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COOPERATIVE COLLISION WARNING SYSTEMS: Concept Definition and Experimental Implementation

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ABSTRACT

The concept of cooperative collision warning (CCW) systems is introduced and explained, followed by presentation of experimental results showing the performance of a first prototype CCW system. The CCW concept provides warnings or situation awareness displays to drivers based on information about the motions of neighboring vehicles obtained by wireless communications from those vehicles, without use of any ranging sensors. This has the advantages of a potentially inexpensive complement of onboard vehicle equipment (compared to ranging sensors that could provide 360 degree coverage), as well as providing information from vehicles that may be occluded from direct line of sight to the approaching vehicle. The CCW concept has been tested on a fleet of five prototype vehicles, supporting a variety of safety services (forward collision warning, blind spot and lane change situation awareness and several modes of intersection threat assessment). The performance of the vehicle position estimation and wireless communication subsystems are demonstrated using samples of experimental data from test sites with both good and bad GPS signal availability.

1. Introduction

This paper is about the design, prototyping and experimental evaluation of a *Cooperative Collision Warning* (CCW) system. Five vehicles were equipped with the sensors, communication hardware, wireless protocols, estimators, and collision warning algorithms necessary to develop and demonstrate the CCW concept. Our CCW prototype provides the driver with both warnings and situation awareness through displays. The warning graphics are designed to capture the attention of the driver, while the situation awareness graphics are designed to not capture the attention of the driver but to provide information on demand. The prototype has been tested at low speeds in an urban office campus with poor GPS coverage, and at high speed on an unused airfield. The system has been put through over 100 km of test driving covering a variety of speeds, inter-vehicle ranges, and GPS conditions.

Collision Warning Systems share a common need: the vehicle needs to know about the locations and motions of all the neighboring vehicles, representing the state of the vehicle neighborhood. Most collision warning systems in the literature try to learn the state of the neighboring vehicles

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or roadway by using sensors like radar, laser, or vision (1) looking forward, to the rear, to the right lane and left lane. In contrast, our collision warning system develops its knowledge of the vehicle neighborhood by listening to the wireless communications of other vehicles and reciprocates with communications of its own. Thus, we call our system *Cooperative Collision Warning (CCW)*.

The CCW concept is motivated by the proliferation of GPS and ad-hoc wireless technologies like Wi-Fi, providing an effective way of learning about the state of the neighborhood. If a vehicle knowing its own GPS position and speed and other key metrics such as turn signal status were to communicate this information to others, it should ameliorate the need to solve difficult signal or image processing problems. These communication-based systems hold significant promise and some specific advantages over sensor-based systems: they allow driver advice and warning in geometries impossible – or very expensive – to implement with systems consisting of in-vehicle sensors. As examples, a CCW system will work with a cut-out revealing a stopped car, or a stopped or slow-moving car before arrival at a blind curve. Moreover, a radio plus GPS could be significantly cheaper than the suite of sensors required to provide a vehicle with 360-degree awareness, making this a potentially inexpensive enabler of collision warning systems. This is the motivation for prototyping a cooperative collision warning system.

On the other hand, the usefulness of a radio based collision warning system depends on its market penetration. Government and industry have moved rapidly on several fronts to promote the penetration of wireless local area networking into the transportation system. The FCC has allocated the Dedicated Short Range Communication (DSRC) spectrum for transportation in the 5.9 GHz band in the U.S. and has ruled that safety messages will have priority access in the spectrum. A USDOT-sponsored standard process under ASTM voted to base DSRC on IEEE 802.11a, and now IEEE has taken up the standardization of DSRC by creating IEEE 802.11p. NHTSA and the automotive OEM's created the Vehicle Safety Communication Consortium (VSCC) to promote vehicle-vehicle networking for safety. FHWA and three state DOTs created the IVI Infrastructure Consortium, which has demonstrated roadside-vehicle communication to reduce intersection collisions.

The first principal contribution of this paper is the definition of our architecture for Cooperative Collision Warning Systems, described in Section 3. It enabled the rapid prototyping of several collision warning applications on multiple vehicles within nine months. One information acquisition system delivers forward collision warning, right-side blind spot or lane change warning, and intersection collision warning capabilities. The architecture is implemented on low-cost hardware emphasizing, wherever possible, components usually present on commercially available vehicles. The system sensors are wheel speed, a yaw rate gyro, a steering angle encoder, and an Ashtech DG12 GPS receiver with a differential correction. The radio is a commercial 802.11b radio boosted with a power amplifier.

The second principal contribution is our approach to compensating for GPS outages and noise to enable a vehicle to know its own GPS position reliably. This is the task of the Estimator component in our prototype and is the subject of Section 4. Since the sensors we use appear on most vehicles, we refer to our approach as GPS/VS (Vehicle Sensor) integration. Our GPS/VS

system is computationally more complex than most GPS/INS systems, but we show that it delivers superior localization performance at potentially lower cost.

Section 5 briefly presents our experience with 802.11b radios, with an omni-directional rooftop antenna and a power amplifier, as the car-to-car communication technology for CCW. Five vehicles are able to communicate a 160 byte payload every 50 msec up to relative speeds of 80 mph. Loss rates are under 1% and delays are low enough, although losses due to multiple access interference could be an issue with larger numbers of vehicles (2). Section 6 describes our warning and situation awareness module designs.

2. Background on Prior Related Research

The concept of vehicle-vehicle cooperation through data communication is not new, and was actually explored in some depth in the European DRIVE and PROMETHEUS programs in the late 1980s and early 1990s, under the label of “cooperative driving” (3). Researchers from General Motors Europe described their work in “cooperative foresighted driving” at the 1994 Annual Meeting of ITS America (4), combining vehicle-vehicle and vehicle-roadside communications to support delivery of traffic control information, cooperative adaptive cruise control and “medium range pre-information” about traffic hazards ahead.

Asher and Galler developed a concept for cooperative collision warning in the mid-1990s (5,6), based on a combination of ranging sensor data and data communicated from neighboring vehicles. Since their concept did not depend entirely on the communicated data, it would be able to work with a mixture of equipped and unequipped vehicles.

The Japan Automobile Research Institute defined a concept for cooperative intersection collision warning based entirely on DGPS positioning and wireless communication among the approaching vehicles (7). Bosch defined a broader concept for wireless communication of safety information among vehicles within a 1-2 km range, but their concept addressed hazardous conditions identified by a variety of means (such as detecting sudden braking activity) rather than relying strictly on differences between the DGPS positioning information as the indicator of a hazard (8).

Oloufa and Radwan proposed use of DGPS positioning for collision avoidance warnings, but in their scheme the conflict predictions would be estimated by a central server, which would then communicate warnings to the vehicles, introducing a variety of additional complexities, latencies and vulnerabilities (9).

In Japan, DGPS positioning and wireless communication among vehicles have been tested and demonstrated for application to fully automated driving of a platoon of five passenger cars on a test track, which is one of the most demanding applications in terms of information accuracy and reliability (10). At the opposite end of the spectrum, Muller, Uchanski and Hedrick (11) showed how vehicle to vehicle communication could be used to supply supplementary information about

the driving environment such as traffic conditions and tire/road friction, rather than more detailed primary information about vehicle positions or speeds.

Our CCW project advances this literature by relying on wireless networks to enable driver decision support on sub-second timescales. For example, if a vehicle brakes hard, the vehicle behind generates a forward collision warning for its driver within 200 to 500 msec. This kind of sub-second decision support has until now been the preserve of sensor based prototypes. The aim of the CCW prototype is to enable the same while relying exclusively on rapid wireless broadcast (every 50 msec) of position by every vehicle. Hence we use a faster communication rate than most other wireless communication based systems in the literature that provide the driver with longer timescale (several seconds) information such as “ice on the road” or “stopped traffic ahead.”

3. System Architecture and Evaluation

We developed vehicles with 360 degree awareness within a short time frame by implementing a well chosen architecture (see figure 3-1). The architecture has significant common elements useful to multiple warning applications. These include:

- an estimator in each vehicle estimating its own position in GPS coordinates despite GPS degradation (e.g., through extended canopies of trees), requiring fusion of onboard sensors such as wheel speed and yaw rate,
- a communication system in each vehicle used to communicate this information to its neighbors enabling each vehicle to continuously maintain estimates of the motions of all its neighbors, i.e., a neighboring vehicle map,
- two displays to furnish the warnings and situational awareness to the driver,
- a modular in-vehicle hardware and software architecture facilitating the incremental addition of new algorithms or sensors.

