Title

Transit Integrated Collision Warning System Volume II: Field Evaluation

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Transit Integrated Collision Warning System Volume II: Field Evaluation

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Final Report for RTA 65A0150

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Transit Integrated Collision Warning System, Volume II: Field Evaluation

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Final Report for RTA 65A0150

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Abstract

This evaluation report examines the performance of the Integrated Collision Warning System prototype developed by the University of California PATH Program and the Carnegie Mellon University Robotics Institute. The evaluation was based on testing the sensors, processing algorithms, and driver-vehicle interfaces in both controlled and real world operational environments. Evaluation metrics and methodologies were used to evaluate the effectiveness of the system. The effort for this evaluation was based on the following tasks:

Task 1: Develop Evaluation Scenarios
Task 2. Perform Closed Course System Testing Under Controlled-Environment
Task 3. Conduct Detection Analysis
Task 4 Analyze Driving Behavior Data
Task 5 Surveys and Interviews

Keywords: Integrated Collision Warning System, low speed collision warning, Transit bus safety

Executive Summary

Transit bus crashes cost agencies money, cause service interruptions and personal injuries, and adversely affect transit reliability and public image. Over the past five years, 30,000 bus crashes have caused 17,000 deaths and injuries, accounting for $800 million in annual insurance claims.[i] Sudden stops or swerves to avoid a crash can cause passenger falls which result in additional passenger injuries and liability. Insurance claims reflect only some of the costs to transit agencies. In addition to the financial cost of insurance claims and vehicle repairs, there are issues with staff resources consumed to process claims, and (more importantly), the issue of lost future rider ship due to adverse public sentiment regarding transit reliability and safety.

Effective collision warning systems for transit buses could address many of these incidents. This project used commercially available sensors with custom developed algorithms to determine the suitability of these types of systems for transit-specific operating conditions. **The evaluation of these systems demonstrated that:**

- **Current sensors for forward collision warning work reasonably well in a typical urban transit operating environment, although some modification will be required**
- **Side obstacle sensors and algorithms also work reasonably well, but have some issues with appropriate threat detection, which require further development of software algorithms**
- **Under-the-bus detection functions did not work well enough in the configuration tested to be enabled for revenue service and would require a higher leap in technology to be useful**.

This project involved test track verification of sensor capabilities and software algorithms and a year of testing in revenue service. Driver reaction to the system in revenue service was generally positive. Thousands of hours of data were collected that could be used for further analysis in future research.

A preliminary cost-benefit analysis of the systems tested indicates that these systems have significant promise. Comprehensive analysis of crash and incident data from 35 California transit agencies (operating a total of 1758 revenue service buses) collected between 1997 and 2001 revealed a total of about 10,000 crashes and incidents, averaging more than one incident per bus per year. Total costs of these crashes and incidents were $36 M ($23 M crash related; $13 M passenger injury related), averaging $4000 per bus per year. Based on these statistics, **if 30% - 50% of transit bus accidents could be prevented by deploying ICWS at a cost of $5,000 per bus, the liability savings alone could pay for the systems in two to four years**. This analysis clearly shows that transit ICWS could be cost effective.

Currently available off-the-shelf collision warning systems are designed primarily for highway use by passenger cars and heavy commercial vehicles (trucks). The highway operating environment represents a less complex threat assessment scenario than the urban and suburban arterial environments in which transit buses generally operate. Commercially available systems are generally designed to operate at highway speeds on roads with primarily moving targets and clearly marked lane boundaries. The urban driving environment represents a particularly complex threat environment for the collision warning systems. Transit buses need to operate in close proximity to many stationary and moving objects, including pedestrians, bus stops, parked cars, moving cars, bicyclists, etc. and often need to make sharp turns with minimal clearance to nearby objects. These factors add to the challenge of making a collision warning system for transit with accurate threat assessment.

This project built on previous research conducted under DOT's Intelligent Vehicle Initiative. Previous research developed and tested frontal, side and rear transit collision warning systems separately. This project tested an integrated frontal and side transit collision warning system. As part of this IVI program, two research teams from California and Pennsylvania, composed of transit agencies, state departments of transportation, research universities, and a bus manufacturer, engaged in the development of Frontal Collision Warning Systems (FCWS) and Side Collision Warning Systems (SCWS). Under that Phase One project (2000-2002), preliminary requirement specifications and prototype FCWS and SCWS were developed. This project represented the Phase Two effort to develop an Integrated Collision Warning System (ICWS).

This ICWS project included the following major efforts:

1. **Development of interface requirements**
2. **Development of two prototype ICWS, including integrated Driver Vehicle Interface (DVI)**
3. **Test track verification tests of ICWS**
4. **Pilot tests and data collection on ICWS in the San Francisco Bay Area, CA and in Pittsburgh, PA for 12 months**
5. **Analysis of field data before and after ICWS activation to analyze any driver behavior changes.**

The development of the ICWS interface requirements and two prototype ICWS were reported in the Transit ICWS Interface Control Document [FHWA-JPO-04-097] and Integrated Collision Warning System Final Technical Report [FTA-PA-26-7006-04]. This evaluation report provides results of the test track verification and field tests. The verification tests of the FCWS and SCWS elements of the ICWS were conducted separately due to differences in their respective system characteristics.

The verification tests for the FCW system showed that the obstacle detection function provided adequate longitudinal measurements in a transit operational environment, but the quality of the measurements of the lateral distance to targets in front of the bus still needed improvements. Test results showed that, under the tested scenarios, the FCWS could correctly identify hazardous targets and generate warnings when driver action was needed. However, errors in lateral position measurements could potentially cause false detections of targets that were not threats, thereby resulting in false positive warnings. Time delays in the sensing and signal processing functions also reduced the effectiveness of the frontal collision warning system.

Tests under controlled conditions showed that the SCWS had no missed warnings or false negatives under specific staged crash scenarios, but there were some issues with false positives. These tests also showed that the false positive warning rates for both contact and under-the-bus incidents were unacceptably high for any reasonable performance requirement, and therefore warnings for these two conditions were not activated and displayed for the operational testing in revenue service. Analysis of field test data showed that of the warnings issued by the SCWS, about 2/3 of the alerts and 1/3 of the imminent warnings were correct warnings. Most of the incorrect imminent warnings were caused by incorrect velocity estimates. Curb detection reduced the nuisance alarms and false warnings on the right side by 30%. The analysis also showed that the remaining nuisance alarms and false warnings were caused by a variety of reasons including vegetation, false or no velocity, and ground returns, etc.

Two buses instrumented with the prototype ICWS were tested in revenue service in the San Francisco Bay Area and Pittsburgh. Data for a total of seven bus operators were analyzed, dealing with issues of driver behavior in general, as well as issues specific to the collision warning systems. The database developed in this project contains both engineering data and video recording of operating conditions and driving behavior. These data represent a valuable asset for evaluation in future research. The data analysis compared drivers' behavior during the period when the ICWS was turned on with the baseline 'before' data (when the systems were active and collecting data, but not issuing any alerts or warnings).

The field data collection and analysis of the usage of the collision warning systems by bus operators have shown that the ICWS increased consistency of driving behavior and had the most noticeable effects on the most aggressive drivers. The general trends in bus operator behavior after activation of the frontal warning system were more cautious or conservative driving, at larger car following gaps and with reduced braking severity. The data also showed that changes in driver behavior with regard to the SCWS were also towards safer driving, but the changes were less evident than for the frontal collision warnings. There were some hints that the SCWS was also used in unintended ways such as driving closer to the guardrails.

In addition to the above main findings, the research team also learned the following lessons:

- The existing commercially available collision warning systems, which were developed for highway applications, are not suitable for transit operations in urban and suburban environments without significant modification. Data collected using instrumented buses in revenue service showed that the transit operation environment involves complex threat scenarios that existing commercial CWS were not designed for.

- The advanced ICWS developed specifically for this project addressed some of the limitations in existing commercial CWS for transit-specific operating requirements. However, improvements are still needed to overcome the limited ability of the systems to detect, classify and track target objects, so that false and nuisance alerts can be further reduced without additional false negatives.

- The verification tests indicated that the sensing approaches used for both frontal and side collision warning systems need refinement to meet transit requirements. Specifically, the FCWS required additional sensing means and sensor fusion to determine the lateral position of obstacles relative to the vehicle path and their threat levels and to compensate for sensor and processing delays and errors. The SCWS may also need to employ additional sensing means and improved algorithms to classify objects as vegetation or ground, and to improve velocity measurements.

- An integrated Driver Vehicle Interface (DVI) for FCWS and SCWS was developed in order to make sure that warnings were intuitive and effective for the drivers. A warning synthesizer to present fewer warnings to the operator was not implemented for several reasons. It was thought that a false positive could potentially suppress a true positive. In operation, very few examples of frontal and side alerts occurred in close proximity to each other during the field tests, indicating very limited potential usefulness of a warning synthesizer for prioritizing the warnings.

- The need for integration of forward and side collision subsystems will depend in part on whether the integrated system will be significantly different in cost or performance from independent ones. In discussions with transit operators and bus manufacturer/suppliers, operators generally prefer to have an integrated ICWS unless the cost is almost as much as the combined cost of two independent systems. If the cost is the same for one integrated system or two single function systems, some operators would prefer separate subsystem options.

- As today’s bus manufacturers have already implemented selected standards for in-vehicle communication networks (J-1939 data buses) and electronic interfaces, it would be desirable if the collision warning systems are integrated with the transit bus electronics through these already standardized electronic interfaces on buses.

From these lessons learned and as a result of the data analysis, the following topics are recommended for future research:

- Additional evaluations of warning strategies in a bus driving simulator

- Further improvements of FCWS and SCWS threat assessment algorithms in a representative transit operating environment

- Larger Field Operational Tests, with more drivers and more buses for a longer duration
- Outreach to transit operating agencies regarding cost/benefit potential of transit ICWS
- Development of an effective under-the-bus warning system
- Additional analyses of existing data.

In conclusion, the verification tests were valuable in establishing parameters for acceptable performance of ICWS in transit-specific urban environments, and the ability of current technologies to meet those parameters. Both raw sensor capability and threat assessment algorithms were verified in the test track work. This work will be quite valuable as a foundation work for development of an ICWS for a larger field operational test or commercial system. In other words, **this project provided the foundation work on what can and cannot be done with currently available sensor, threat assessment, and data fusion capabilities to meet typical transit operating requirements**. This project also performed initial driver acceptance testing of systems using current capabilities, as well as pioneering integrated DVI work. The field testing in revenue service provided useful lessons that could be used as the basis for larger scale field tests.

Transit operators participating in this project were generally enthusiastic about the potential of these systems. We believe that the ICWS technologies developed under this project have great potential for improving safety of transit operations and could contribute to the effective performance of ICWS systems for other vehicle platforms in urban/suburban scenarios. However, **more work is needed on the threat assessment algorithms and sensor suite to develop an ICWS that is suitable for a typical transit operational environment in terms of accurate threat detection and driver acceptance. We therefore recommend that the Federal Integrated Vehicle Based Safety Systems (IVBSS) initiative be expanded to include a transit IVBSS FOT.**

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Introduction

1.1. ICWS Program Need

Bus crashes have been a major concern for transit operators. Over the past five years, 30,000 bus crashes have caused 17,000 deaths and injuries, accounting for $800 million in annual insurance claims. Bus crashes have resulted in property damage, service interruptions and personal injuries; they also affect transit efficiency, revenue and image. In addition to collision damage, passenger falls resulting from emergency maneuvers also contribute to an increased potential for passenger injuries and liability. Comprehensive analysis of crash and incident data from 35 California transit agencies (operating a total of 1758 revenue service buses) collected between 1997 and 2001 revealed a total of ~10,000 crashes and incidents, averaging more than one incident per bus per year. Total costs of these crashes and incidents were $36 M ($23 M crash related; $13 M passenger injury related), averaging $4000 per bus per year. Furthermore, a transit collision ripples through the agency and consumes additional resources to settle claims and results in significant loss of good will. The study showed that if 30% - 50% of transit bus accidents could be prevented by deploying ICWS at a unit cost of $5,000, the liability savings due to crashes and incidents could pay for the system in two to four years. These results clearly show that transit ICWS can be cost effective.

Existing work including SAE and ISO standards, have all been focusing on collision warning for highway applications[ii] [iii]. Currently available off-the-shelf collision warning systems are also designed for highway use, primarily for commercial vehicle operations. The highway operating environment is much simpler than the urban and suburban arterial environments in which transit buses generally operate. Transit buses need to operate in close proximity to many stationary and moving objects, including pedestrians, bus stops, parked cars, moving cars, bicyclists, etc. and often need to make sharp turns with minimal clearance to nearby objects. Because of sensor limitations, the commercially available collision warning systems tend to give too many warnings to the drivers when used in urban / suburban environments, causing drivers to ignore the system or disable it. These factors add to the challenge of making a collision warning system that contributes to safety and that transit operators will accept. The critical issue is to improve the accuracy of the warnings in order to be effective in advising drivers to take corrective action.

Under the Transit Intelligent Vehicle Initiative (Transit IVI) program sponsored by the U.S. Department of Transportation and based on recommendations from transit stakeholders, the Federal Transit Administration (FTA) initiated development efforts on transit collision warning technologies. Two research teams from California and Pennsylvania, composed of transit agencies, state departments of transportation, research universities, and a bus manufacturer, have engaged in the development of Frontal Collision Warning Systems (FCWS) and Side Collision Warning Systems (SCWS). Under the Phase One program (2000-2002), preliminary requirement specifications and prototype FCWS and SCWS were developed. FTA, with the advice of the transit IVI stakeholder group, decided to move forward with integrating the FCWS and SCWS into an Integrated Collision Warning System (ICWS) in Phase Two (2003-2005).

The Integrated Collision Warning System evaluated herein was built and integrated on two transit buses operating in revenue service. They were operated in the San Francisco Bay Area, CA and in Pittsburgh, PA for about one year in order to collect adequate data for evaluation of the effectiveness of the ICWS.

1.2. ICWS Goals

The goals identified by the ICWS team were as follows:

1. Develop a Functional ICWS
2. Create System Acceptable to Operators (Drivers & Operations)
3. Demonstrate a Potential for Reduction in the Severity and Frequency of Collisions
4. Prove Technical Feasibility Through Field Test of Prototype System(s)

1.3. ICWS Evaluation Report Scope

This evaluation report examines the performance of the Integrated Collision Warning System prototype in order to verify if the integrated system achieved these goals. The evaluation was based on testing the sensors, processing algorithms, and driver-vehicle interfaces in both controlled and real world operational environments. Evaluation metrics and methodologies for testing advancement towards these goals were generated in order to evaluate the effectiveness of the system against the goals. The effort for this evaluation was based on the following tasks, which are described in more detail in the following paragraphs.

1. Task 1: Develop Evaluation Scenarios
2. Task 2. Perform Closed Course System Testing Under Controlled Environment
3. Task 3. Conduct Detection Analysis
4. Task 4 Analyze Driving Behavior Data
5. Task 5 Surveys and Interviews

1.3.1 Task 1: Develop Evaluation Scenarios

As the first step of this evaluation, the ICWS team developed two sets of evaluation scenarios and refined the metrics and methods for the subsequent tasks. The first scenario set was used to quantitatively evaluate the performance of the integrated system including the sensing, detection, and warning functions (for Tasks 2 & 3). The second set included scenarios designed for examining driver behavior for baseline (none), independent (left, forward, right), and integrated warnings (for Task 4). Specific survey questions were also developed to examine driver acceptance and system performance (for Task 5).

