to determine the type of vehicles on the low-speed leg. Because larger vehicles require larger gaps (both because of size and acceleration capability), this classification data will be used to “customize” the timing algorithms that determine when it is unsafe to enter the intersection.

Once the system is in place, the system-wide target data, as well as other parameters (vehicle type, weather conditions, etc) will be collected over a period of few months. This data can be used to determine driver behavior at the intersection cross-correlated with various parameters. Other traffic statistics, such as average speed, speed adjustments at the intersection, gaps in traffic, etc can also be determined.

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REFERENCES