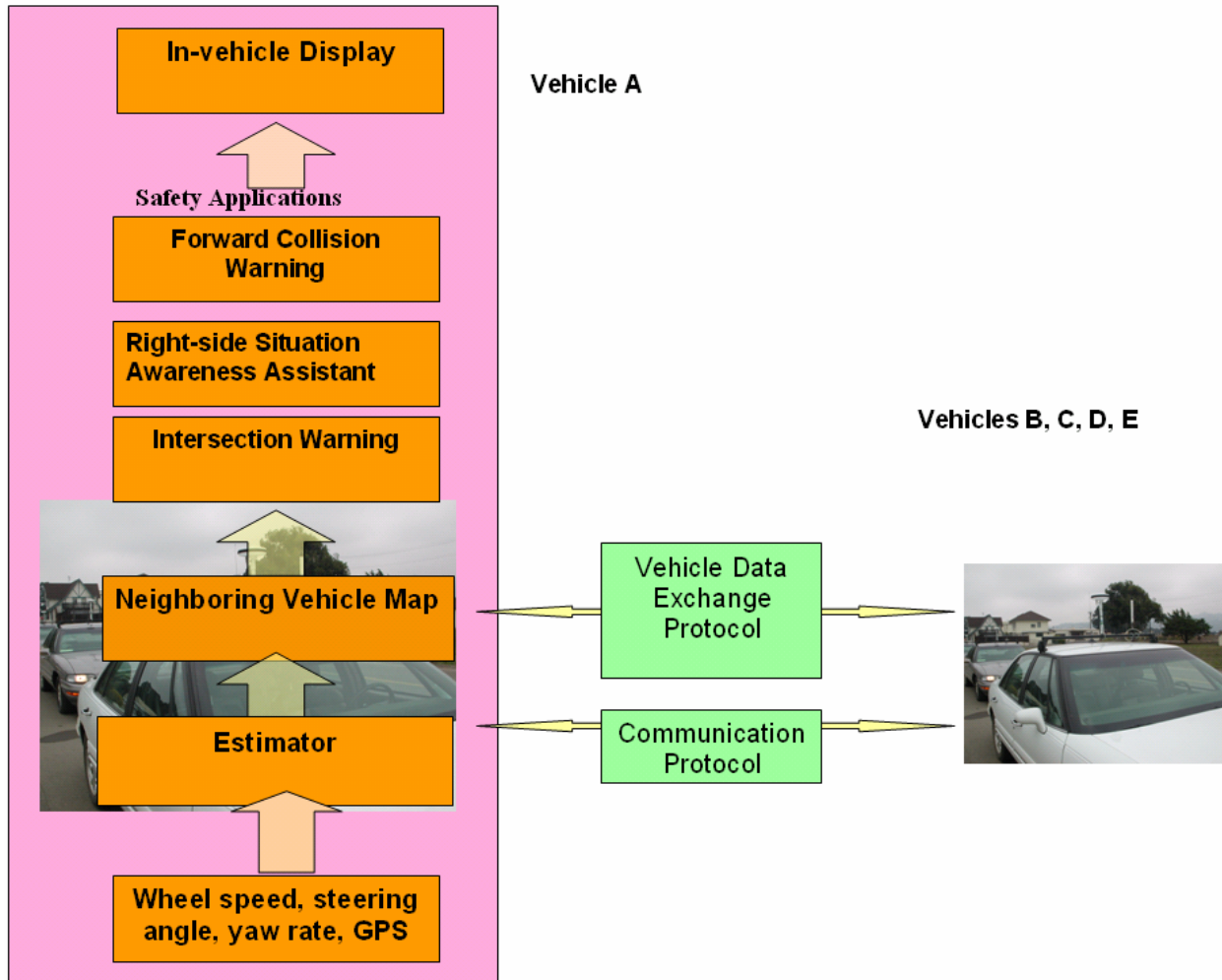


Figure 3-1: CCW System Architecture

Figure 3-2 shows the neighboring vehicle map as observed from an engineering diagnostic display (not intended for use by the driver) within one of the demonstration cars. The car itself is represented by the arrow at the center of the screen, pointing in the direction of travel. The other arrows correspond to the relative positions and orientations of two other cars. This sort of map is continuously displayed during demonstrations to reveal 360 degree awareness. The rest of the information in the display indicates the status of the sensors in the vehicle. Meters are used to show vehicle speed (separate hands for wheel speed and GPS speed), GPS heading, steering angle and yaw rate. Health indicators show status of wireless communication (with a three state icon, controlled by recent transit times of received messages) and quality of GPS (indicated by number of satellites).

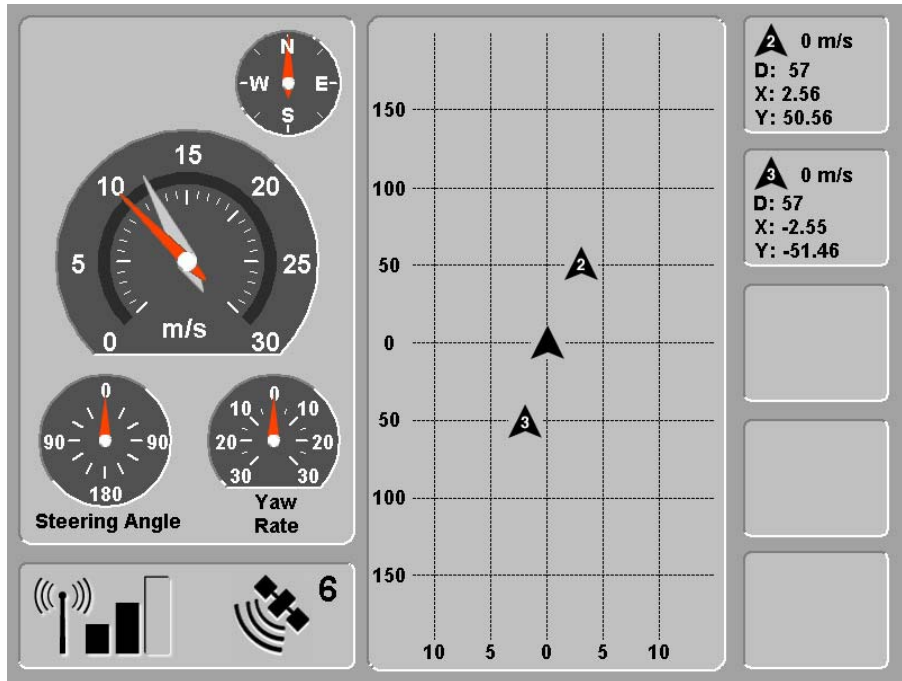


Figure 3-2: Neighboring Vehicle Map Screen Shot

The neighboring vehicle map is the single information structure processed by the higher level collision warning modules. Figure 3-1 shows the three modules in our current prototype, which execute different geographical queries to read the map. For example, the Forward Collision Warning Module queries for vehicles in front of the center arrow while the Right-side Situation Awareness Module queries for information to the right of the center arrow. Since the map provides 360 degree awareness, other collision warning modules can be added on top of the Neighboring Vehicle Map layer in the architecture.

The Neighboring Vehicle Map layer in each vehicle has several functions:

- It passes the GPS position, speed, and heading information produced by its Estimator to the Vehicle Data Exchange Protocol Entity for transmission to other vehicles.
- It receives the GPS position, speed, and heading messages sent by other vehicles from the Vehicle Data Exchange Protocol Entity.
- It transforms this information to relative coordinates and plots it on the Neighboring Vehicle Map as shown in figure 3-2.

Thus our architecture requires the standardization of two protocols, shown as the Vehicle Data Exchange Protocol and Communication Protocol in figure 3-1. Vehicles need to send position, speed, heading, and possibly other data in a format understood by all vehicles. This is the Vehicle Data Exchange Protocol (VDEP). Our prototype sends a UDP message with a 160 byte payload every 50 msec. The VDEP messages need to be sent over a communication protocol and radio standardized across vehicles. In our case this is 802.11b, but in the future we would expect this to be 802.11p Dedicated Short Range Communications.

The architecture permits all modules other than the VDEP and Communication protocol to differ across vehicles, thus enabling them to be proprietary. Different vehicles might estimate their own positions using different technologies, use different collision warning algorithms, or furnish information to their drivers in different ways. The prototype requires vehicles to agree only on the format of GPS position, speed, and heading and other vehicle state information.

3.1 System Evaluation

The performance of the system was evaluated at two sites: the PATH Richmond Field Station (RFS) facility and Crow's Landing, approximately 90 miles from the RFS. RFS is an urban office campus where driving speeds have to be under 30 mph, with frequent stops and starts. RFS has a heavy tree canopy that degrades GPS or cuts it out completely, so localization is especially challenging at RFS. The RFS tests enabled us to test the functioning of the system when GPS is biased. We were also able to test the ability of the position estimator to work through frequent stops, the GPS heading measurement being very poor during the stops.

Crow's Landing is an open airfield, with runways over a mile long and excellent GPS coverage. The Crows Landing tests gave a good feel for the effectiveness of cooperative collision warning at speeds as high as 60 mph, where vehicle-vehicle conflicts are very salient. Moreover, the excellent GPS allowed us to quantify the robustness of the position estimation to GPS cut-outs. To test the robustness of the position estimator we could deliberately cut the GPS input to the estimator.

These tests established the proper functioning of our CCW prototype. The tests involved up to five cars, and collectively covered more than 100 km of driving. The position estimation data analysis follows in section 4 and the communication data analysis is in section 5.

In addition to testing the robustness of the vehicle neighborhood map and communication, we constructed eight scenarios to test the proper functioning of the *Forward Collision Warning Assistant* as well as *Right-side Situational Awareness Assistant* and *Intersection Assistant*, plus a combination of these "assistants". These scenarios were executed at RFS and Crows Landing multiple times, showing the warnings to activate correctly. The scenarios are as follows.

1. Lead Vehicle Stopped –Forward Collision Warning Assistant with a stopped vehicle in lane.
2. Lead Vehicle Decelerating –Forward Collision Warning Assistant operates when a vehicle in front decelerates at rates ranging from gentle to aggressive, causing the warning to go from yellow to red.
3. Vehicle Cut-out to Reveal Lead Vehicle Stopped (figure 3-3) - Forward Collision Warning Assistant operates when there is a stopped vehicle in lane that would have been invisible to radar until the middle vehicle cut out.
4. Right Side Overtaking – information provided by the Situational Awareness Assistant about vehicles in the blind spot, vehicles present to the right and rear at different distances, and a vehicle overtaking from the right.
5. Straight Crossing Path – Intersection Assistant "STOP" icon displayed when there is a vehicle passing through the intersection on the cross street.