1.3.2 Task 2: Closed Course System Testing in a Controlled Environment

Certain scenarios do not occur frequently enough in real world driving to adequately test how the system handles specific events. Events of key interest are actual frontal and side collisions, pedestrian under bus warnings, and bicycle side collisions. Closed course testing allowed tests to be run using staged scenarios to gather data that would not be possible with the bus in revenue service.

Controlled testing of this nature also allowed evaluators to collect accurate system performance data to identify sensor bias, misclassifications, and other subtle system errors. Independent measuring systems were established in order to identify the sensor and system errors and delays.

1.3.3 Task 3: Conduct Warning Analysis

Perhaps the largest concern for an integrated collision warning system operated in an urban environment is that the system will be susceptible to false alarms and unable to consistently identify real threats. Using manually encoded real threats from recorded video data, the system warning outputs were examined and classified. Metrics for this task included:

1. <u>True positives</u>: when the system correctly identifies a real threat.
2. <u>False negatives</u>: when the system does not identify a real threat.
3. <u>True negatives</u>: when the system does not identify a threat when none is present.
4. <u>False positives</u>: when the system identifies a threat when none is present.
5. <u>Fault tree distribution</u>: for false positives and false negatives, where does the fault originate?
6. <u>Scenario parsing</u>: Under what driving scenarios do false and nuisance alarms occur? False alarms may be caused by faults (system malfunctions) or incorrect classification of a safe situation as a threat, while nuisance alarms are situations when the system functions correctly, but the driver finds the alarm annoying.

1.3.4 Task 4: Analyze Driving Behavior Data

On-board collection of driver behavior data provided insights to the use of an assistance system and the potential for safety benefit. Such data were valuable because they were collected during field-testing in revenue service.

The analysis of these data included a longitudinal human factors analysis of driving behavior. The periods of data collection were:

(A) Baseline - DVI off, but system on and recording
(B) Full System - DVI on and system on and recording

Metrics used in evaluating driver behaviors were:

1. Behavior when within CWS DVI activation range: does time gap change, and in what way, when drivers are following a lead vehicle and the DVI is activated? Do drivers alter their lateral behavior as a result of DVI activation?
2. Normal following distances: do drivers alter their following distances as a result of the system?
3. Time within each CWS DVI category (alert, warn): the quantity of time drivers occupy activated DVI categories. This includes analysis of whether drivers try to exit such threat regions earlier than when DVI is not present.
4. Braking rate: there is concern that the DVI may lead to more hard braking events and therefore increase risk of passenger falls. This is an attempt to determine if the system increases such risk.
5. Swerving rate: this is similar to braking behavior but focused on lateral behavior.
6. Frequency of warnings over time: this is a measure of how overall driver behavior may or may not shift towards safer driving habits.

1.3.5 Task 5: Surveys and Interviews

Driver perceptions of the system were quantified through carefully constructed surveys and interviews.

Metrics for this task included:

1. False and Nuisance alarms: the false positives, as well as true positives that drivers find annoying.
2. Driver sensitivity ratings/reports: survey or discussion based data collection that quantified driver opinion on the appropriateness of system sensitivity.
3. Driver perception of safety benefit: these data include subjective reporting of safety improvements or degradations for the whole system, and specific events (e.g., simultaneous warnings). This line of data collection included driver perception of system impact on their workload.
4. Self-reports of alterations in driving behavior: these data involved documentation of behavior shifts as a result of system use.
5. Satisfaction with system performance: This metric involved documentation of how drivers perceived the system with respect to overall performance of the whole system, and specific factors (e.g., reliability in inclement weather, details relevant for training, etc.).
6. Perception of system accuracy: This metric is related to feedback on false and nuisance alarms but is more general. For example, the system may accurately detect threats but incur an unacceptable delay before issuing a warning. Another example is that drivers may feel the system improperly elevates certain threats from an alert to a warning.
7. Relaying of passenger queries and comments: the team fully expected passengers to notice the DVI and external sensors. Documentation of their comments and opinions via the drivers and existing rider feedback options permitted an initial read on how riders perceive the system.

1.4. Document Organization

This first chapter of this document describes the program need, goals and scope. It provides a summary of the tasks accomplished in the evaluation process, document organization and presents a high level ICWS Overview describing the system architecture, hardware, sensors, operator interface and the areas of coverage around the bus. It also includes a list of reference documents for additional information on the Frontal, Side and Integrated Collision Warning System Programs.

Chapter Two describes the closed course testing and results, which involved separate testing of the forward and side looking components of the ICWS. The Frontal Collision Warning System testing involved driving the equipped bus through scenarios featuring static objects and other vehicles in known positions, and evaluating the correctness of the responses of the warning system. The side collision warning testing involved staged scenarios of collisions and near collisions to calibrate and evaluate the performance of the system, including its curb detection and object-under-bus detection capabilities.

Chapter Three describes the field testing of the buses in revenue service. This includes descriptions of the test conditions and data acquisition, and the results of the analysis of the data, including measures of changes in safety-related driver behavior. Also included is a summary of the operator feedback and analysis.

Chapter Four describes in more detail the conclusions, lessons learned and recommendations as a result of building, testing and evaluating this system

The appendices provide additional technical details and are organized by the chapters that they refer to. Specifically:

> Appendix A provides data, results and recommendations after testing the ICWS Driver Vehicle Interface display in simulation.
>
> Appendix B provides additional data and analysis for Chapter 2: "Engineering Verification of ICWS under Controlled Environments". These data include backup for the sensor verification and calibration closed course tests:
>
> - Verification of inter-vehicle distance measurement error
> - Verification of static object lateral distance measurement, prediction / estimation error
> - Time Delay Test Data Analysis
> - Gyro rate angle measurement tests
>
> And the scenario based system verification data for
>
> - Vehicle Following
> - Detection of moving target in adjacent lane
> - Cut-in and cut-out test
> - Low speed approaching/crashing to a static object

Appendix C contains more detailed data plots and analysis for Chapter 3: "Measurements of Driver Usage of Collision Warning Systems"

- Database records of driving statistics for seven bus operators
- Cumulative distributions of brake pressure applied by operators
- Cumulative distribution of accelerations
- Cumulative Distributions of Time to Collision (TTC)
- Cumulative Distributions of Required Deceleration Parameter

Appendix D describes the feedback from transit operators and transit agencies, obtained from questionnaires, emails, meetings, phone calls, and demonstrations, as well as the feedback received from drivers on ride-alongs during the course of the field testing.

Appendix E contains the questionnaire used for obtaining the operator feedback.

Appendix F contains the metric conversion tables and formulas.

1.5. ICWS Overview

1.5.1 ICWS Architecture

Figure 2-1 shows the architecture of the Integrated Collision Warning System (ICWS) Prototype.

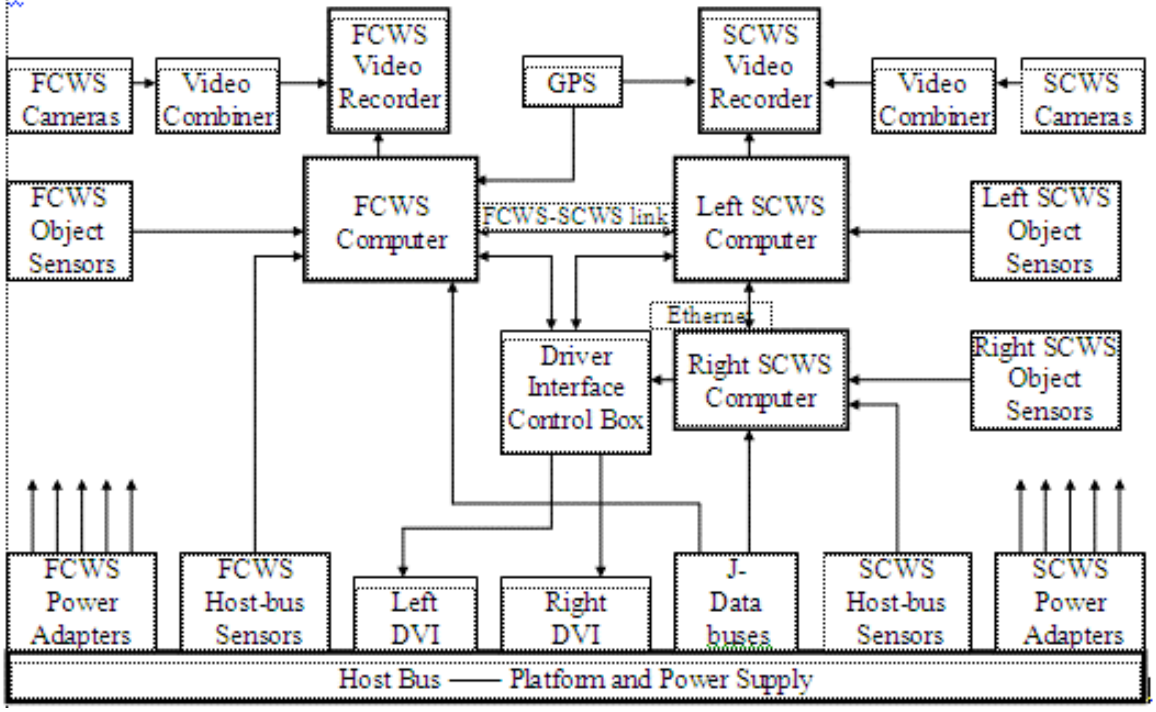

Figure 2-1 - System Architecture

The overarching design philosophy was to integrate the frontal and side collision warning systems through information integration. In implementing the integrated prototype hardware, we wanted to ensure that each system could operate even if the others go down. With separate computing systems this dictated a level of independence that does not need to be reflected in the end commercial product.

The three computers which are executing the warning algorithms are integrated together through a FCWS-SCWS serial communication link. This link was used to synchronize the time basis for data collection, to pass warnings between the frontal and side systems and was proposed to pass obstacle data at the boundaries between the frontal and side systems. The time stamps and the warnings were used extensively for post processing data analysis, but the obstacle data were not shared in this program. It remains to be shown whether the data sharing is useful in an integrated collision warning system.

An integrated DVI displays the warnings from both the FCWS and the SCWS. The DVI and Driver Interface control box are responsible for presenting integrated warnings to the transit operator.

A common coordinate system was used to enable the integration of the frontal and side areas of coverage.

This integration at the higher level facilitated the ICWS development and testing activities, building on prior research on the separate FCWS and SCWS. However, future generation systems for commercial use are likely to be integrated at lower levels to economize on component costs, volume and weight. The next steps in this program should include developing an initial commercial prototype which would integrate the hardware subsystems, overlapping sensor fields of view and developing common software modules between the frontal and side collision warning systems.

1.5.2 FCWS Hardware Overview

1.5.2.1 FCWS Computer Enclosure Layouts

Figure 2-2 shows the layout of the FCWS computer enclosure.

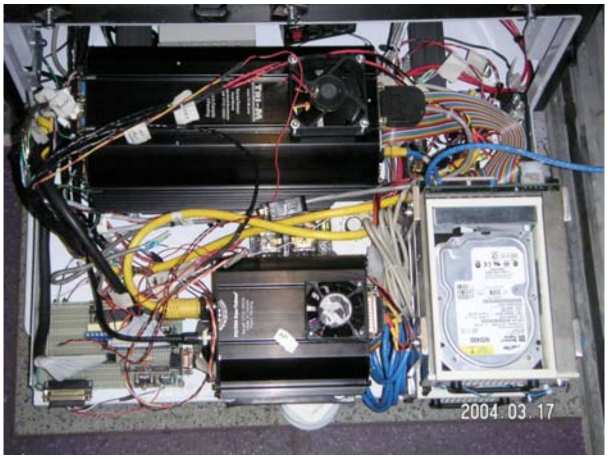

Figure 2-2 - Layout of the Frontal portion of the ICWS computer enclosures

1.5.2.2 FCWS Sensors

Figure 2-3 shows the layout of FCWS object sensors and video cameras as well as the SCWS Curb Detector on the front face of SamTrans bus 601. The positions of each sensor/camera are measured in a FCWS reference frame. The frame is originated on the ground under the center point of the front bumper with positive directions of x-, y- and z-axes pointing to driver-side, upward, and forward respectively.

Vehicle speed is recorded from the vehicle’s SAE J1939 interface on the SamTrans bus and the J1708 interface on the PAT bus and also by measuring the analog speed signal directly from the transmission. A rate gyro is mounted in a waterproof enclosure on the underside of the bus floor near the rear axle and a yaw rate accelerometer is mounted within the electronics area. Brake pressure is measured using a pressure transducer mounted on a spare port of the air brake system under the floor of the driving area. A proximity sensor mounted near a universal joint on the drive shaft is used to determine if the bus is moving at speeds lower than 2-3 miles per hour. Turn signal activation and backing light status are recorded by tapping off the existing turn signal circuit and backing lights. A DINEX module was added to read the door open status, turn / hazard flashers and as a time delay after power up to enable power to the Collision Warning System hardware. Windshield wiper activation is determined with a proximity sensor mounted on the windshield wiper mechanism. The GPS antenna is mounted on the rear of the roof near the exhaust for the HVAC, and the GPS computer is mounted in a waterproof enclosure near the HVAC evaporator unit in the rear of the bus. The GPS and CDPD modem antenna are mounted on the rear of roof near the exhaust for the HVAC, while the GPS and CDPD modem computers are mounted in a waterproof enclosure near the HVAC evaporator unit in the rear of the bus.

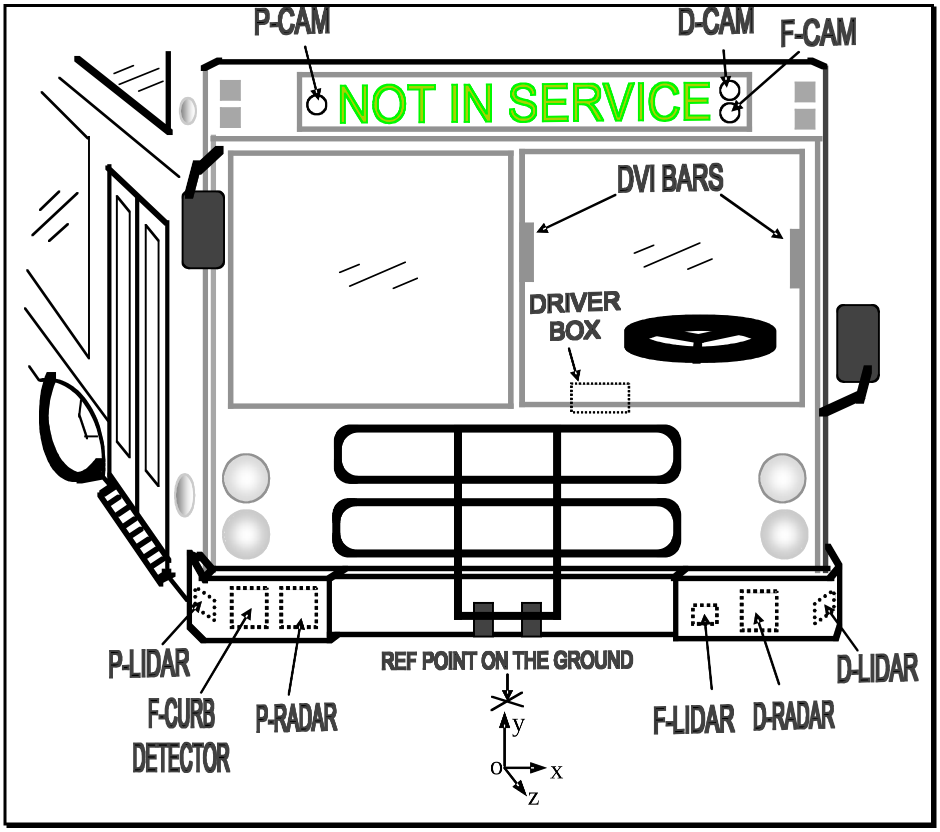

Figure 2-3 - Layout of FCWS sensors, cameras, DVI and SCWS curb detector

1.5.3 SCWS overview

1.5.3.1 SCWS Computer Enclosure Layouts

Figure 2-4 shows the layout of the SCWS computer enclosure.