6. Left Turn Into Path (figure 3-4) - Intersection Assistant “No left turn” icon displayed when there is a vehicle passing through the intersection on the cross street.
7. Left Turn Across Path (figure 3-5) - Intersection Assistant “No left turn” icon displayed when there is a vehicle passing through the intersection from the opposite direction.
8. Aggressive Driver (Multiple Scenarios) –integrated operation of multiple collision warning modes in the face of a neighboring vehicle weaving between traffic across lanes, while accelerating and decelerating aggressively to use the gaps in the traffic.

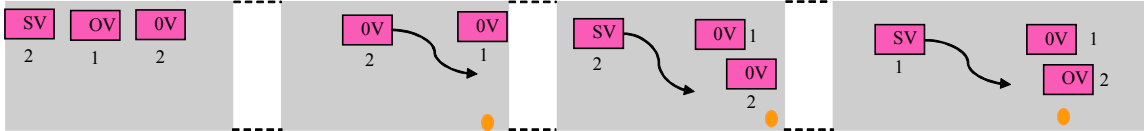


Figure 3-3: Vehicle Cut-out to Reveal Lead Vehicle Stopped

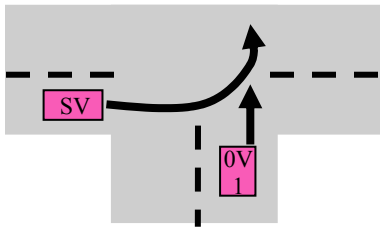


Figure 3-4: Left Turn into Path

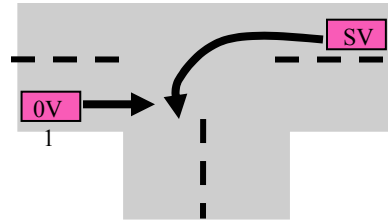


Figure 3-5: Left Turn Across Path

4. Positioning Accuracy

Monte-Carlo analyses were used to determine the probability that useful CCW warnings could be provided, as a function of the accuracy of the vehicle position and velocity information. The details of the analysis can be found in (12). The principal finding is that the governing accuracy requirement is associated with the need to assign the vehicles to the correct lanes, which requires a standard deviation of positioning accuracy of about 50 cm in order to support reliable and consistent warnings.

Most vehicle localization systems integrate GPS and INS to compensate for GPS outages and errors (13-17). By contrast, our localization system relies on sensors that are already in the car. Our Estimator Component integrates GPS with wheel speed encoders, a yaw rate gyro and a steering angle sensor. Therefore, we refer to our localization system as a GPS/VS (Vehicle Sensor) system. The sensors are integrated through an Extended Kalman Filter (EKF). To do this we use a bicycle model. A full description of the EKF appears in (24).

The GPS updates at 5 Hz and the VS updates at 20 Hz. The steering angle sensor, yaw rate gyro and wheel speed encoder noises have standard deviations of 1 deg, 0.3 deg/sec, and 0.3 m/s

respectively. They have no significant bias and have resolutions of 0.1, 0.2 deg/sec, and 0.9 m/s, respectively.

We use Ashtech DG 12 GPS receivers with a local differential correction obtained from base stations installed at our two test sites. The GPS gives measurements of position, heading and inertial velocity. Under the best conditions, i.e., eight satellites or more, the standard deviation of GPS error is about 30 cm. However, when the number of satellites is seven or less due to occlusions by buildings or trees, the errors can be as large as 10 meters. Moreover, at six satellites or less, the error usually has a bias as shown in figure 4-1. Figure 4-2 shows typical GPS problems in our RFS test circuit during the afternoons. Furthermore, at low speeds the heading measurement is poor, and appears completely random when the vehicle stops.

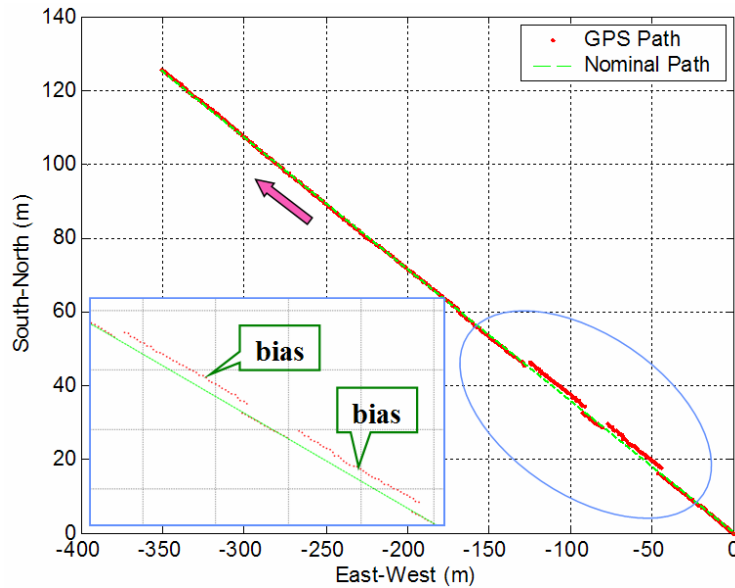


Figure 4-1: GPS bias
GPS and Estimated Trajectories

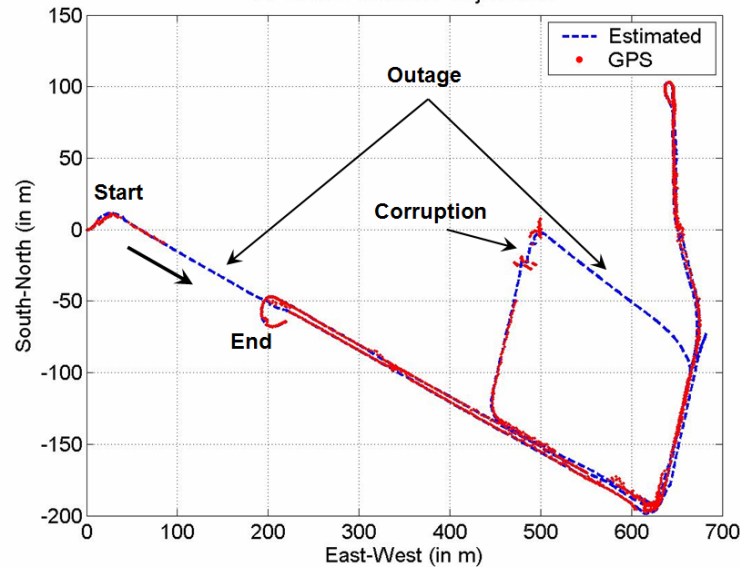


Figure 4-2: Typical GPS problems in our RFS test circuit

We are aware of two prior GPS/VS systems (18,19), both of which used wheel speed, yaw rate, and an accelerometer, although the system in (19) also used a compass. The goal of the system in (19) was to achieve 2 cm accuracy using carrier-phase DGPS. It works well. By contrast, the aim of our design is robustness to GPS outages and corruption, while permitting inaccuracies up to about 90 cm. Unlike our system, neither of these prior studies included steering angle in their design. Because we use this sensor, the prediction step of our Kalman filter is based on a dynamic (bicycle) model. To the best of our knowledge, this is the first paper using a dynamic model to integrate the yaw rate, velocity and steering angle sensors, in contrast to the prior literature using kinematic models (18-23). We present experimental results showing how the dynamic model improves localization during high speed driving and fast turns.

Figure 4-3 shows the layout of the Estimator. The state vector is $X = [x \ \dot{x} \ y \ \dot{y} \ \phi]^T$. The elements of the vector are lateral position, lateral velocity, longitudinal position, longitudinal velocity and heading angle. $(v, \alpha, \dot{\phi}_{fog})$ are the VS measurements of velocity, steering angle, and yaw rate, respectively. \hat{X} denotes the estimated value of X . All these are measured in the universal GPS coordinate system (west-east, south-north) with the origin at the local base station.

Since the VS measurements are good, we use them to directly drive the process model (“prediction” block). This is used to predict the states of the system at time k based on all measurements until time $k-1$. This prediction model is based on a bicycle model of our cars, which includes the dimensions of the car, its mass, moments of inertia, and the cornering stiffness of its front and rear tires. This prediction is then combined with the GPS measurement in the “measurement” block to produce the estimate of the state at time k based on measurements up to time k . For further details of the design see (24).

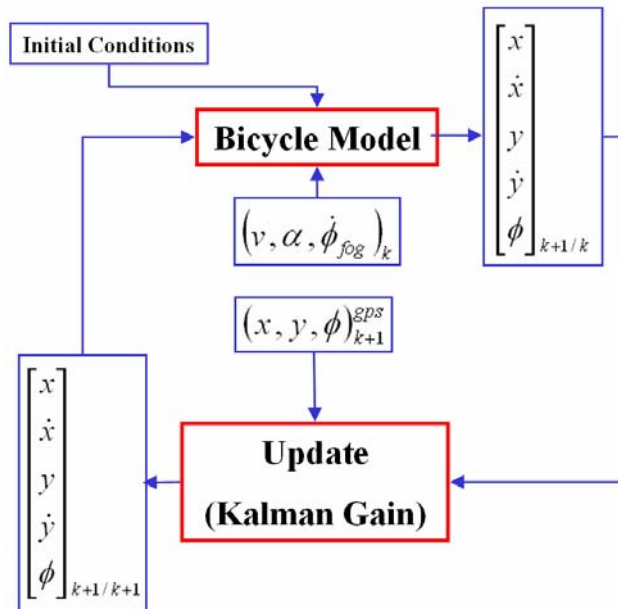


Figure 4-3: The layout of the Estimator

We have analyzed more than 100 km of driving data to understand the performance of our Estimator design. The data were collected in the eight scenarios mentioned earlier, at the two test sites having good and bad GPS. The vehicles were accelerating, decelerating, changing lanes, stopping, turning, and so on at speeds between 5 and 25 meters/second. The main features of the Estimator design are:

1. Errors are small enough to correctly discriminate the lane of the vehicle in most situations (see comments below),
2. the dynamic process model delivers accuracies that are significantly superior to the kinematic model more common in the literature,
3. it responds to turns such as lane changes or U-turns with less than 100 msec delay (two sample times of the VS system),
4. it responds to GPS corrections with less than 500 msec delay, i.e, 2.5 GPS sample times,
5. it maintains accurate heading estimates at low speeds even though raw GPS has large heading errors.

We point out feature 1 because our system engineering analysis (12) identifies this as the most stringent requirement on Estimator errors. Feature 2 is identified because most work in the GPS/INS integration literature does not use a model like ours. Therefore, we see feature 2 as a contribution to the GPS/INS integration literature. Feature 3 appears because it is important to detect turns and lane changes with small delay because this filter is a component of on-board safety systems. These need to detect turns rapidly and warn the driver within 500 msec or less. Item 3 says 100 msec of this delay budget is being consumed by the filter, which is two VS sample times. Thus, the filter does not give too much weight to the GPS, but remains sensitive to the accurate and fast VS.

At the same time, when GPS becomes good, i.e., seven satellites or more, and there is a big difference between the position estimated by the filter and GPS measurement, we would like the filter to converge quickly to the GPS measurement. Item 4 asserts the time constant of the response to a GPS step is about 500 msec. Thus, the filter is responding in about 2.5 GPS sample times. It would be hard to get faster while remaining sensitive to the VS for fast response to turns and lane changes. Thus we feel this filter cannot be tuned to do much better, and significantly enhanced performance would require a significantly different design. This fortunate combination of rapid response to all sensor inputs is due to the dynamic process model and is being driven directly by the VS measurements.

The rest of this section presents data illustrating these five features.

4.1 Lane Discrimination

Figure 4-4 shows the estimated trajectory of the car and the raw GPS plot during a test done at RFS on a straight two-way road with one lane each way. The true positions of the lane centerlines have been determined through repeated measurement. The car starts at (0,0) and goes to the other end of the road while doing some lane changes on the way. The test driver attempts to keep the center of the car on the center of the lane when going straight. At the end of road, the car makes a U-turn and returns to the starting position by driving straight. It then makes a U-turn

to repeat the pattern. This loop is traveled three times on each day. This daily experiment has been repeated 10 times, representing over 40 km of driving.

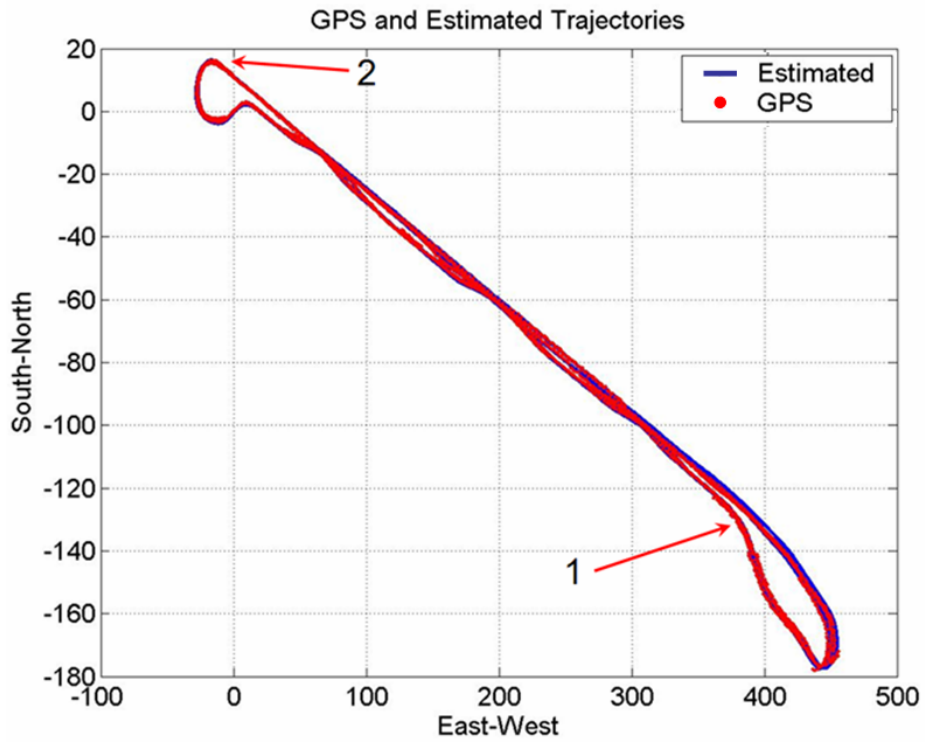


Figure 4-4: Vehicle Route at RFS with lane changes

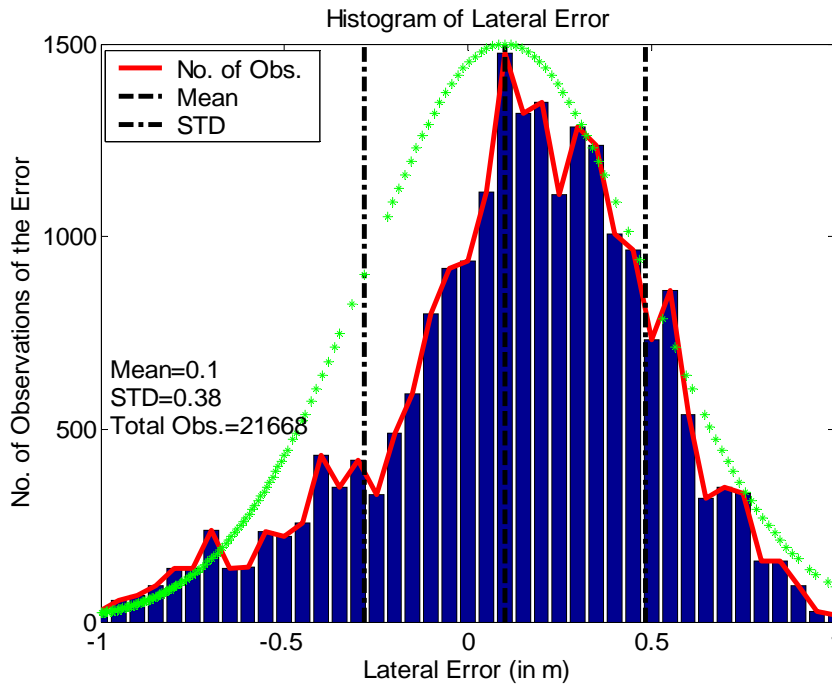


Figure 4-5: Distribution of Lateral Position Error

Along the road at RFS, there are trees and buildings that interfere with the GPS signal. The average number of satellites during this run is about six. With six satellites, our GPS position readings have more than 1 meter error generally.

Figure 4-5 shows the frequency distribution of lateral position error defined as in figure 4-6, based on 20 Hz sampling of the 40 km of driving data. Since error in figure 4-6 is defined with respect to the centerline of the lane, some of this error is due to the inability of the driver to track the centerline of the lane and the rest is due to the Estimator, but we cannot separate these two components. The standard deviation of the error is 38 cm, which is within the 50 cm requirement for lane discrimination. The errors are not zero-mean Gaussian as assumed in the system engineering analysis. The bias is 10 cm. This is probably because the average number of satellites is six. When GPS position is obtained from six satellites or less at RFS, the measurements have bias.

We have also examined the worst-case errors. Figure 4-6 plots the lateral position error versus time for this experiment, with additional boundary lines shown at ± 90 cm. The standard width of a lane is 3.6 m and the width of the car is about 1.8 m, so if the center of the car is displaced by more than 90 cm from the center of the lane, it might be considered as being in the next lane. If this displacement is an error it could activate an erroneous warning. Thus it is desirable that the lateral position error be beneath 90 cm at all times. We see from figure 4-6 that there are four violations of this threshold in the 40 km, of driving even though the average GPS error is over 100 cm.

Points 1 through 4 in figure 4-6 represent typical conditions in which our localization system fails to keep the lateral error small enough. The filter is able to correctly discriminate the lane of the vehicle except in two kinds of conditions. If GPS is lost or goes bad for a long time (order of 10 seconds or more) the position errors become large enough to place the vehicle in the wrong lane. The exact duration of outage depends on factors like speed, number of lane changes, etc. The second kind of condition refers to bad GPS during a turn. If GPS is bad during a turn involving a large change of heading, such as a U turn or a right angle turn at an intersection, the filter is off on the heading at the end of the turn by a small amount (less than a degree). In addition, if the GPS remains bad or unavailable after the turn, this small heading error cannot be corrected. It is integrated by the process model, eventually result in large position errors and an assignment of the vehicle to the wrong lane.