Figure 2-4 - Layout of the Side portion of the ICWS computer enclosures

1.5.3.2 SCWS Sensors

Figure 2-5 shows the right (top drawing) and left side (bottom drawing) of the transit bus. The SCWS object sensors are SICK laser scanners mounted on the left and right sides of the transit bus and a curb detector mounted in the right side of the front bumper. The SICK laser scanners sit approximately 24 inches above the ground.

The Curb Detector is mounted inside the front bumper as shown in Figure 2-6. The underside of the front bumper is shown, with the blue arrow pointing to the laser and the red arrow pointing to the camera.

Figure 2-7 shows the forward part of the left side of SamTrans bus number 601. The data collection camera that looks toward the rear of the bus can be seen in the upper left corner of the figure. There are four of these cameras, whose locations are shown in Figure 2-5.

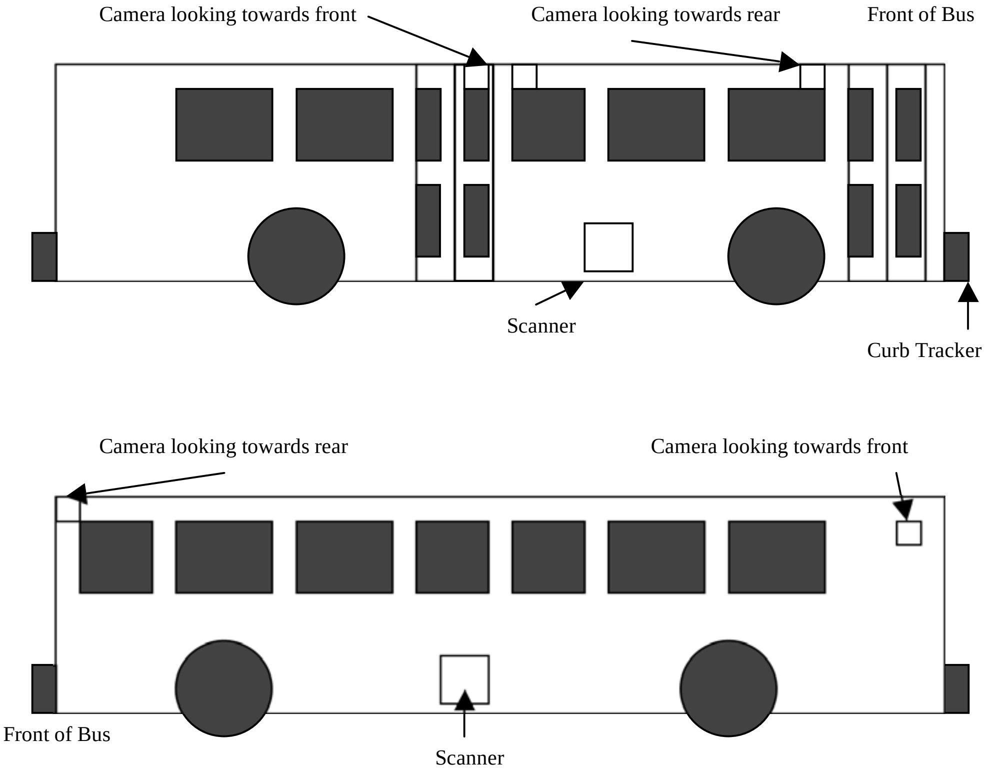

Figure 2-5 - Right and Left Side Collision Warning System Sensor Layout

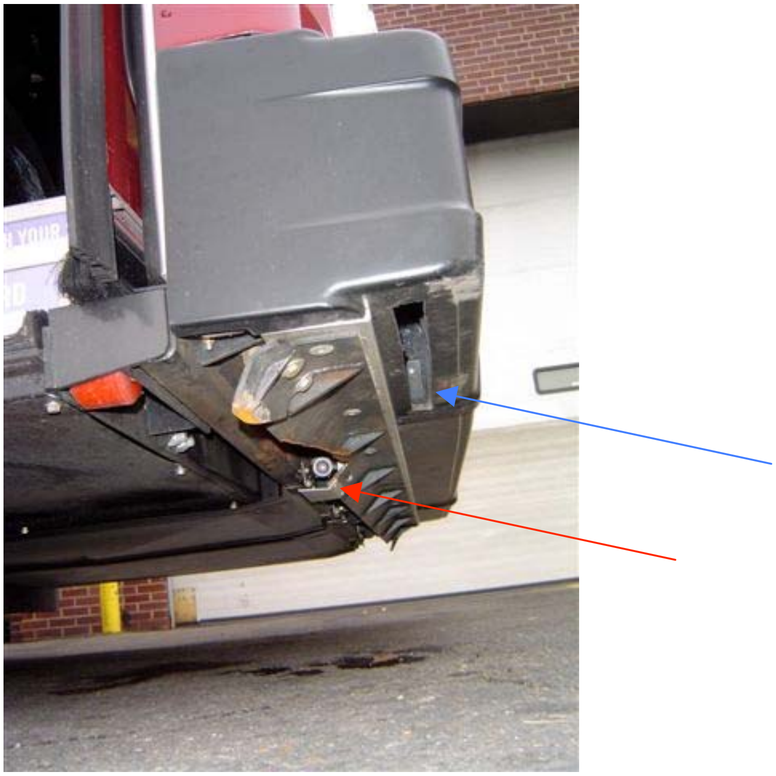

Figure 2-6 - Front bumper with the laser (blue arrow) and camera (red arrow) visible

Figure 2-7 - Left Side Camera on SamTrans Bus 601

1.5.4 ICWS Driver Vehicle Interface

The main components of the DVI are two LED assemblies – one on the left-hand A-pillar and the other on the center pillar. Both assemblies are constructed identically, with seven LED segments filling the top and two LED segments filling the bottom (See Figure 2-8). All LEDs in the displays have the capability to be either amber or red. The upper LEDs are 3 x 2 cm and the lower LEDs are 3 x 3 cm, with a triangular mask pointing towards the side for which it is displaying the warning. The total assembly dimension is 4 x 22 cm. The LEDs have a maximum luminance intensity of 90/60 mcd and a viewing angle of 100 degrees.

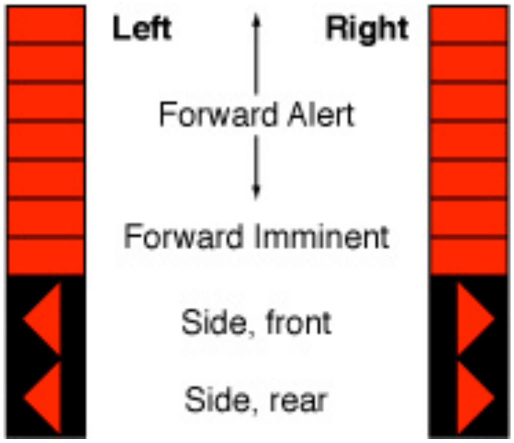

Figure 2-8 - ICWS DVI

1.5.5 ICWS Sensors Field of View

Figure 2-9 and Figure 2-10 illustrate the Fields of View of the two buses equipped with the ICWS system. The farthest detectable range for the FCWS in the same lane is 100 m (330 ft) and the closest detectable range in the same lane is no greater than 3 m (10 ft). The maximum detectable side-looking angle from the front bus corners is 30 degrees on SamTrans bus 601 and 20 degrees on the PAT bus. The detectable lateral position for the forward sensors is over 6 m (20 ft). The side looking sensors can closely track objects that are within 3 meters of the bus however, objects can be detected as far as 50 meters away.

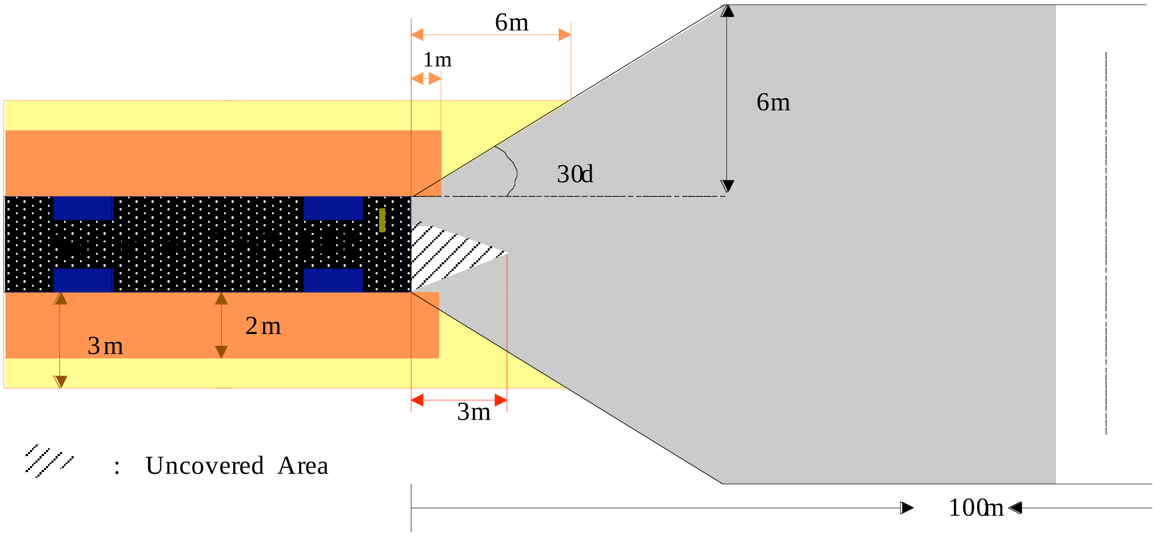

Figure 2-9 - Integrated system spatial coverage on SamTrans bus

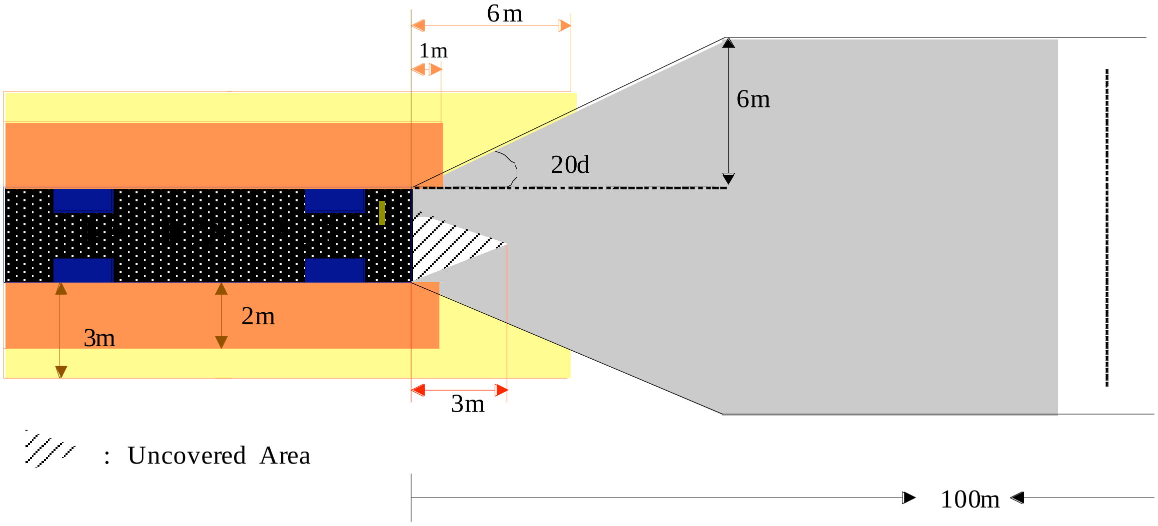

Figure 2-10 - Integrated system spatial coverage on the PAT bus

1.6. ICWS Reference Documents

The "Integrated Collision Warning System" (ICWS) project was preceded by two projects, one concerning frontal (FCWS) and the other concerning side (SCWS) collisions. This section lists the documents which were produced by these three projects. The journal articles, conference papers, etc. related to these projects are shown at the end of this document. Most of the documents are available at

http://www.ri.cmu.edu/projects/project_324.html (SCWS) and
http://www.ri.cmu.edu/projects/project_498.html (ICWS).

Side Collision Warning System:

1. "A Summary of Commercially Available Side Collision Warning Systems", AssistWare Technology, Inc., 1998
2. "A New Focus for Side Collision Warning Systems for Transit Buses", S. McNeil, *C.* Thorpe, and C. Mertz, ITS2000, Intelligent Transportation Society of America's Tenth Annual Meeting and Exposition, May, 2000.
3. "Side Collision Warning Systems for Transit Buses", C. Mertz, S. McNeil, and C. Thorpe, IV 2000, IEEE Intelligent Vehicle Symposium, October, 2000.
4. "Side Collision Warning Systems for Transit Buses: Functional Goals", D. Duggins, S. McNeil, C. Mertz, C. Thorpe, and T. Yata, Technical Report - CMU-RI-TR-01-11, Robotics Institute, Carnegie Mellon University, 2001.
5. "Facts and Data Related to Bus Collisions", Carnegie Mellon University Robotics Institute, April 2002
6. "Functional Goals", Carnegie Mellon University Robotics Institute, April 2002
7. "Assessment of Technologies", Carnegie Mellon University Robotics Institute
8. "State of the Art of Technology", Carnegie Mellon University Robotics Institute, April 2002
9. "Side Collision Warning System (SCWS) Performance Specifications", Carnegie Mellon University Robotics Institute, May 2002
10. "A Performance Specification for Transit Bus Side Collision Warning System", S. McNeil, D. Duggins, C. Mertz, A. Suppe, and C. Thorpe, ITS2002, proceedings of 9th World Congress on Intelligent Transport Systems, October, 2002
11. "Development of the Side Component of the Transit Integrated Collision Warning System", A.M. Steinfeld, D. Duggins, J. Gowdy, J. Kozar, R. MacLachlan, C. Mertz, A. Suppe, C. Thorpe, and C. Wang, IEEE Conference on Intelligent Transportation Systems (ITSC), 2004
12. "A 2D Collision Warning Framework based on a Monte Carlo Approach", C. Mertz, Proceedings of ITS America's 14th Annual Meeting and Exposition, April, 2004.
13. "Collision Warning and Sensor Data Processing in Urban Areas", C. Mertz, D. Duggins, J. Gowdy, J. Kozar, R. MacLachlan, A.M. Steinfeld, A. Suppe, C. Thorpe, and C. Wang, Proceedings of the 5th international conference on ITS telecommunications, June, 2005, pp. 73-78.

Front Collision Warning System:

1. "Preliminary Safety Analysis of Frontal Collision Avoidance", El Miloudi El Koursi, Ching-Yao Chan, Wei-Bin Zhang, 3rd IEEE International Conference on Intelligent Transportation Systems, Dearborn, MI, Oct. 1-3, 2000
2. "Develop Performance Specifications for Frontal Collision Warning System for Transit buses", Wei-Bin Zhang, et al. 7th Intelligent Transportation Systems World Congress Turin, Italy, November 6-11, 2000
3. "Integrated Multi-Sensor System: A Tool for Investigating Approaches for Transit Frontal Collision Mitigation", Xiqin Wang, Wei-Bin Zhang, Scott Johnston, Dan Empey, and Ching-Yao Chan, ITS World Congress, Sydney, Australia, 2001

4. “Functional Analysis of Frontal Collision Warning System”, M. El Koursi, E. Lemaire, Ching-Yao Chan, Wei-Bin Zhang, ITS World Congress, Sydney, Australia, 2001
5. "Studies of Accident Scenarios for Transit Bus Frontal Collisions", Ching-Yao Chan, Kun Zhou, Xi-Qin Wang and Wei-Bin Zhang, ITS America Annual Meeting, Orlando, Florida, 2001
6. "Scenario Parsing in Transit Bus Operations For Experimental Frontal Collision Warning Systems", Ching-Yao Chan, Xi-Qin Wang, Wei-Bin Zhang, IEEE Intelligent Vehicle Conference, Tokyo, Japan, 2001
7. "A new maneuvering target tracking algorithm with input estimation", Kun Zhou, Xiqin Wang, Masoyashi Tomizuka, Ching-Yao Chang, and Wei-Bin Zhang, American Control Conference, Anchorage, Alaska, 2002
8. “Development of Requirement Specifications for Transit Frontal Collision Warning System,” California PATH program, March 2002.
9. "Development of Requirement Specifications for Transit Frontal Collision Warning System", Xiqin Wang, Joanne Lins, Ching-Yao Chan, Scott Johnston, Kun Zhou, Aaron Steinfeld, Matt Hanson, Wei-Bin Zhang, PATH Technical Report, UCB-ITS-PRR-2003-29, November, 2003
10. "Development of Requirement Specifications for Transit Frontal Collision Warning System- Final Report", Xiqin Wang, Joanne Chang, Ching-Yao Chan, Scott Johnston, Kun Zhou, Aaron Steinfeld, Matt Hanson, and Wei-Bin Zhang, PATH Technical Report, UCB-ITS-PRR-2004-14, May 2004
11. "Studies of Accidents and Cost data for Transit Buses", Kun Zhou, Wei-Bin Zhang, Gary Glenn, Xiqin Wang, and Ching-Yao Chan, ITS World Congress, Nagoya, Oct. 2004

Integrated Collision Warning System:

1. “Transit Bus Integrated Collision Warning Systems Performance Specifications (Draft)”, joint publication with Carnegie Mellon University Robotics Institute and California PATH program, December 2002
2. “Integrated Collision Warning System Interface Control Document”, joint publication with Carnegie Mellon University Robotics Institute and California PATH program
3. “Integrated Collision Warning System Final Technical Report”, FTA-PA-26-7006-04.1, joint publication with Carnegie Mellon University Robotics Institute and California PATH program

2 Engineering Verification of ICWS under Controlled Environments

An ICWS needs to provide threat warnings to the driver correctly and in time. Correctly means that the system only provides warnings to the driver in situations when an object in the path of the bus could potentially cause a frontal or side collision. To achieve this, a transit ICWS system needs to be able to accurately detect obstacles, to determine their threat level and to provide warnings early enough to allow the driver to react. Nuisance warnings, which violate the driver's expectations about the necessity of the warnings, need to be minimized.

These basic principles for the design of a warning system are simple enough to state in qualitative form, but it is not straightforward to turn them into quantitative system requirements. The top-level performance requirements for a collision warning system have to be defined based on considerations of acceptability to drivers and compatibility with their driving behavior, because the driver is an essential component of the combined driver/vehicle safety system. At the same time, these requirements have to be tempered by realistic constraints based on the limitations of available components, especially sensors.

The field testing element of this project, to be described in Chapter 3, provides a good opportunity to observe the effects of the collision warning system on driver behavior and the responses of the drivers to warnings. The test-track testing under controlled conditions reported in this Chapter provides complementary information about the capabilities of the sensors and the warning system software to distinguish hazards from non-hazards. The combined results from both sets of tests improve our understanding of how to improve the performance of the collision warning system iteratively, rather than in a top-down design process driven by *a priori* system requirements. The extensive work of CAMP for passenger car collision warning systems has shown how challenging it can be to define such *a priori* requirements.

The objectives of the controlled-condition tests reported here were:

1. to understand the error characteristics of the measurements and parameter estimations based on the vehicle on-board sensors;
2. to calibrate the measurements;
3. to evaluate the ability of the ICWS to issue warnings in known hazardous conditions and avoid issuing warnings in known non-hazardous conditions.

This chapter describes the results of tests that have been conducted for multiple scenarios under controlled conditions, apart from the field tests in public service, and which have been designed to represent situations that could be encountered by a bus driven in a real urban or suburban environment. Since the ICWS is operated autonomously and warnings are completely based on real-time detection/estimation from measurement by remote sensors such as LIDAR (laser radar), three factors are crucial for the system to have good performance:

1. tracking of objects that have relative motion with respect to the bus

2. detection, estimation and prediction of the motions of the objects – their position, speed and acceleration with respect to the bus
3. short time delays associated with these processes.

The original FCWS specification [iv] mainly concentrated on system hardware characteristics, including sensors and vehicles. There was no specification of warning system functional requirements such as false negative or false positive warning rates. However, two aspects of the original specification are closely related to the quantitative testing:

1. **System operation environment**: Along bus routes on urban streets, objects such as trees, poles, traffic signs, parked cars, pedestrians, bicycles, motorcycles, and other vehicles, will be encountered. This motivated the quantitative tests to include typical representatives of those static and moving objects.

2. **Time delay**: The processing delay from system input to output should be no longer than 0.5 s (this includes the maximum 0.3 s sensor delay).

From sensor detection to warning issuance, there are several complicated processes:

> Sensor detection ➔ tracking ➔ prediction ➔ warning (threat assessment) algorithm + warning threshold ➔ warning issuance

It would be desirable to have quantitative specifications for the warning issuance such as false negative or false positive warning rates. Errors in any of the intermediate processes would affect this performance. It would be difficult to specify the error level in advance to satisfy the end requirement for the following reasons:

1. Sensor measurement limitations in precision: most sensor manufacturers specify their products under ideal situations. For example, when LIDAR and radar sensors are mounted to a solid pole on the ground, their measurement accuracy can satisfy the error specifications. However, if they are mounted on a moving bus with random vibrations and rotational movements caused by unevenness of the road, the target angles will be distorted significantly;
2. Some processes in the chain are algorithm dependent, and alternative implementations would lead to different error magnitudes;
3. Proper algorithms for tracking and filtering would reduce error magnitude, while improper algorithms would magnify one error or the other;
4. Many factors would affect the *a priori* specification of those intermediate parameters. In fact, much work would be necessary to quantitatively determine how the error bound specification of each factor in the chain would affect the end performance.

Since there is no way to specify the error bound in advance for all those intermediate parameters, the quantitative tests can identify the magnitudes of the errors without *a priori* criteria to compare to. An iterative design process is necessary to improve the end performance through the refining of each of the intermediate processes. The development and testing of the warning system in this project are part of this iterative process.

The key results of the testing under controlled conditions include the performance of the obstacle detection system's sensors, i.e., their ability to discriminate hazardous obstacles from non-hazardous ones, and the performance of the collision warning system, including the ability to generate correct warnings under staged crash situations and the rate of incorrect positive and negative warnings.

Because of the different characteristics of FCWS and SCWS, two different approaches were taken for the verification tests:

- For the frontal system, it is possible to validate the obstacle detection system with reference to ground truth and to verify the overall system performance through a limited number of scenarios that will cover most of the possible situations the system will be exposed to. Staging these scenarios and comparing the system outputs with ground truth will give the desired information.
- For the side system, there is a much greater variety of possible situations, including a greater diversity of objects and a greater variety of dynamic arrangements. It was therefore necessary to find situations that are likely to cause false warnings by first examining operational data and then staging appropriate situations.

2.1. Terminology for Warning System Processes

The process of using a transducer inside a sensor system to represent aspects of the physical environment in electronic form is ***observation***. The process of determining whether an object exists or not, is defined as ***detection.*** The process of measuring the object status, such as location and velocity, from the observations, is defined as ***estimation***. The estimated parameters are random variables, because they are calculated from observations and the observations are random samples from a probabilistic set. The results of detection and estimation are called ***measurements*** in this report. A measurement may come from single or multiple observations.

The results of detection and estimation of objects are called ***tracks*** or target tracks, and the process to initiate, manipulate and end tracks is called ***tracking***. A track is a stochastic process generated by a sensor to represent an object. Tracks from different sensors may represent the same object, but these tracks must be fused into one track in order to be useful. ***Threat assessment*** is the process whereby the current situation is projected into the future to assess the severity of a potential encounter with an object.

The detection is an internal process for sensors, which usually has some time delay. Tracking may also introduce extra data when the tracks have been built. To reduce the overall time delay from detection to warning issuance, a technique called ***prediction*** is introduced, which is based on algorithms such as Kalman filtering, which predict (in real time) the parameter(s) to be measured at the next time step. Although prediction may reduce time delay, it may also produce extra measurement errors at the same time. In this collision warning system, prediction of parameters is used for threat assessment and thus will be emphasized.

2.2. Verification and Validation of FCW System

In contrast to frontal collision warning systems designed for highway applications, a transit collision warning system needs to perform obstacle detection and threat assessment and to determine the need for warnings in complex urban environments where a significant number of targets is always present. In order to correctly detect hazardous situations and to minimize false positives, it is essential that the obstacle detection function in an FCW system accurately detects all obstacles near the vehicle path and discriminates the obstacles that may potentially cause threats to the vehicle from the ones that do not.

The FCWS obstacle detection system consists of a combination of sensing and data analysis processes. The range sensors detect various targets within their range and build numerical ‘target tracks’. The tracking process determines the consistency of the detected obstacles and selects those that are most relevant as firm tracks. Because the transit FCWS threat assessment algorithm is built upon the estimation of the distance between the target vehicle and the bus and the estimation and prediction of the velocity and acceleration of the target vehicle, it is critical to understand the characteristics of the measurements and estimations relevant to obstacle detection. The most effective way to evaluate these characteristics is to conduct a set of tests in a known environment, which involves setting up targets in predetermined locations and allowing the target vehicles and the instrumented bus to travel in a predetermined manner without disturbances. Additional sensors are used to establish ground truth measurements so that performance of the system can be quantitatively characterized.

Certain scenarios may not occur frequently enough in real world driving to adequately test how the system handles specific events, such as collisions which are very unlikely to be encountered during the limited testing period in revenue service. The controlled closed-course testing allows tests to be run using staged obstacles, which the bus can crash into without causing any problems.

The verification tests of FCWS were conducted at Crows Landing, an abandoned NASA airfield, which provided multiple straight lanes (runways) without extra disturbances. A number of test scenarios were defined to represent the majority of the urban driving environment. The tests were designed and conducted to quantitatively measure several aspects of system performance:

(1) ***Sensor measurement errors*** and ***time delays:*** The sensors that require calibration and verification include the range sensor (LIDAR in this case), speedometer and yaw rate Gyro. It is critical to understand the accuracy and time delays of the range and azimuth measurements obtained from the range sensors. Because the tracking algorithm also uses speed, yaw angle and yaw rate measurements, disturbances generated from minor yaw movements (even on straight roads) would affect the sensor detection accuracy. Such disturbances become prominent

when the bus is driven on an uneven/bumpy road. Similar to the obstacle detection sensors, vehicle status sensors also introduce measurement errors and time delays.

(2) ***Target tracking reliability and robustness***: Target missing may occur in the process of sensing, target detection or tracking. Causes of target missing may include the following: (a) the sensors themselves do not detect the target at all, which may happen to both LIDAR and radar; and (b) incorrect algorithm and/or improper threshold values may cause target missing. Even if a target track for an object is established, tracking errors may still cause nuisance and / or unnecessary warnings. For example, the target position may be miscalculated/misestimated due to measurement errors, or tracking, filtering and/or fusion algorithm problems.

(3) ***System estimation/prediction error*** and ***processing time delay:*** The quality of estimation and prediction of range, range rate, target vehicle speed and acceleration would be affected by the sensor errors and delays. Since these parameters are essential for target tracking, threat assessment and warning issuance, it is critical to understand the errors and time delays associated with these measurements.

(4) ***Warning characteristics***: The verification of warning characteristics will focus on crash scenarios in order to evaluate the performance of the warning algorithm, including the correctness of the warning and delay factors.

2.2.1 Methodology

The design of the verification tests includes defining the arrangement of static objects and planning the target vehicle and bus trajectories in a known environment. A static target may be either a parked car or a cardboard box put in known places with respect to the center of the road, which are placed to represent roadside parked vehicles, mail boxes, traffic signs, etc. To represent different objects, cardboard boxes of different sizes were chosen. In order to make them radar / LIDAR sensitive, the boxes were wrapped with reflective covering materials. Moving vehicle targets were represented by a passenger car driven along a known course in the same or opposite direction along the bus driving course, or as a lead vehicle in front of the bus.

Both the bus and the target vehicle were driven along predetermined straight paths defined in the coordinate system shown in Figure 2-1 with the origin at point **O**. For measurement consistency, each bus run always started from a known position. Based on the ground position of the targets and the running distance of the bus, one can calculate the relative position between the bus and the targets.