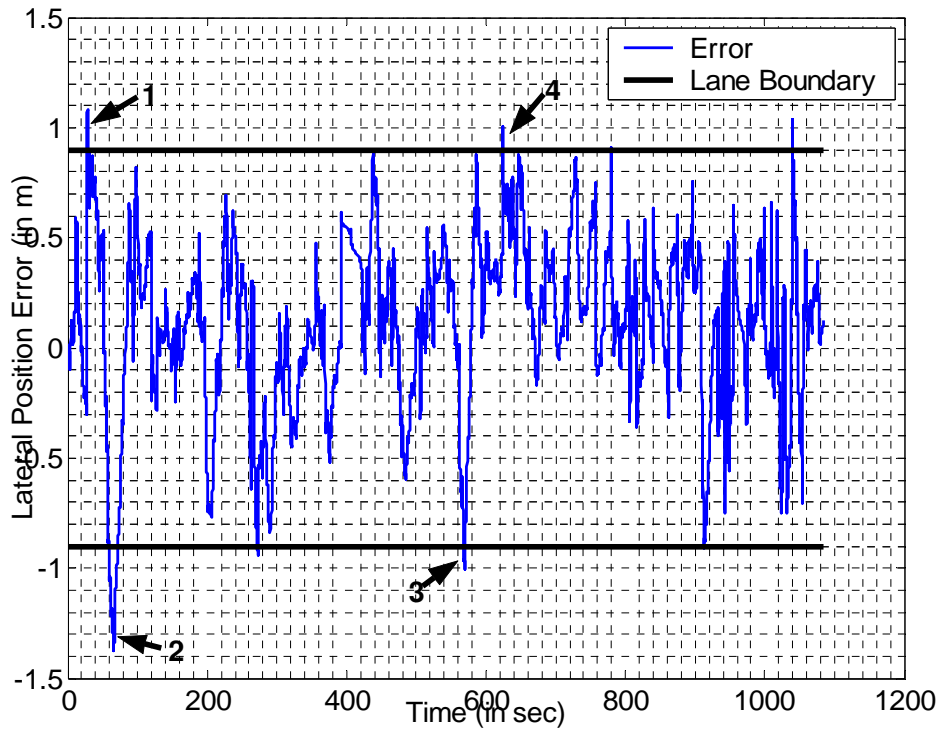


Figure 4-6: Lateral Position Error

4.2 Comparison of Process Model, GPS Outage

Figure 4-7 shows the trajectory plot for a run, including a left turn, carried out at Crows Landing. The GPS path is very accurate (less than 20 cm error from the true path), because GPS coverage is good throughout this run. Estimated trajectories computed by integrating both dynamic and kinematic process models are also shown in figure 4-7. GPS updates are cut deliberately after 10 seconds, while the VS data continue to flow to the filters, so that they are running open loop (just running the dynamic or kinematic model) after 10 seconds.

Figure 4-8 shows the absolute innovation (the Euclidean distance between a point on the GPS path and the corresponding point on the estimated path) and the lateral position error. The lateral error of the dynamic model is within the lane boundary even though the outage is more than 30 seconds long. In fact, the kinematic model does not see the inertial delay and as a result, during turns it turns earlier and causes errors. In this run, the speed is about 20 m/s when going straight and 10 m/s during the turn. Similarly the curves for total position error show that the dynamic model does better. These plots are representative of analyses executed on the entire 40 km of driving data collected at Crows Landing.

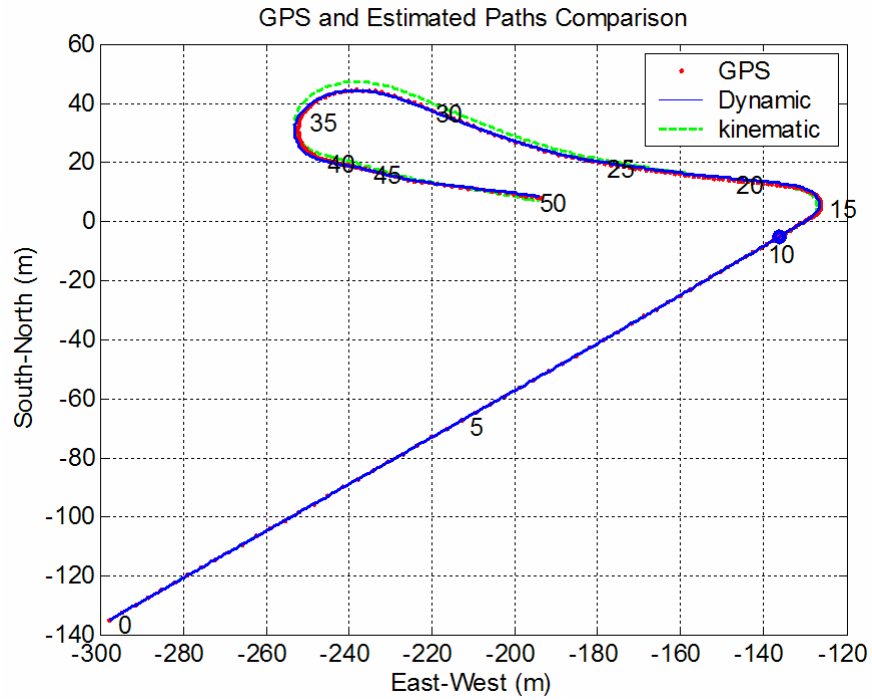


Figure 4-7: A Trajectory plot at Crows Landing

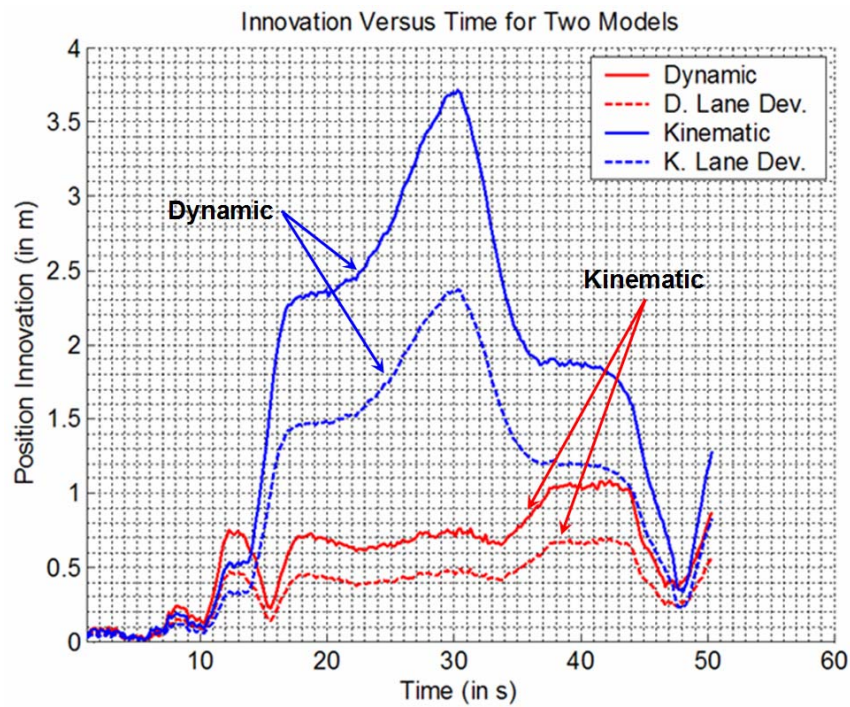


Figure 4-8: Innovation plot for two models in run of figure 4-7

4.3 Delay in Response to Turn

We illustrate the delay exhibited by the filter in responding to a turn by using the same test case that was shown in figure 4-4, focusing on point 1 (shown with an arrow on figure 4-4). We compare the true starting time of the turn and the starting time as determined from the heading and position output by the filter, using data shown in figure 4-4.

We assume the true beginning time of the turn (shown with an arrow in figure 4-9) is approximately when there is an increase in the yaw rate as measured by the yaw rate gyro, which is known to a precision of 50 ms. The heading estimated by the filter shows a clear response delay within 100 ms. The delays observed in the rest of our data are similar. Thus, the response delay of the filter to a turn seems to be about 100 msec. The number of satellites at point 1 is 3. Hence, the delay is not related to GPS quality. This is because we have a good process model and heading is predicted directly using the yaw rate sensor output, which is quite accurate in short-term.

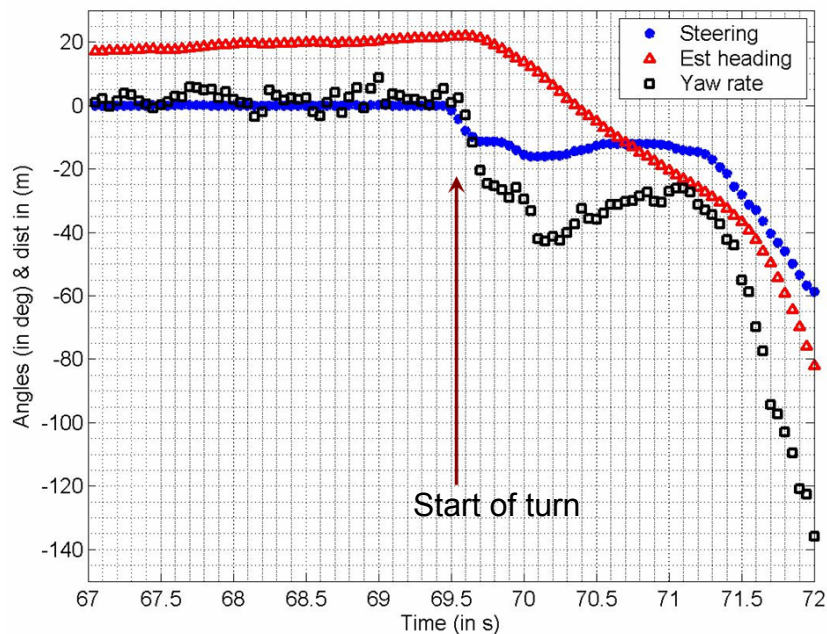


Figure 4-9: Turn Detection Delay at point 1 in figure 4-4

4.4 Delay in Response to GPS Correction

When GPS data are good, we would like the filter to converge quickly to the GPS readings. We illustrate the response of our filter using the test run in figure 4-10, where the superimposed numbers mark different points visited during the trip. The car travels from the start point (0,0) toward point 1, then to 2, makes a U turn there, and then comes back to 1. From point 1, the car travels a loop through points 3, 4 and 5. After finishing the loop, the car goes to the end point and stops. The average number of satellites for this run is less than 5, which means that average position errors are worse than 2-3 meters.

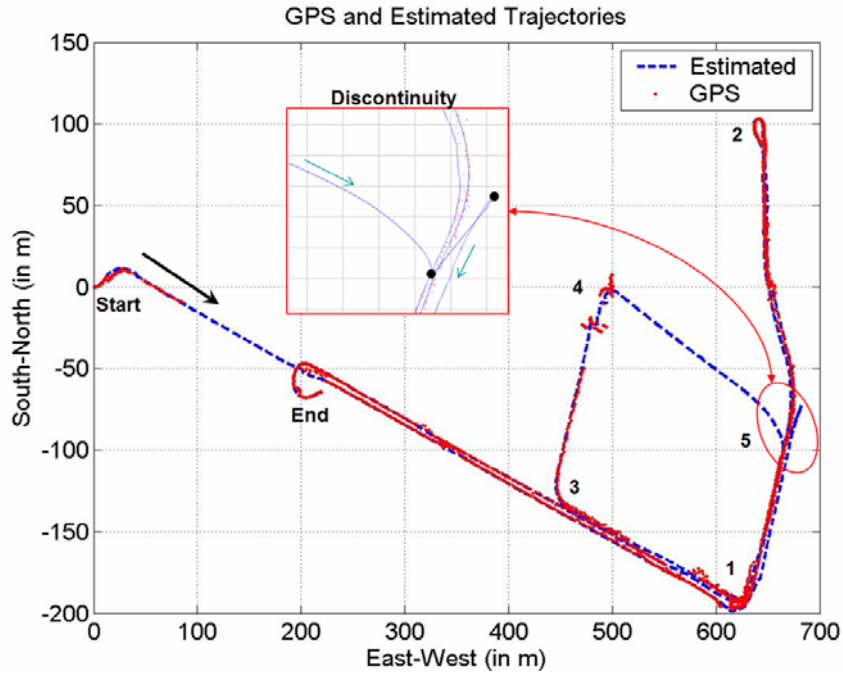


Figure 4-10: A Trajectory plot at RFS with bad GPS data

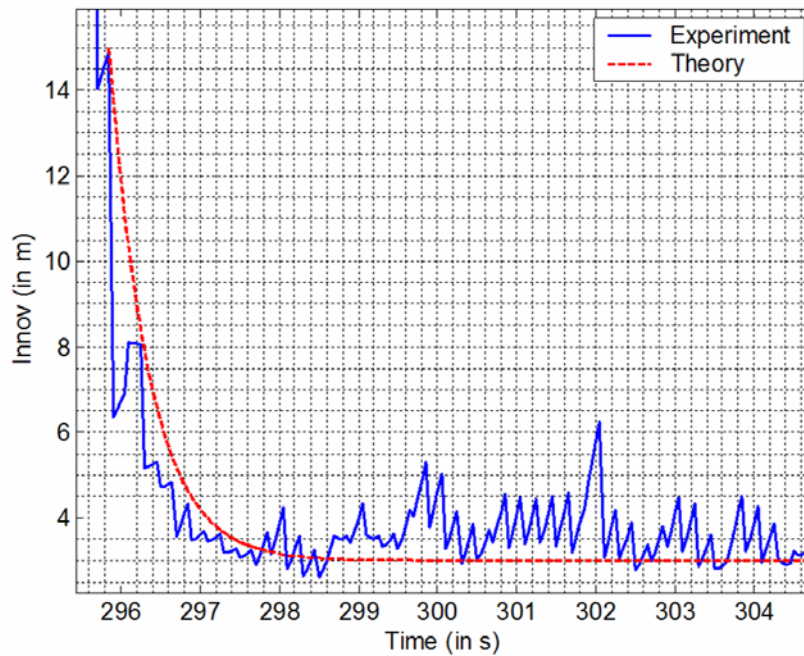


Figure 4-11: Delay in Response to GPS correction

To see the misleading effect of bad GPS readings, consider the travel along the loop from point 3 to 4 to 5. GPS outages before and after point 4, together with faulty observations at point 4, mean that the filter is essentially running open loop with bad initial conditions, which causes divergence from the true path and significant error. The discontinuity in the estimated path at

point 5 is due to this. When the good GPS data are received at point 5, the error is quickly removed by the filter as shown by the segment from 5 to 1.

Figure 4-11 shows the data around the convergence at point 5. On reaching good GPS coverage, the filter attempts to remove the error using the GPS observations. The solid line in figure 4-11 plots innovation; i.e., the difference between the GPS measurement and the filter's position output, showing that the filter is stable. The dashed line is the step response of a first-order system with a time constant of 500ms. This dashed curve has been a good fit to all the data we have analyzed, indicating that the filter time constant seems to be about 500 ms or about 2.5 GPS sample times.

4.5 Low Speed

GPS heading data are very poor at low speeds and appear completely random when the vehicle stops. Nevertheless our data, as in figure 4-12, show that the filter is able to compensate for this. The filter is able to maintain accurate tracks even as the vehicle stops and starts. Figure 4-12 shows that even though the GPS heading error becomes as large as 160 degrees when the vehicle stops, the estimator heading error does not grow.

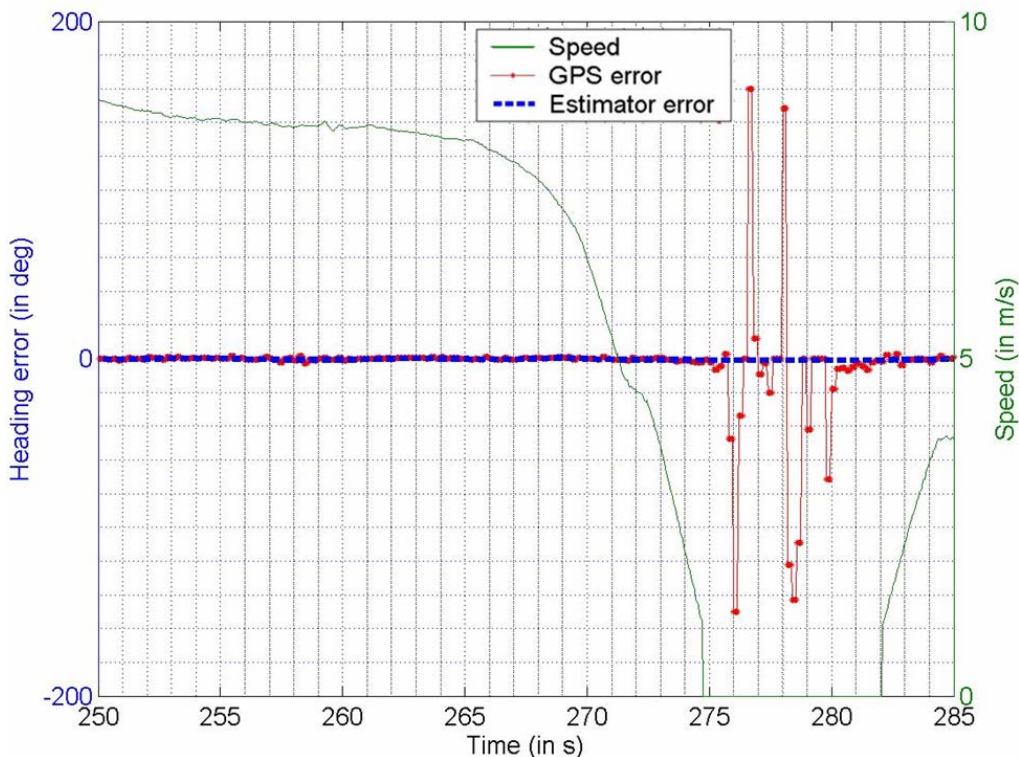


Figure 4-12: Heading estimation at low speeds

These tests were designed to verify the installation and implementation of hardware and software subsystems, and to show that performance is adequate for demonstration of driver assistance applications. These tests were not designed to completely characterize or exhaustively compare the performance of the different sensor and communication equipment used.