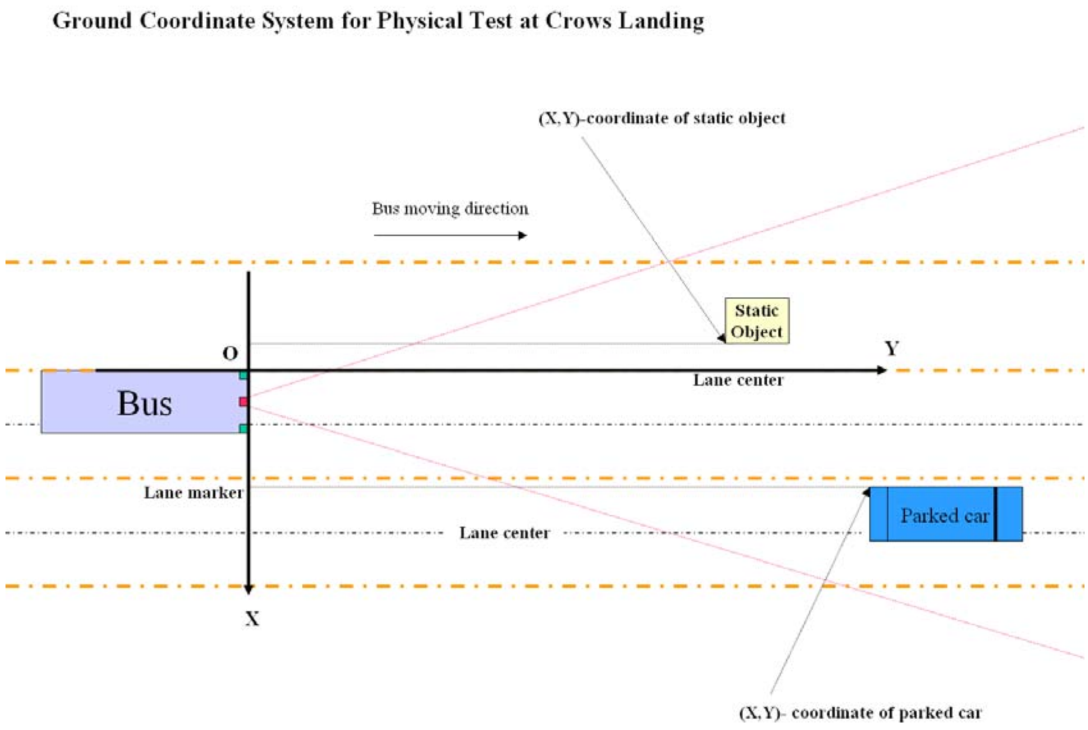

Figure 2-1 - Bus is driven along the left lane marker instead of the lane center

The test involved the SamTrans ICWS bus with the following additional instrumentation:

- A test car as a target vehicle equipped with data acquisition system and a wireless communication system
- An AMETEK Rayelco Position Transducer with a maximum range of 50 ft (string pot) installed on the rear end of the target vehicle and connected to the front bumper of the bus for measuring the distance between the bus and the target vehicle.
- A fifth wheel was mounted on the target vehicle to measure true vehicle speed and running distance, free from any tire slip and tire pressure variations
- A wireless communication system for synchronization and to pass the measurements of the target vehicle to the bus.

The true bus speed was obtained through the following process. Since the bus did not have a fifth wheel and the bus tachometer could only provide a wheel speed, several test runs were conducted at different speeds to collect data used to calibrate the wheel speed measurements. The distance traversed on each run was measured precisely and compared with the integral of the wheel speed measurements. The relative error after calibration could be as small as 0.3~0.5%.

In the discussion throughout this chapter, the true measurement means use of one of the ground truth references listed above.

Figure 2-2 shows the instrumented target vehicle and static target placements. The placement of the static obstacles and the instrumentation provide means for collecting independent and ground truth data regarding range, range rate and lateral displacement of the obstacles. This information is compared with the data collected and processed within the FCWS to independently determine the soundness of the warning signals.

(a) Two vehicles used for cut in/out

(b) Fifth wheel for target vehicle speed measurement

(c) String pot for target vehicle distance measurement

(d) Road side static objects detection test

Figure 2-2 - Photos of the test instrumentation and setups

2.2.2 Sensor Calibration and Validation

Two sets of calibration and verification tests were conducted, including a set of tests aiming at validating and calibrating the characteristics of the sensors and processing algorithms and scenario-based tests to verify the performance of the system.

2.2.2.1 Sensor Verification and Calibration Tests

The following tests were designed to validate and calibrate (a) error characteristics of inter-vehicle distance measurement, (b) error characteristics of lateral distance measurement, prediction and estimation from the obstacle detection sensor, (c) time delay associated with obstacle detection sensor, and (d) error characteristics of gyro measurement.

2.2.2.1.1 Error characteristics of inter-vehicle distance measurement

The longitudinal distance between the subject vehicle and the target vehicle, their relative speed and relative acceleration are essential for determining the threat level. The longitudinal distance is obtained from the range sensors. Some sensors can provide relative speed (range rate) as well. The relative acceleration, however, needs to be estimated based on the range and range rate measurements. In many cases, the FCWS algorithm derives predictions from these measurements in order to compensate for sensor delays. In the prototype FCWS algorithm tested under this project, an intermediate parameter *Arq* (required deceleration parameter) is used for estimating the threat level. *Arq* is closely related to, but not equivalent to, the inverse of time to collision. If the *Arq* exceeds the threshold, a warning will be issued.

Tests were designed to verify and validate the range measurements, relative speed and relative acceleration of a moving target acquired by the ranging sensor, and their prediction. In order to verify the error characteristics of the sensor measurements and predictions based on them, independent measurements were collected using a string pot connected between the rear end of the target vehicle and the bus, a fifth wheel mounted on the target vehicle and wireless communication transceivers installed on both target vehicle and the bus. In order to minimize interference for target track processing, no other targets were placed in the field of view of the sensors. There is no accelerometer on either the bus or the target vehicle. The true acceleration of the forward target vehicle is obtained using a fifth wheel and through linear filtering and numerical differentiation of the fifth wheel speed measurements. Acceleration of the bus is obtained using similar processing of the calibrated wheel speed measurements on the bus. Based on the difference between those two measurements, the “true” relative acceleration is obtained, which is used to compare with the prediction using the tracking algorithm.

The tests were conducted with the bus following the target vehicle along a straight path defined by reference lines. The target vehicle accelerated to predetermined speeds (5 mph, 10 mph, 15 mph, 20 mph) for a short duration and then decelerated at approximately 0.2 m/s^2, 0.5 m/s^2, or 0.8 m/s^2. Because the total length of the string was 16 m, the tests were conducted to limit the range variations within 6.4 m in order to avoid breakage. Figure 2-3 depicts the configuration of this set of tests.

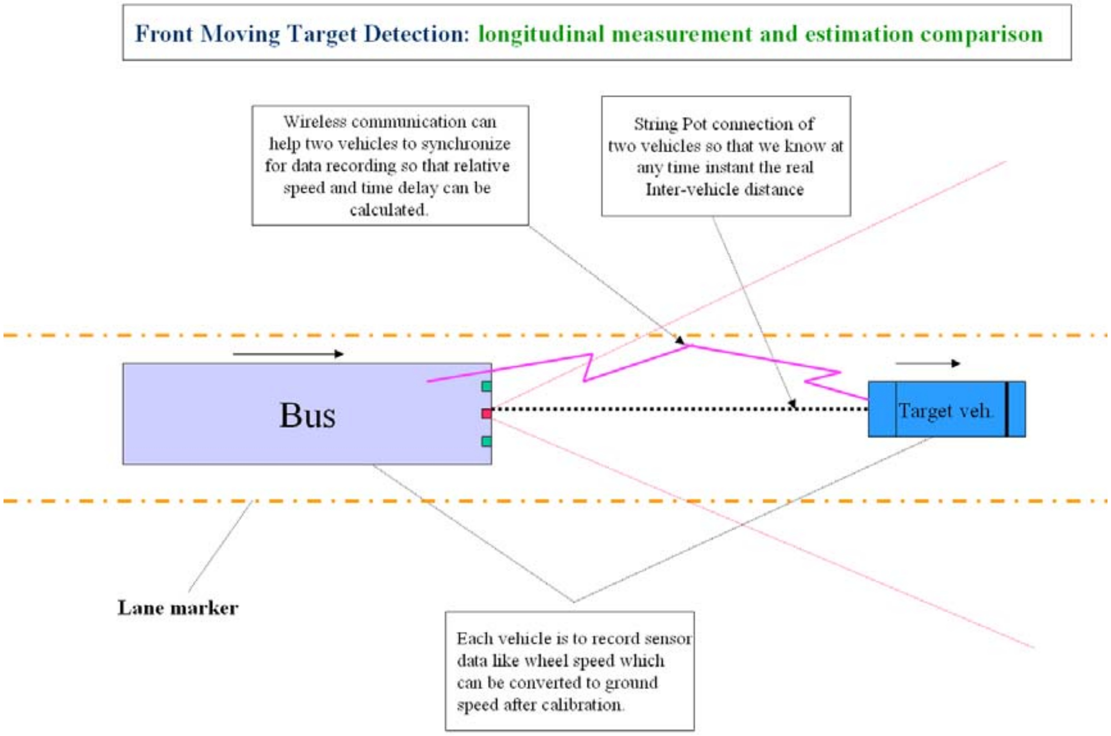

Figure 2-3 - Tests for longitudinal measurements wrt a frontal moving target

Data analysis is shown in Table 2-1, with results based on test data shown in the Appendix B, Figure B-1 - Figure B-3.

Table 2-1 - Measured errors in forward target vehicle prediction

Parameter	Prediction Errors
Longitudinal distance	Directly used the measurement; No prediction.
Longitudinal relative speed	8%
Longitudinal relative acceleration (RMS)	0.2280 m/s^2

The time points for speed error calculation were selected at t = 25, 50, 75, 100, and 125 seconds of the data in Figure B-1 - Figure B-3**.** Relative speed error was calculated at each of these points and then averaged. Here the Root Mean Square (RMS) value was used for acceleration error calculations, while relative error was used for speed. The acceleration error calculation has been averaged over the whole time interval (Figure B-4).

The test results are compared with the preliminary specifications defined for the FCWS system by this project team in the previous phase of the project.[v] The preliminary specifications specified the closest and farthest detectable range in the same lane to be greater than 3 m (10 ft) and less than 100 m (330 ft) respectively, with a resolution to be finer than 1 m (3.3 ft). The test results show that the LIDAR can effectively detect objects between 0.5 ~ 120 m, which therefore satisfies this specification. The preliminary specifications also specified the relative speed or range rate measurements to be valid from -44 m/s (-100 mph, approaching) to +20 m/s (+45 mph, separating). The test results show that the LIDAR can satisfy these requirements as well. Note that the preliminary specifications did not specify the absolute accuracy of the parameters. Since inaccurate measurements would cause false detections, which in turn would result in false positive warnings or false negative detections, the acceptable levels of false positives and false negatives will determine the sensor and processing requirements. Therefore, extensive field operational tests need to be conducted to first determine the system level performance requirements and then the requirements on the acceptable level of error tolerance for the sensor measurements.

2.2.2.1.2 Error characteristics of lateral distance measurement, prediction and estimation from the obstacle detection sensor

Roadside parked cars can create challenges for transit FCWS. It is necessary to understand how well the forward obstacle detection sensors detect a static side target along the roadside and distinguish it from those in the path of the bus. In most cases, the static side targets are not hazardous. In less frequent cases, side targets may present hazards when a car door is opened or a car begins to move out of a parking space. In order to determine if a side target is potentially hazardous to the bus, it is necessary to have accurate knowledge of the target lateral distance from the bus. The lateral distance is derived from an azimuth angle measurement by the forward ranging sensor.

In order to verify lateral distance measurements, static targets were placed along the vehicle path. Two parked cars and a box were staged on the right hand side and left hand side at predetermined distances with respect to the center of the bus path, as shown in Figure 2-4 and Figure 2-5. The bus was driven straight ahead at speeds of 5 mph, 15 mph, 27 mph, 30 mph and 35 mph. The left door of a car parked on the RHS was opened occasionally (Figure 2-5). The open car door detection scenario was included among the tests based on feedback from bus drivers. They considered that the suddenly opened door of a roadside parked car was a real threat to the bus and should be detected if possible. Our experience shows that this is extremely difficult to achieve using current sensors.

Side static target distance measure relative error is calculated as in Table 2-2 based on data corresponding to Figure B-22: The distance of the closest target edge line in the ground coordinate with respect to the Y axis (Figure 2-3) is 3.0 m.

Table 2-2 - Static Object Lateral Position Prediction Error in Azimuth Angle

Data Source	Average Prediction Error	Note
Azimuth Error in Figure B-22	0.025 rad (1.17 deg)	Averaged at time points t=161, 162, 163, 164, 165; The object is placed 3 m from the center of the bus path
Azimuth Error in Figure B-23	0.0163 rad (0.93 deg)	Averaged at time points: t=156.4,156.8,157.2,157.6,158.0;

The calculation of the parameters is based on several randomly selected time points as noted in the table. Data analysis showed that the azimuth error is sufficient small for identifying targets within the vehicle path. This error may still be larger than desired for estimating the lateral position of roadside targets that are located at the boundary of the vehicle path. The test results show that the LIDAR sensor has difficulties to distinguish the door opening situation for vehicles parked immediately near the path of the bus. This could be attributed to the yaw motion and vibration of the subject vehicle (the bus) and the azimuth resolution of the LIDAR, which was designed for a less demanding application. Future improvements could be investigated by using a video camera to assist the radar or LIDAR to detect the target. A video sensor could potentially provide better knowledge of the target location relative to the vehicle path. Although video cameras may also be subject to disturbances, fusion of the vision and LIDAR/radar could help to achieve robust performance.

The preliminary requirements developed under the previous phase of the project specified that the maximum detectable side-looking angle from the front bus corners should be at least 30 degrees and the maximum lateral position should be at least 6 m (20 ft). The LIDAR tested satisfies these requirements. However, the accuracy requirements were not yet given in the previous phase. Because urban operating conditions are complex, it is recommended that further quantitative tests be conducted under a variety of conditions in order to determine the correlation between the accuracy requirements for azimuth angle or lateral position measurements and the overall system performance.

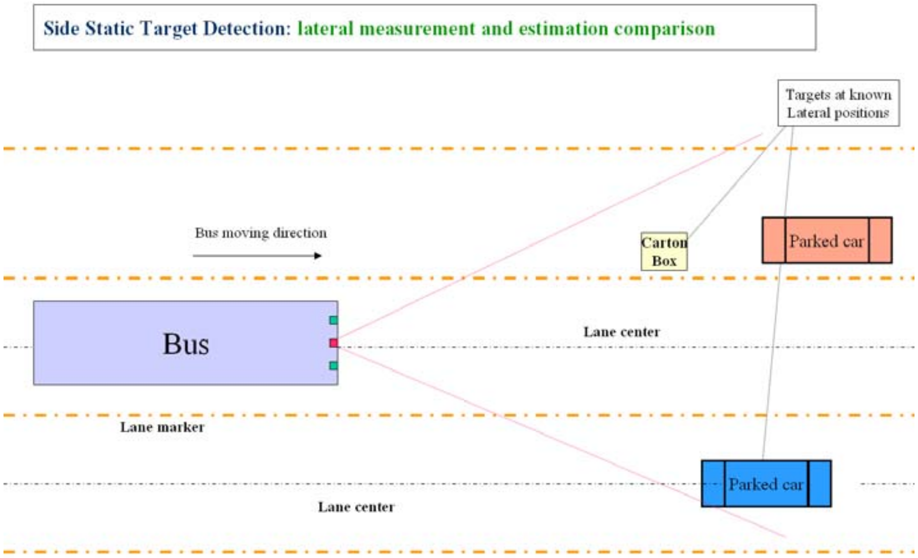

Figure 2-4 - Parked cars on both sides, with all car doors closed

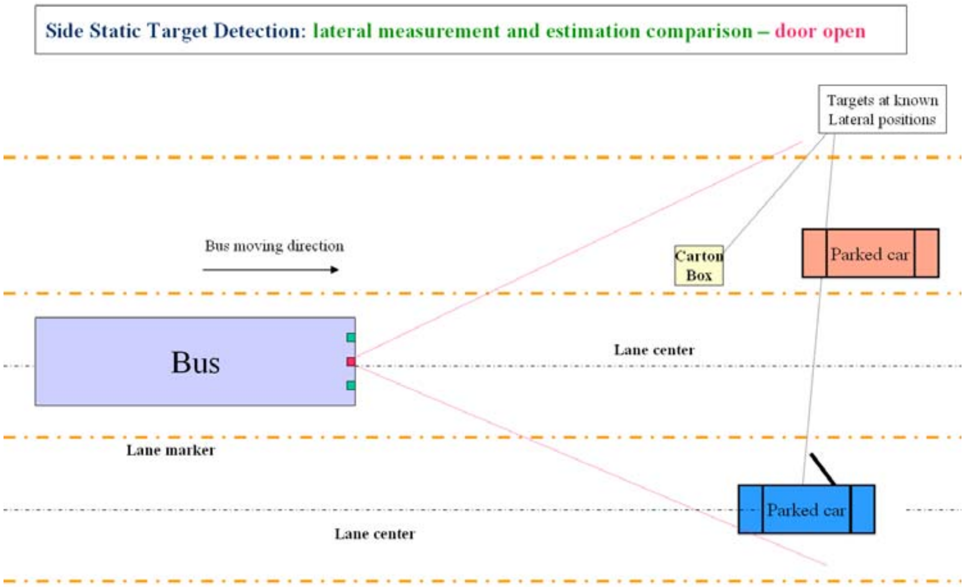

Figure 2-5 - Parked cars on both sides, with one door open

2.2.2.1.3 Verification Test of Time Delay Associated with Obstacle Detection Sensors

Time delays exist in a variety of processes, including sensor detection, prediction, tracking and warning generation. Delays for sensor detection are mainly contributed by the physical properties of the sensor detection principle and the front end processing algorithm, which is specific to sensor design. Additional time delays can be generated through target parameter prediction and can be FCW algorithm dependent. These time delays can introduce difficulties for threat assessment

This verification test is to quantify time delays associated with the sensor and the processing of the target tracking algorithm. The target vehicle was driven with sinusoidal speed variations, with maximum speeds of 10 mph, 15 mph, and 20 mph. The frequency of the sine wave was between 0.1 ~ 0.5 Hz and the magnitude of the variation was as large as 40% of the maximum speed. The sinusoidal speed profile would not be encountered directly in normal urban driving, but this scenario was chosen based on the following considerations:

- Urban bus driving typically involves many alternations between accelerator and brake pedals. The sinusoidal speed profile is an approximation to these speed variations;
- It was hoped that, by using a sinusoidal speed profile, the maximum and minimum speed points could be identified in order to measure the phase shift between true speed trajectory and predicted speed trajectory. Such a phase shift would be a strong indication of time delay.
- The following cases are easy for prediction: constant speed (zero acceleration) and constant acceleration / deceleration, which are impossible to achieve in practice. The challenging cases, which need to be tested, are variable accelerations.

The bus followed the target vehicle at a reasonable distance, with a variation within the range of the string pot. The time delays were to be identified from the phase shift between recorded (from on-vehicle sensor), detected (raw data), estimated and predicted distance/speed/acceleration. Due to the difficulty of using other analytical methods for data analysis, some representative points are selected for peak and valley points as well as points on up/down slopes. It is expected that those selected points can represent most speed change situations.

In the data analysis as shown in Appendix B, overall time delay is composed of two parts: sensor internal measurement delay and target parameter prediction delay. The results are shown in Table 2-3.

Table 2-3 - Time Delay Analysis for Overall System

	Sensor internal measurement delay	**Signal processing delay**	**Combined delay, average**	**Combined delay, Standard Deviation**
Prediction	0.5 s	0.5 s	1.0 s	0.17 s

It should be noted that the results about delays shown in Table 2-3 may involve observation errors. The initial test plan called for the bus to be operated in such a way that the distance between the bus and the target vehicle would follow a sinusoidal profile. The bus ranging sensor response time delays would be quantified by the phase shift of the

LIDAR sensor outputs with respect to the driver input “truth” measurements from the string pot. The difficulty, however, is that the bus driver cannot adjust the distance between the bus and the target vehicle to precisely follow a sinusoidal profile. Instead of analyzing the phase shift of the sensor output, the time delay is achieved by manually selecting comparable time points and calculating the delay values at the selected points. This selection may not be objective and can create observation errors. Nevertheless, the measurement magnitude of the delay is still very significant, enough to degrade the performance of the collision warning system.

In the initial FCWS specification stage, the analysis recommended that the sensor delay not exceed 0.3 seconds and the overall processing delay not exceed 0.5 seconds. Table 2-3 shows that that the tested prototype system cannot meet these requirements, in part because the sensor front-end internal processing delay is about 0.5 seconds instead of 0.3 seconds. The additional 0.5 second delay is likely attributed to the following signal processing processes. The first time period is from the instant of receiving sensor data to processing, which is determined by the sensor system update rate. The FCWS sensors have an update interval of 0.075 seconds. The tracking process takes 3 samples to build the firm track, which resulted in a 0.225 second delay. Additional procedures such as transformation to ground coordinates and transformations back also take additional time. The processing delays may be attributed to the prediction method, which may produce some over-shoots when the target accelerates or decelerates. Recovery from the over-shoots can cause additional time delays and errors.

Although the sensor delay is large and the crash tests in the controlled environment (described in 2.2.3.1) showed that the prototype system would not be effective for hazards that involve stationary obstacles and a very short detection time, the field testing data revealed that the FCWS was still effective at warning drivers in most cases. This is because the transit drivers are trained to drive at large time gaps. Warnings, though later than desired, can still be received by drivers and reacted upon. In practice, there will be inherent delays regardless of what type of sensor or warning system is used. The extent to which drivers can tolerant warning delays in the urban driving environment needs to be further studied through serious human factors studies. Furthermore, alternative designs of sensing and signal processing approaches can reduce this delay. Examples of these approaches include implementing the tracking processing directly from raw data from the sensor front end and/or sensor fusion using sensors that can provide additional lane and target information. However, the unavailability of sensor front end data and project resource limitations did not allow the project team to investigate these approaches.

2.2.2.1.4 Error characteristics of yaw angle measurements

Steering angle measurements are used in conjunction with obstacle detection and lane detection to determine whether forward obstacles are within the vehicle path and if they pose any threat. Steering angle measurements can be achieved through a number of means, including direct measurements of ground wheel angle using displacement sensors, measurement of steering wheel angle using a potentiometer, or through indirect estimation using a gyroscope. The earlier prototype system developed under the FCWS project used a ground wheel displacement sensor. Tests showed that the ground wheel sensing can achieve a high degree of accuracy when it is well calibrated. However, due to its contact nature, the displacement sensor is very easy to be out of calibration or malfunction, therefore a non-contact method was selected for the prototype system tested under the ICWS project. The gyro readings provide the yaw rate of the bus, and the yaw angle is obtained by integrating the yaw rate,

The evaluation tests focused on the error characteristics of the gyroscope, which is typically presented in the form of accumulated error. To test the error accumulation, the bus was driven in irregular circles as shown in Figure 2-6 and finished each run by returning to its initial parked position. Physically, the bus had turned 720 degrees with respect to the original position and returned to its starting position. Through the circular driving, the accumulated errors were obtained and potential errors from other sources were cancelled. The tests were conducted at maximum speeds of 5 mph and 15 mph. The data analysis in Appendix B shows that after the bus completed a 720 degree turn, the error in the accumulated gyro yaw angle estimation was within 0.1% (Figure B-17 and Figure B-18) compared to the known accumulated angle change of 720 degrees.

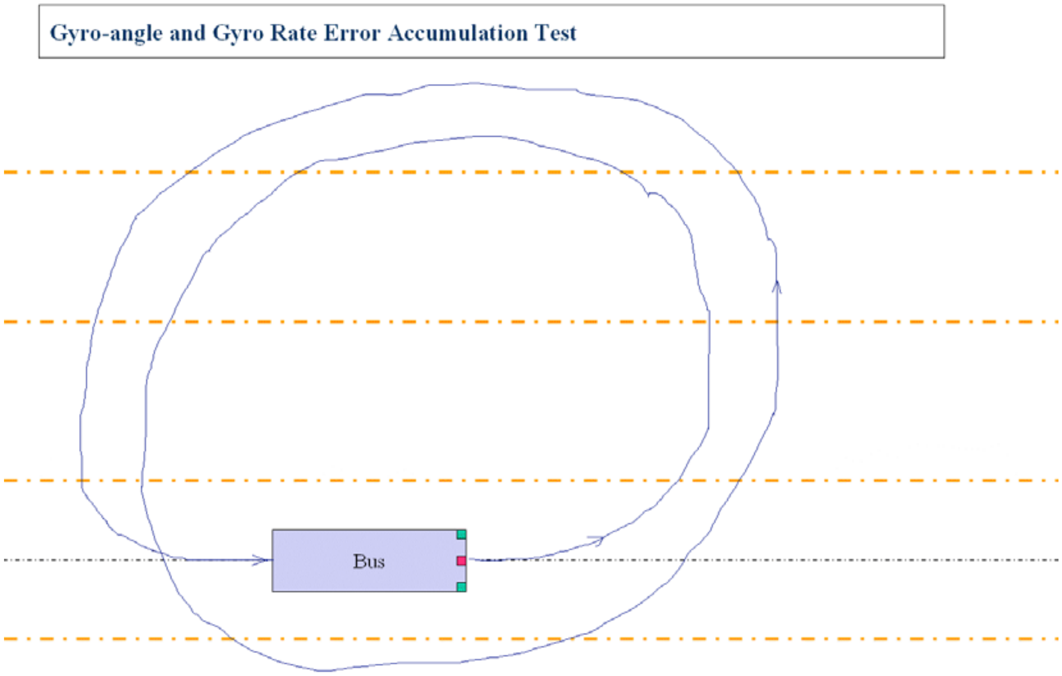

Figure 2-6 - Verification of Gyro yaw rate accumulation error test

In the initial transit FCWS specifications, we defined that the measurement range of the front wheel angle should be at least 50 degrees to both right and left, though it is preferable if all possible front wheel angles are covered. The yaw rate $\dot{\theta}_b$ of the bus should be known to within +/- 1 deg/sec.

The test results show that the gyroscope can provide yaw rate measurements with a resolution of less than +/- 1 deg/sec and it can support accurate estimation of the steering angle beyond the specified range. Tests show that the gyro yaw angle measurement is adequate for supporting the intended target identification purpose. Furthermore, the results obtained from this verification test provide a basis for the refinement of the requirement specifications.

2.2.3 System Testing Under Controlled Environment Scenarios

The scenario-based tests were performed to verify the performance of the FCWS in several scenarios that are typical of urban bus driving conditions. Several basic scenarios were identified, including: (a) vehicle following with static target (such as parked car) in adjacent lane, (b) moving target in adjacent lane, (c) target vehicle cut-in and cut-out movements, and (d) low speed approaching/crashing to a static object.

2.2.3.1 Vehicle following

Vehicle following, as represented in Figure 2-7 is one of the primary scenarios in bus operation. Assessment of the threat posed by a forward moving target vehicle is mainly determined by the relative distance, relative speed, and in some algorithms, relative acceleration of the two vehicles. The accuracy of the estimation and prediction of these parameters is essential. The vehicle following test is designed to focus on the evaluation of dynamic measurement, estimation and prediction of the lateral position of the target vehicle and side static targets and longitudinal relative distance, speed and acceleration between the host vehicle and the target vehicles and side static targets.

The setup involves a target vehicle equipped with fifth wheel, wireless communication between the host bus and target vehicle, and static targets located to the left and right of the vehicle path. Because the string pot was not connected, the bus could operate at much higher speeds, with higher relative speed and larger variations. During the tests, the target vehicle ran at constant speeds of 5 mph, 10 mph, 27 mph, 40 mph, or 50 mph. It was up to the bus driver to determine a safe and comfortable inter-vehicle distance compatible with vehicle speed and relative speed. The moving target vehicle accelerated or decelerated at rates of 0.2, 0.8, or 1.5 m/s^2. The maximum relative speed recorded was 4.6 m/s or approximately 10 mph.

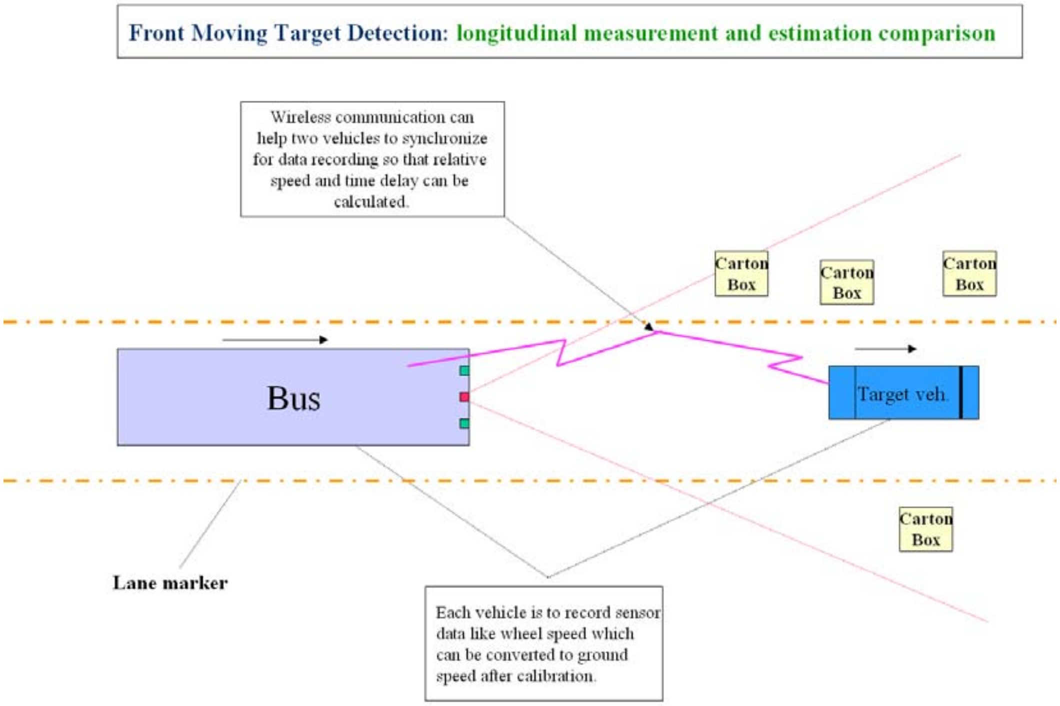

Figure 2-7 - Vehicle following, without use of string pot

Table 2-4 showed the average prediction error for side static target converted into azimuth based on LIDAR measurement of Figure 2.17 – Figure 2.22 in the appendix. It is noted that, unlike the front moving target, tracking for side static target only lasted for a shorter period of time. This might be due to the relatively small size of boxes used as target: a small target at longer distance is more difficult for LIDAR and radar to detect.

Table 2-4 - **Measured errors in forward target lateral estimation**

Parameter	Average prediction error	Standard deviation	Maximum error
Lateral Azimuth Error (RMS)	0.107 rad (6.09 deg)	0.168 rad (6.96 deg)	0.305 rad (17.7 deg)

Table 2-5 shows the errors in the measurements of the relative speed of the frontal moving target vehicle, which is calculated based on the data shown in Figure B-19 and Figure B-20.