5. Communication System Performance

The PATHLAB test kit is built to collect data about a wireless channel. It tests the performance of the wireless link between two mobile stations. Each station is composed of two laptop computers equipped with a DGPS receiver and an IEEE 802.11b wireless card. The test kit consists of four applications: Sender, Receiver, Notation, and Diagram. The Sender application in the sending station sends a configurable burst of UDP broadcast packets to the Receiver application in the receiving station. Every packet sent and received is logged with the corresponding timestamp and GPS position of the two stations. The Notation application records special events that influence the packet reception, such as obstacles between the two stations. With all the data acquired the Diagram application is used to compute and display graphs showing the performance of the radio as a function of the mobility and dynamic scenario when the packets were sent.

Data collected during the GPS testing at Crows Landing have been processed to characterize typical delays that could be expected during driver assistance scenarios. Clock skew adjustment was performed. Since the data were obtained from many short runs for the car following, lane assignment and lane change tests, all of which have similar results, only a sample from the high speed car-following is shown here.

In table 5-1, the **Count** column is the number of data lines in the log of the receiving vehicle, after duplicate timestamps (representing multiple recording of the same message) are removed. **Dropouts** are calculated as delays greater than 500 msec or one second – dropout delays are not included in the average or worst case delays. One dropout typically occurs at the beginning of each run because of stale data in the database, representing the last packet received from the preceding run.

We have made a series of two-vehicle runs on roads and test tracks at the Richmond Field Station, using a variety of parameters for the wireless testing. Table 5-1 summarizes results in terms of dropouts, where a dropout is defined as a time between messages of greater than 500 milliseconds, inter-arrival time (average time between messages) and measured transit time (the difference between remote send and local receive, after adjusting for clock skew). P5 and P9 are the names of the two vehicles.

Table 5-1: Radio Performance Measurements (Dropouts and Delays)

Vehicle, wireless type, update interval	Count	Dropouts (>500ms)	Interarrival Time (average)	Transit Time (msec)		
				ave	min	max
P5, broadcast, 25 ms	21241	6	0.031	0.010	0.004	0.046
P9, broadcast, 25 ms	26167	5	0.025	0.008	0.003	0.038
P5, broadcast, 50 ms	9955	8	0.054	0.014	0.011	0.113
P9, broadcast, 50 ms	10522	6	0.051	0.013	-0.002	0.063

The message loss rates are low and the average delays are between 8 and 14 msec. Based on results like the above, we found that 802.11b broadcast performed well as the wireless communication protocol for the CCW prototype.

In addition to the dropout statistics, we also examined the communication range of 802.11b broadcasts. The blue lines in figure 5-1 are GPS traces of the test routes and the colored discs denote locations where the vehicles lost communications. In figure 5-1, there are two yellow points, representing the locations of the two vehicles when they lost communications. The two yellow points are about 450 meters apart. At less than 450 meters the radios work with our power amplifiers. Thus the range is adequate for the CCW prototype.

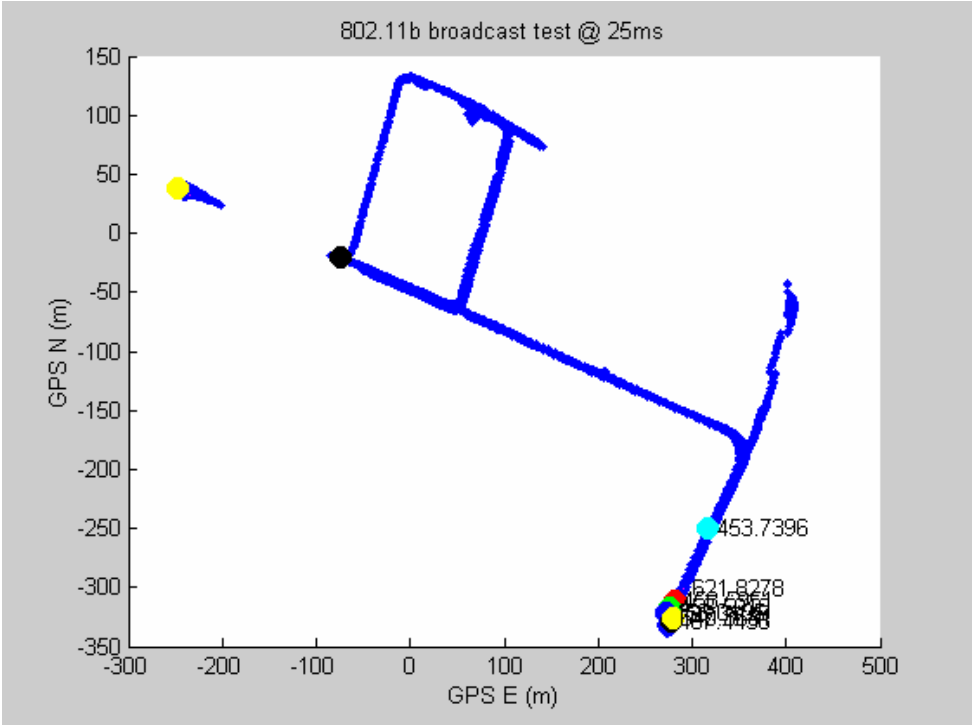


Figure 5-1: Vehicle trajectory with communication dropout points

6. Display and Warning Design

Our system has Forward Collision Warning, Intersection Collision Warning, and Right-Side Situation Awareness Modules. The three read the neighboring vehicle map as shown in figure 1. The warning modules are designed to attract the attention of the driver to threats predicted by the system. By contrast, the purpose of our situation awareness module is to experiment with the efficacy of providing information to the driver on demand. We summarize the situation awareness module in section 6.1 and the warning modules in section 6.2.

6.1 Situation Awareness Module

This module is designed to not attract the attention of the driver while conveying high density information whenever the driver directs attention at it of her own volition (see figure 6-1). For example, all icons take more than 100 msec to loom to avoid stimulating the visual cortex from the periphery of the visual field. On the other hand the loom rates are fast enough to stimulate the motion pathways of the visual system when the display is in the center of the visual field. Our SA component provides awareness of vehicles to the right of the driver. It helps the driver recognize threats in the blindspot and when changing lanes to the right. Therefore it drives a display located at the front right A-pillar. This is where the driver would look for information when contemplating changing lanes to the right.



Figure 6-1: Situation Awareness Display

We partition the lane to the right and rear into three zones as illustrated by figure 6-2. Each zone is chosen so that the driver will tend to associate different actions with different zones as follows:

- *very close*: if a vehicle is in this section, the driver will not change lane,
- *close*: if a vehicle is in this section the driver will consider a lane change including a slight acceleration as she overtakes,
- *far*: if a vehicle is in this section, the driver will know that there is a vehicle in that region but does not have to change behavior.

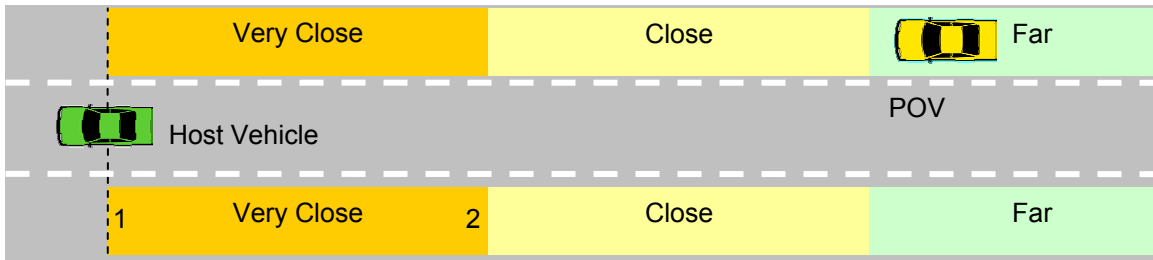


Figure 6-2: Zone Description

The display is partitioned into a “main area” and reservoir. Vehicle icons may appear in either area. Vehicle icons appearing in the reservoir area correspond to vehicles detected as being to the right and rear but classified as being too far away to affect the drivers’ decision to change lane, i.e., in the “far” zone. Thus an icon in the reservoir area merely indicates presence.

The main area icons are of different sizes. These sizes represent the proximity of the POV to the host vehicle, the closer the POV, the bigger the icon, the further the POV, the smaller the icon. The icon transitions through a sequence of sizes. The shortest looming period is 150 ms long. A rate faster than 100 ms usually attracts visual attention to an icon, our goal being to display information without attracting visual attention. The driver should not be made to look at the display every time a vehicle passes. The average driver dwell time on a mirror when determining the safety of a gap is about 1600 ms. Our longest cycle lasts one second, ensuring it will be seen.

The icons are designed to loom at different rates to inform the driver about the closing rate of the rear vehicle. In order to implement the looming, we display four images and change the timing for which they appear. We designed looming rates for depicting three type of closing rate: “Approaching Slow”, to which corresponds a slow looming, “Approaching Fast”, to which corresponds a fast looming, and “Approaching Very Fast”, to which corresponds a very fast looming.

Our design is based in part on research by deVos et al. (25) on the minimum gaps accepted by drivers performing lane changes. We also extrapolated the model developed by Hoffman and Mortimer (26) of the way humans respond to the loom of on-coming vehicles to a side-view mirror. De Vos et al. identified problems with the use of different types of mirrors when detecting vehicles in the blind spot, but also when assessing POV position relative to oneself as well as the time required to understand POV motion. They also mention the difficulties experienced by elderly drivers when turning their head to check the mirrors. We believe that the system we have demonstrated would alleviate some of these problems. The other steps would include an iterative design where the assumptions put in this prototype would be tested with naïve drivers and adapted based on their feedback and where the design would also be revisited to account more for automotive rules for in-vehicle display design.