Table 2-5 - Measured errors in forward target vehicle estimation

Parameter	Average prediction error	Note
Longitudinal relative speed	11.3 %	The calculation is derived from the integration of the relative speed error over the time interval and averaged over time on the interval.

The calculation of the average prediction error is derived from the integration of the relative speed error and averaged over time for the selected data set. The test results show that the tracking, estimation and prediction algorithms can correctly track all the moving and static obstacles within a reasonable range. Note that there is always a trade-off between the prediction error and time delay. The prediction is intended to reduce time delay but could also induce additional errors, particularly in situations when relative speed varies. The results show that the estimation and prediction errors for longitudinal relative distance, relative speed and relative acceleration are of similar magnitude to those of the measurements obtained from the sensor verification testing. The errors in these measurement predictions may directly affect the correctness and timeliness of the warning issuance. However, it is not possible to draw quantitative conclusions about the impact of the prediction errors on the overall system performance with the limited set of testing conducted under this project. Further tests and data analysis will be necessary. Meanwhile, future improvements of measurement accuracy, delay characteristics and robust warning algorithms will be needed. Recommendations from the project team include adaptation of sensors that can require shorter track acquisition time or direct range rate measurement sensors (such as Doppler radars) and sensor fusion.

2.2.3.2 Detection of moving target in adjacent lane

Moving targets in adjacent lanes are another main cause of false positives, particularly if the moving vehicle is too close to the bus. It is necessary to understand how well the obstacle detection sensors and tracking algorithm can distinguish and properly track moving targets in the adjacent lanes in the field of view of the obstacle detection sensors. Data analysis was focused on detection, estimation, and prediction of range, relative speed, relative acceleration and lateral offset of the target vehicle.

In this scenario, a target car was running in the left lane adjacent to the bus path at a fixed lateral distance. Tests were conducted with the car traveling in the same and opposite directions as the bus traveled, with no other obstacles along the bus path. The maximum speeds of the car for test runs were 10 mph and 30 mph. The bus ran at approximately the same speed as the car, but with slight speed variations (non-constant) so that there was moderate relative movement between the two vehicles (Figure 2-8 shows the test setup).

Table 2-6 - Parameter estimation for moving target in adjacent lane

Parameter	Prediction error	Explanation
Average azimuth angle error	6.7 %	Time points chosen are: t = 36, 40, 44, 48, 52 s

The calculation in Table 2-6 is based on the data corresponding to Figure B-26 in Appendix B. Note that the error is measured with respect to the center of the target vehicle. Also noted is the fact that the LIDAR used for the prototype system can directly provide lateral position of the target. However, we used azimuth angle instead of lateral position for evaluation because the magnitude of error for lateral measurement is proportional to the distance of the bus to the target because the sensor measurements are based on detecting azimuth angle. The azimuth errors are calculated using the lateral and longitudinal measurements at five time points, which are then averaged.

Target lateral distance is used to discriminate detected non-hazardous objects from hazardous ones. Under the tested condition, the obstacle detection can correctly recognize the front target. The error characteristics obtained from this set of tests also suggest that, when a forward obstacle is placed very close to the vehicle path and is combined with slight road curvature, it is easy for the obstacle detection algorithm to misjudge the location of the obstacle at a distance.

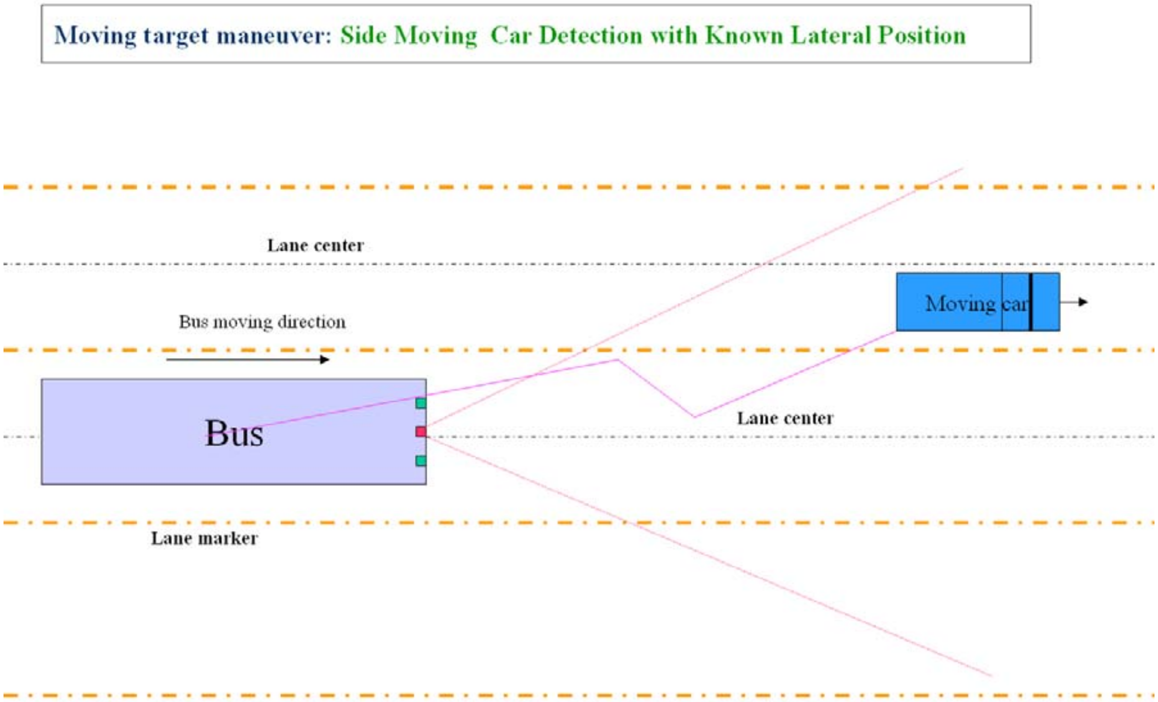

Figure 2-8 - Moving target vehicle in adjacent lane

2.2.3.3 Target vehicle cut-in and cut-out movements

Cars cutting in and out in front of a bus is a very common maneuver encountered in urban and suburban operation. A cut-in vehicle suddenly decelerating may potentially cause a threat to the bus. It is thus necessary to test if the obstacle detection sensor and tracking algorithm are capable of detecting and properly tracking the cut-in target. From an algorithm point of view, quickly building a target track for the cut-in vehicle, estimating its relative distance, speed and acceleration, and ending the tracking when it cuts out (leaving the field of view of the sensor) are critical for enabling correct threat assessment and warning.

The cutting-in test involved a target vehicle driven in an adjacent lane in the same direction as the bus at a known lateral distance, at speeds of 10 mph, 20 mph, and 35 mph for a short period of time before accelerating to overtake the bus. Figure 2-9 shows the test scenario. The target vehicle then moves out of the bus path as shown in Figure 2-10. The speed of the target vehicle varied, and the bus driver had to decide the appropriate inter-vehicle distance for car following. The test was set up to evaluate whether tracking can be established as soon as the target vehicle cut in, if tracking continues while the target vehicle is lane changing on both sides, and whether the tracking ends at an appropriate time.

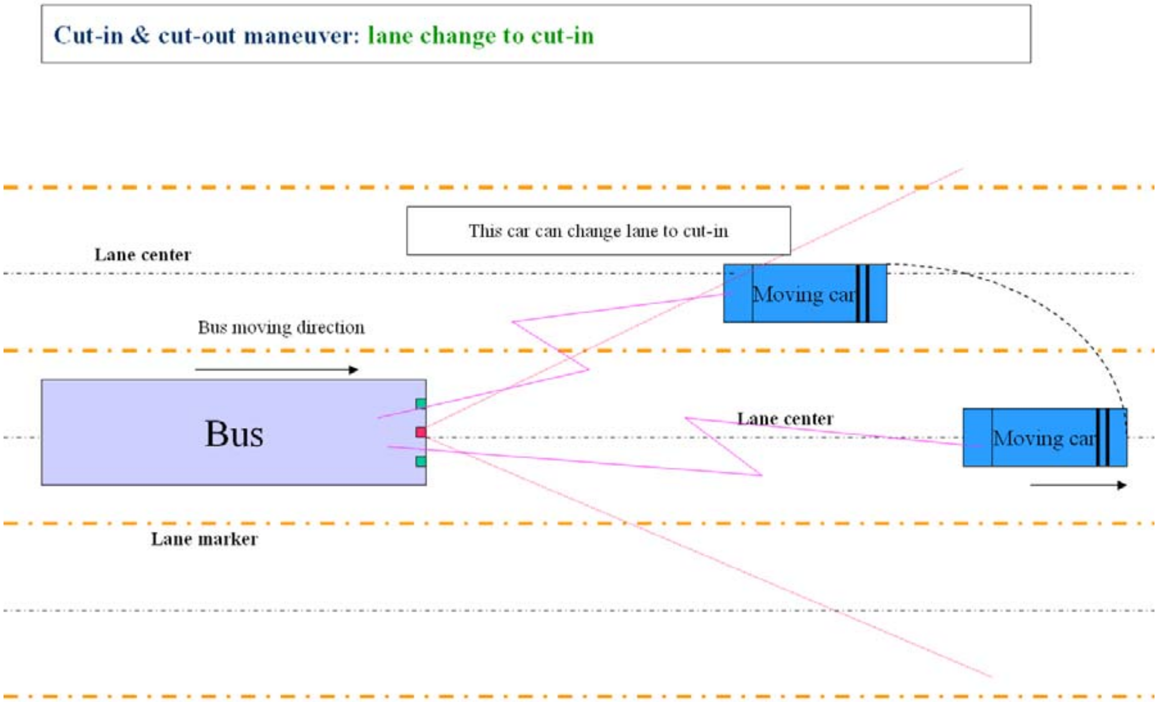

Figure 2-9 - Cut-in to test lateral movement detection

The detection of cut-in and cut-out maneuvers involves detection of vehicles in adjacent lanes (left/right), keeping a tracking record of those vehicles, and measuring and predicting their behavior based on previous and current information. Data analysis in the Appendix shows that track building starts when the inter-vehicle distance is about 5 m, while the target vehicle is still completely in the left lane early in the cut-in maneuver. The target track is dropped at about 7 m inter-vehicle distance after the target vehicle has completely moved out to the right lane for the cut-out maneuver. This detection is quite effective, fully tracking the cut-in and cut-out motions of the target vehicle. This is consistent with the LIDAR lateral measurement characteristics in the results obtained from the testing described in the sensor verification section.

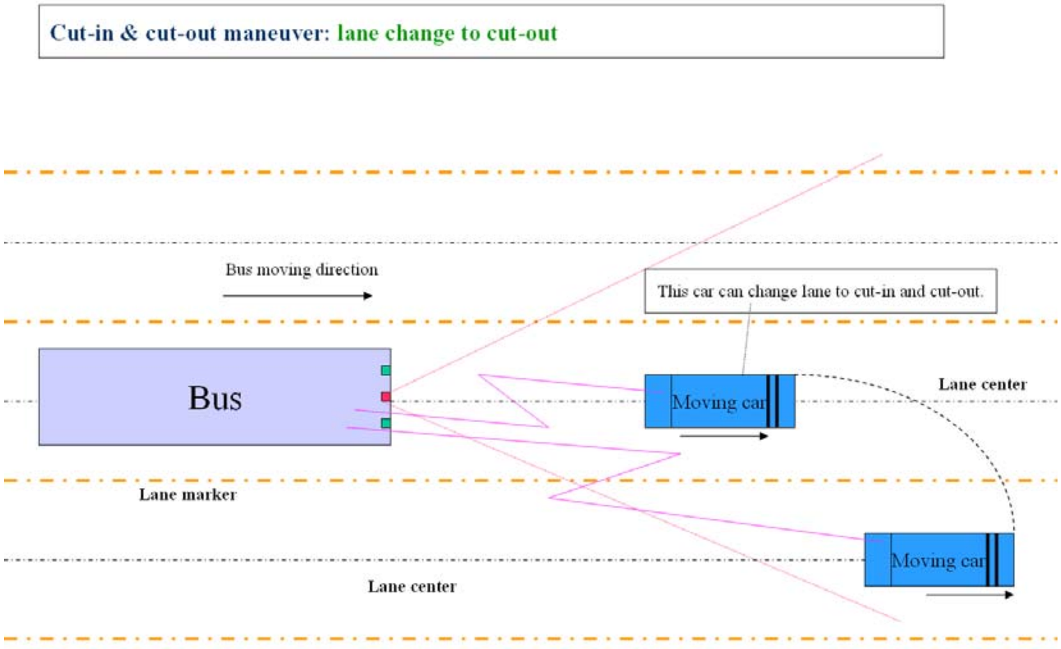

Figure 2-10 - Cut-out to test lateral movement detection

In order to discriminate non-hazardous vehicles from hazardous vehicles, it is necessary to have reasonably good lateral position or azimuth measurements and predictions. The test results show that the LIDAR sensor and obstacle detection algorithm are adequate for tracking the behavior of lane changing vehicles in adjacent lanes. The system is able to build up a tracking record when the vehicle is in the field of view of the sensor and to keep a record of the movement of the detected vehicle until it disappears from the field of view.

2.2.3.4 Low speed approaching/crashing to a static object

Crashes are rare events and the likelihood of capturing crashes in the field testing is very small. Therefore, a low speed crash testing scenario was created on the test track in order to understand the effectiveness of sensor detection and estimation, threat assessment and warning generation of the prototype FCWS as the bus approached a static object and crashed into it.

In order to perform the crash tests, a cardboard box (covered with foam blocks to avoid any damage to the bus) with radar reflectors was put in the middle of the bus driving course. Three additional boxes were placed left and right of the bus path as static targets. The bus approached the objects at speeds of 15 mph and 5 mph to test the reactions of the warning system (Figure 2-11).

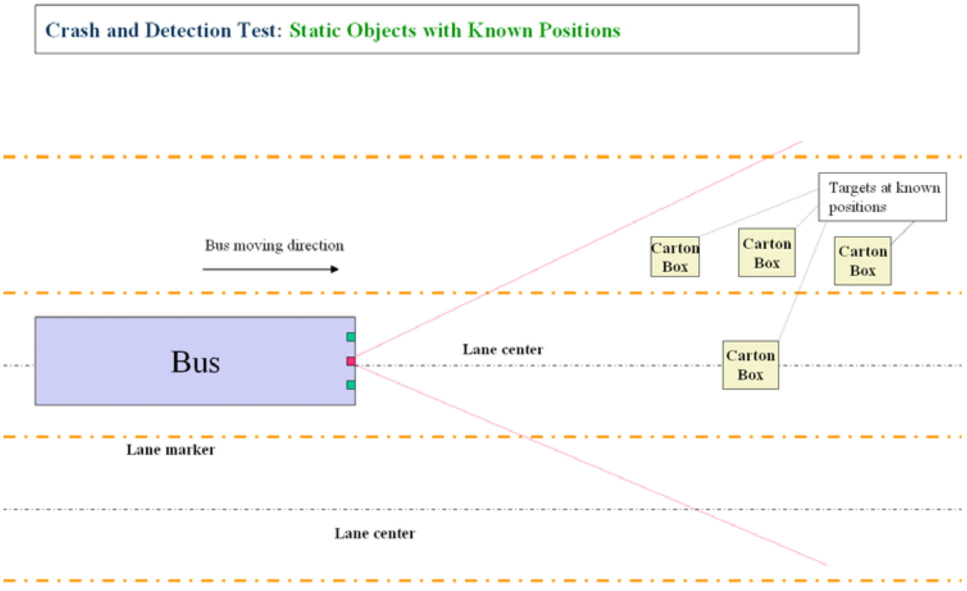

Figure 2-11 - Low Speed Crash Test

Test results showed that the tracking algorithm was able to effectively distinguish the target as the bus approached the stationary target for the in-path crash scenario. Consequently, the threat assessment algorithm generated consistent warning signals to the driver slightly earlier than 1 second prior to the bus crashing into the obstacle.