6.2: Warning Modules

6.2.1 Forward Collision Warning Algorithm



Figure 6-3: Forward Collision Warning Display

Figure 6-3 shows the forward collision display icon. The icon transitions through progressively bigger sizes, as the vehicle in front gets closer. Eventually it reaches its maximum size and turns red to indicate the imminence of collision.

The forward collision warning algorithm is based on the ACAS warning algorithm designed by General Motors (27). We note one important difference between the ACAS and CCW algorithm: in the CCW version, four warning levels are issued to drivers for different levels of actions to be taken to avoid collisions. The level of warning is based upon the acceleration required for collision avoidance:

Table 6-1: Forward Collision Warning levels and Acceleration limits ($g = 9.81 \text{ m/s/s}$)

Warning Level	Lower Limit on Required Acceleration	Upper Limit on Required Acceleration
Level 1:	0.01 g	0.07 g
Level 2:	0.07 g	0.15 g
Level 3:	0.15 g	0.30 g
Level 4:	0.30 g	

To activate this warning, the heading difference between the two vehicles must be within ± 5 degrees. Care must be taken such that these ranges of required accelerations for each warning level do not switch back and forth between two levels while a vehicle's acceleration is at the boundary. Therefore, a 0.01g buffer zone is added as a warning transcends a level. For example, if current warning level is at level 3, the acceleration has to be less than 0.06g in order to switch to level 2 or larger than 0.16g in order to switch to level 4.

6.2.2 Intersection Warning Algorithms

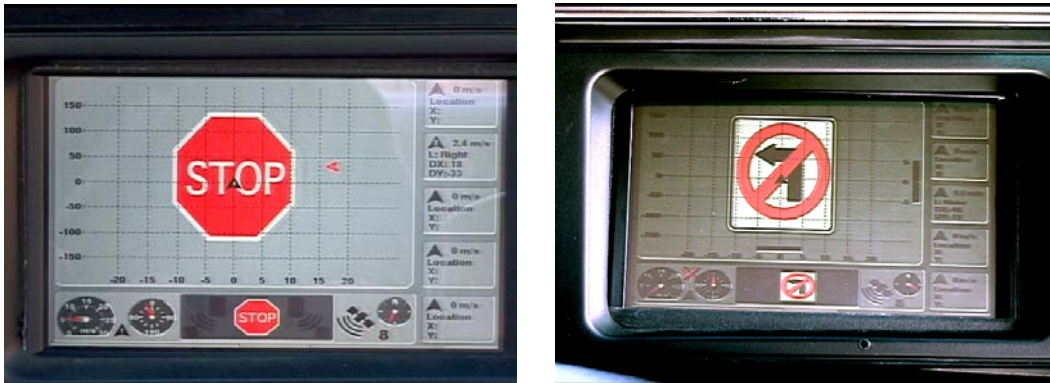


Figure 6-4: Intersection Warning Display in the Straight Crossing Path and Left Turn Across Path Scenarios

Figures 6-4 shows the two display icons used in our CCW prototype. The “No left turn” icon is triggered if the driver puts on the left turn signal at an intersection and the system detects a conflict. Otherwise, on threat detection at an intersection, the system displays the “STOP” icon.

The warning algorithms are standard in the literature. We summarize them briefly. The warning is time and distance based. Time to collision (TTC) and distance to collision (DTC) are the parameters used to trigger the warning. Before calculating TTC and DTC we determine a collision point. The collision point is a conflict point derived by projecting trajectories of vehicles in the neighboring vehicle map assuming they will keep going straight. This is illustrated by figure 6-5.

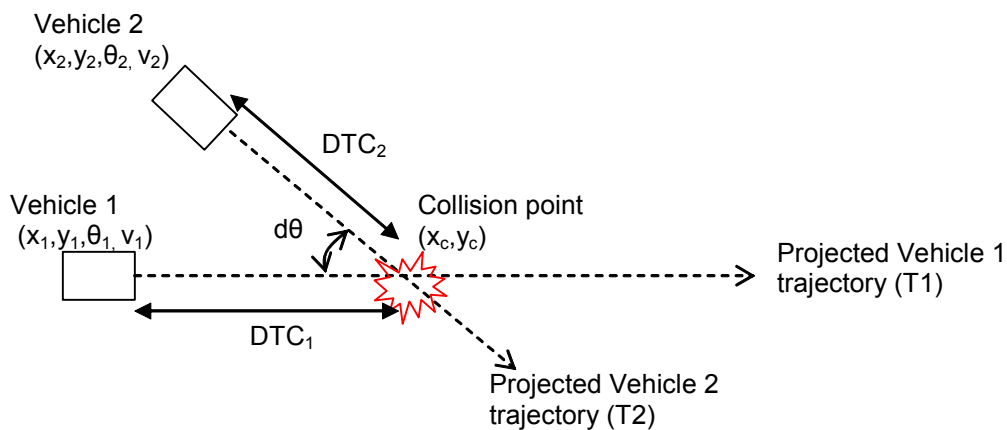


Figure 6-5: Projected Collision Point

$d\theta = |\theta_1 - \theta_2|$ is the heading difference between the two vehicles. To activate this algorithm, $d\theta$ must fulfill either $175 \geq d\theta \geq 5$ or $355 \geq d\theta \geq 185$, where $d\theta$ is in degrees. If one of the conditions

is fulfilled, the TTC is calculated based on the vehicle velocity at the time instant by $TTC = DTC/v$. Then the following logic applies:

```

If  $TTC_1 < 7$  s and  $TTC_2 < 7$  s then
    Issue warning
else if  $DTC_1 < 50$  m and  $v_1 < 10$  mph and  $TTC_2 < 7$  s then
    Issue warning
Else
    No warning
  
```

In the case of a left turn across path conflict with an opposite direction vehicle (see figure 6-6) the definition of TTC in this algorithm is different. Here, TTC is defined as $TTC = D / (v_1 + v_2)$, where D is the distance between the two vehicles as shown in figure 6.7, and v_1, v_2 are their two speeds. The warning algorithm is activated when $d\theta$ is $175 \leq d\theta \leq 185$ (degrees). The no left turn warning will be issued when $TTC < 7$ s.

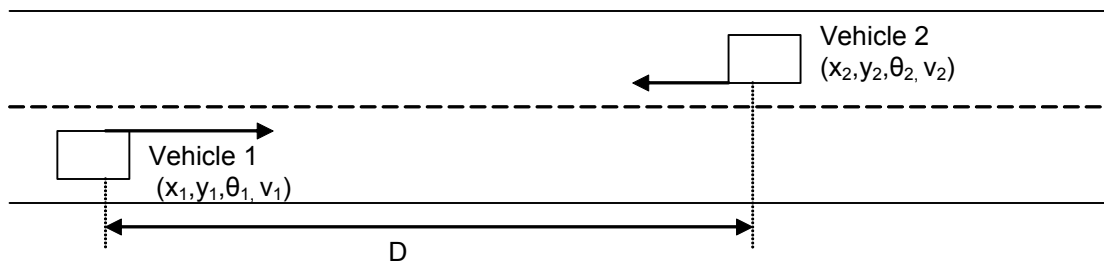


Figure 6-6: LTAP/OD warning development

7. Conclusions

We have shown the technical feasibility of vehicle-vehicle cooperative systems delivering vehicle safety services, given 100% market penetration and sufficient wireless spectrum. These cooperative systems hold significant promise and advantage over vehicle-based systems: they allow driver advice and warning in geometries impossible – or very expensive – to implement with systems that depend entirely on in-vehicle sensors. As examples, a CCW system will work with a cut-out revealing a stopped car, or a stopped or slow-moving car before arrival at the curve.

The principal limitation of the concept is that effectiveness depends on the neighboring vehicles being CCW equipped. There is an ongoing effort to find alternative communication-based active safety concepts able to deliver safety benefits at low or moderate market penetrations.

The prototype has several limitations that could be resolved with further technical research. The prototype does not use maps or any other means of providing the vehicles with awareness of the local road geometry. Warnings are issued assuming that the centerline of the lane is aligned with the heading of the vehicle and the lane width is 3.6 meters. Thus to avoid error, in our tests and demonstrations the vehicles providing warnings drive straight and do not change lanes. Lane

changes or turns are made by the other vehicles. This limitation can be overcome by incorporating digital maps, since we localize robustly enough in GPS coordinates for map matching (28). However, map matching as a realistic component of collision warning systems remains a subject of technical research because the maps would have to be considerably more accurate than currently sold digital maps. Thus, one must either wait for more accurate maps or use better algorithms than map matching to work with inaccurate maps.

A second limitation is the communication rate and range. Simulation studies (2,29) have shown that if all vehicles on a freeway or an urban area were to radiate power at our CCW prototype levels (to cover 300 – 400 meters) and send messages at the CCW rate (every 50 msec) over an 802.11 radio using DCF as the medium access control protocol more than 10% of the messages would be lost due to colliding transmissions. Thus, research is needed to achieve the localization precision of our prototype with lower communication rates and ranges or research has to produce medium access control protocols that are more efficient than 802.11 DCF. While the wireless MAC literature has many protocols that use spectrum more efficiently than DCF, they have not yet been shown to work at the volumes of vehicular traffic.

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