Design requirements for FCWS were provided by this research team under the previous phase FCWS work, recommending that it will be necessary for a transit bus FCWS to induce a driver response no slower than under normal conditions. No thorough study on bus driver response time to collision warning systems can be found from the literature. However, it is evident that the 1+ second warning time prior to collision does not provide the driver with adequate reaction time to avoid the crash. There are at least three possible explanations of the lateness for the warning. One obvious reason for a portion of the delay is the interruption of obstacle detection. As seen in Figure B-28, signal dropout from the LIDAR measurement occurred at 3.5 seconds to 2.5 seconds prior to the crash. This dropout impaired the threat assessment ability of the system for more than one second. Additional delays were contributed by the delays involved in the obstacle detection, as discussed in Section 3.2.2.1.3. Furthermore, since collision with a stationary obstacle has not been considered as a high probability crash scenario that the FCWS must deal with, the selected threat assessment algorithm is more heavily weighted on relative acceleration than on the closing rate. Consequently, the warning algorithm is less responsive to the tested scenario (i.e., constant speed toward a stationary obstacle until the hazardous condition becomes imminent). We decided not to adjust or alter the warning algorithm because the evaluation testing was conducted in the middle of the field testing in revenue service. The purpose of the testing under controlled environment was intended to establish a baseline for data analysis of field test data. Changes to the warning algorithm at this mid-project stage would have made the data collected in the controlled environment invalid for the original intended purpose.

The testing of crash scenarios does provide valuable information for future improvements of the detection and warning algorithms. While a specific maximum delay threshold value remains to be defined through additional tests, it is generally believed that even small savings in response time can be considered beneficial, as they will help reduce the probability of a crash. In the event of an unavoidable crash, small improvements in response time will reduce the severity because the speed of the bus will likely be lower.

2.2.4 Evaluation of FCWS Test Results

The tests reported in this section were intended to verify and validate sensor and system performance in a controlled environment in order to represent some typical operation environments for urban driving. These tests made use of calibrated independent measurement instrumentation such as a fifth wheel for speed measurement and linear potentiometer for distance measurement and with static and moving targets staged at known locations in front of the bus within and along the vehicle path Two categories of tests were conducted, including: 1) sensor verification/validation tests and 2) scenario related tests. The sensor tests verified sensor detection capabilities (including range sensor and gyroscope), measurement prediction accuracy and time delays. The scenario tests involved four basic scenarios that could be encountered in urban transit operations, including the bus following another vehicle, a moving vehicle in adjacent lanes, a vehicle in an adjacent lane cutting-in and a vehicle in the bus' path cutting-out, and low speed crashing into a static obstacle.

1. The test results from the sensor validation and verification tests showed the strengths and limitations of the sensor and signal processing elements of the prototype FCWS and have provided useful information to indicate directions for future improvements. Table 2-7 summarizes the results of all the sensor validation tests. The results show that the sensing and tracking algorithm can correctly detect moving and stationary obstacles under most of the test conditions. However, improvements are needed in the following areas:

    - The accuracy of azimuth angle measurements may not be sufficient to support reliable and consistent discrimination of targets within the vehicle's path from the ones that are close but not in the vehicle's path, particularly when targets are far from the bus. This finding is consistent with the lessons learned through tests conducted under the ACAS project[vi].

    - Delays associated with LIDAR/radar processing may affect the system performance the most. Parameter prediction has been introduced to efficiently reduce some time delays in estimation; however, there is a tradeoff between prediction error and reducing time delay. Prediction could reduce time delay but might potentially increase estimation error and thus produce high warning threshold values, which lead to more false or nuisance warnings.

- It is recommended that sensor fusion involving range/range rate sensors and vision sensors be incorporated in order to better discriminate hazardous obstacles from non-hazardous ones and more advanced filtering and processing to reduce sensor delays

2. The results of the scenario-based tests showed that, despite the errors and delays in the sensing system, the prototype FCWS has multiple target tracking capabilities and its tracking and warning algorithms can support effective warning issuance under most of the tested conditions. In general, track building was consistent and the tracking continuation was reasonably persistent. Consistency of target track formation (initialization) and continuation were comparable for both longitudinal and lateral distances. Assessment of the threat posed by a forward moving target vehicle is mainly determined by the relative distance, relative speed, and in some algorithms, relative acceleration of the two vehicles. Therefore, the accuracy of the estimation and prediction of these parameters is essential.

   Test results show that measurement predictions can produce satisfactory results for vehicle following scenarios. Adjacent lane vehicle cut-ins and cut-outs were detected and tracked successfully. However, the lateral position or equivalently the azimuth angle of the target vehicle still has large errors that could cause false warnings. Preliminary results showed that threat assessment and warning generation can provide consistent warning signals to the driver for static forward targets. However, the crash tests involving static obstacle show that, although warnings can be correctly issued, significant delays in the warning signals may not give drivers adequate time to respond to this hazardous situations.

It is recommended that the threat assessment and warning algorithms be fine tuned to allow better tolerance of inherent measurement errors and delays that can not be overcome due to technical constraints posed by sensors and the operating environment.

Table 2-7 - Target Detection/Estimation/Prediction Characteristics Including Accuracy

Target type or test case	Parameter & error type	Average error μ	Standard Deviation	Maximum Error
Front moving target	longitudinal acceleration prediction (RMS)	0.228 m/s^2	0.265 m/s^2	1.75 m/s^2
Front moving target	longitudinal relative speed prediction	0.080 m/s	0.137 m/s	1.25 m/s
Adjacent lane Moving target	azimuth angle for side target prediction	0.067 rad (3.83 deg)	0.0125 rad (0.72 deg)	0.082 rad (4.7 deg)
Static target	azimuth angle for side target prediction	0.0184 rad (1.05 deg)	0.0138 rad (0.79 deg)	0.056 rad (3.22 deg)
Static target	longitudinal relative distance prediction	1.2 m	0.8 m	
Accumulated yaw angle	Gyro angle from rate; Accumulated error over 4π radian motion	0.774 degree	0.057 degree	1.1 degree

2.3. Verification and Validation of SCW System

The SCWS consists of many parts. The sensors send their raw data to analysis modules, which determine physical quantities like speed and position, and these data are combined to create warnings for the bus driver. Each part of the system needs to be calibrated and tested. In this section we describe the calibration and test procedures and report the quality of the output of each part, such as measurement errors of the sensors or false warning rates of the full system.

Some of the calibration and testing has been done by the manufacturer of the sensors. A large part of the analysis of the quality of the low-level sensor data and the derived quantities of vehicle and object states has already been reported in the document "Integrated Collision Warning System Final Technical Report", so we will only give a summary of these findings here. The larger part of this section concerns the calibration and validation of the warning algorithms. The analysis of the false positive warnings was done based on data from field tests and is reported in Section 3.3.4. The analysis of false negative warnings was done using data from the closed course tests. The closed course tests were performed on the parking lot of the Pittsburgh Zoo in December 2004.

The calibration and testing of the sensors and the analysis modules were done before the field testing of the system. The warning algorithm that created alerts and imminent warnings was mostly calibrated before the field test, but some of the calibration was done during the field test when we found that the first calibration was not sufficient. The evaluation was performed after the deployment. The under-the-bus warnings and notification were not activated on the bus during the field test, but the calibration and evaluation of these two warnings were done at the end of the field test.

The tests were designed and conducted to calibrate and evaluate the following:

1) ***Sensor measurement errors:*** The ranges, resolutions, and accuracies of the laser line striper, the laser scanner, the speedometer, and the yaw rate gyro were determined. The laser line striper measures the distance to the curb, which in turn is used to better analyze the situation and suppress nuisance warnings. The other sensors are necessary to determine directly or indirectly the state of the bus or the objects. From these states the warning level is calculated. Errors in the sensors can therefore result in errors in the warning levels issued to the driver.
2) ***Object velocity errors:*** The velocity of the objects is derived from the laser scanner data by the DATMO algorithm (detecting and tracking of moving objects). The object velocity is part of the object state and as with the other sensor data can result in errors in the warning levels.
3) ***Range of laser scanner***: The area the laser scanner needs to cover to detect all warnings.
4) ***Warning characteristics***: The warning algorithms are calibrated and the correctness of the warning levels is evaluated. A warning is correct if the observed situation is as dangerous as indicated by the warning.

2.3.1 Methodology

For many of the sensors the calibration and specifications of the sensor were provided by the manufacturer. For the other cases we compared the measurements of the sensors with independent, preferably better measurements of other sensors, e.g., the speed from the bus speedometer was compared to the speed from GPS and the speed derived using the SICK laser scanner. These comparisons gave us calibration and error characterizations.

The first step in the calibration of the warning algorithms was to select relevant events. These could be staged collisions or situations which triggered the (preliminary) warning algorithm. Then we examined the video footage of each event and determined if the warning was appropriate, and when necessary we changed the algorithm or its parameters. We iterated this process until we were satisfied with the warning outcome.

The validation was done in a similar manner, beginning with selection of events other than the ones used for the calibration. Then the events were analyzed to determine the validity of the warning level. The end result was statistics about the false warning rates and the causes of false warnings.

2.3.2 Sensor Calibration and Validation

2.3.2.1 Laser Line Striper

The range and resolution are dependent on the sensor configuration. In the following table they are shown for three different fields of view:

Table 2-8 - Range and Resolution of Laser Line Striper

Field of view [deg]	30	55	105
Angular resolution [deg]	0.05	0.09	0.16
Max. range (ideal) [cm]	700	520	300
Max. range (typical) [cm]	300	200	130
Range resolution [cm]	1.4	2.6	5.0

The maximum range is for ideal conditions (high reflectivity objects, etc.), but for typical conditions, it is about half that distance. The range resolution is for a 2 m distance, and resolution varies with the square of the distance. The range resolution was improved by employing sub-pixel resolution. With sub-pixel resolution one can increase the resolution by a factor of about 5 if the detected signal is strong. The range resolutions shown in the table can therefore be considered as upper limits. The FOV of the line striper mounted on the bus was 30°. This gave the best range (up to 3 m) and we found that the 30° FOV was sufficient for curb detection; i.e., the curb was still in the FOV at 3 m even when the bus was leaning due to uneven ground or uneven passenger loading.

For details see Section 1.11 of the Final Technical Report[vii].

2.3.2.2 SICK Laser Scanner

The basic properties of the laser scanner are:

Angular range:	180°
Angular resolution:	0.5° or 1.0°
Range:	up to 80 m
Range resolution and accuracy:	1 cm
Update rate:	37.5 Hz or 75 Hz (depending on angular resolution)

The manufacturer's claim that the resolution and accuracy of the SICK laser scanner are 1 cm has been confirmed by our experiments, including variations over space and time. See Section 1.32 of the Final Technical Report[viii] for details.

2.3.2.2.1 Object velocity

In order to get a good characterization of the error function of the full DATMO (detection and tracking of moving objects) algorithm we studied a 40 second long data set. During this time the bus was driving at about 10 m/s past a series of fixed objects: parked cars, mail boxes, and lamp posts, while DATMO detected 312 different objects. The distribution of the measured velocities shows the error function.

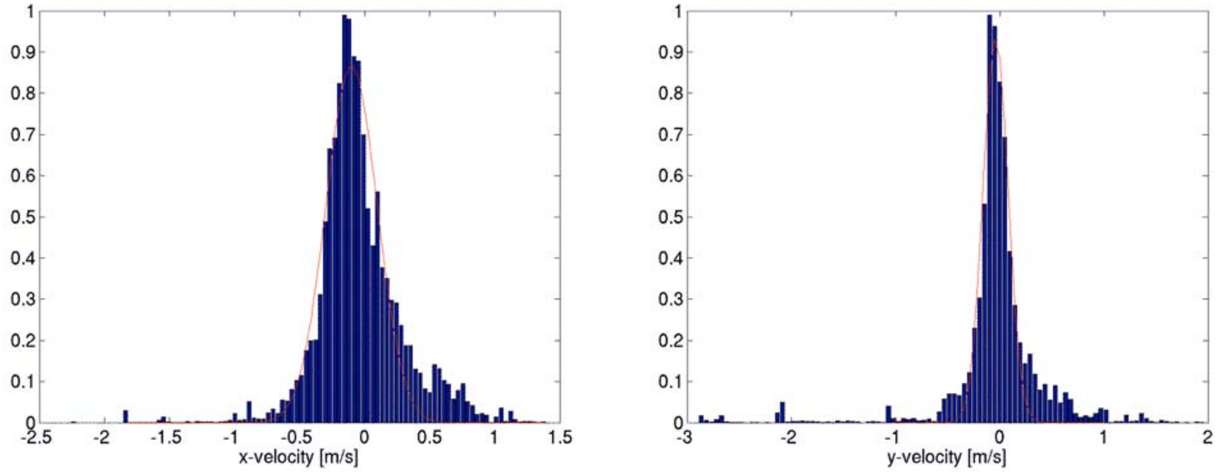

Figure 2-12 - Distributions of the errors in velocity

Figure 2-12 shows the distributions of the velocity errors in the x and y directions (normalized so that the maximum is 1). The left plot shows the velocity error in the x direction and the right shows the y-direction.

Gaussian curves were fit to the distributions (shown in red) and gave the following parameters:

x-velocity center: -0.10 m/s σ: 0.20 m/s
y-velocity center: -0.04 m/s σ: 0.13 m/s

The centers of both distributions are not exactly at zero, even though the objects are known to be stationary. The offset for the x-direction can be explained by a 1% inaccuracy of the speed of the bus. The offset for the y-direction could be due to a misalignment of 0.2° of the laser scanner. Both of these errors are very small and well within the known accuracy of the bus speed and the sensor alignment.

The distributions are fairly well described by the Gaussian curve, except for their tails, which are much stronger. These outliers can come from inconsistent scanner data; e.g., if the scanner sees different parts of an object or does not get any return from certain parts of an object. The bus itself was not level and therefore the sensor plane was not parallel to the ground. This would explain why we did not always get consistent returns; *i.e.*, the scanner probed the objects at different heights depending on the distance of the objects. For details see Section 9.4 of the Final Technical Report[ix].

For the great majority of objects, the velocity determination worked well; i.e., it was accurate enough to analyze a situation and issued appropriate warnings. The few outliers can occasionally cause false warnings (see Section 3.3.4 for details).

2.3.2.2.2 Bus speed

We used two different methods to calibrate the speed of the bus. In the first, we used the GPS installed on the bus, which has an accuracy of a few tens of meters. When traveling short distances, the speed derived from GPS position can therefore be very inaccurate. But since the error in position is not cumulative, the long-term average speed using GPS is a good measure of the average speed. With this average GPS speed, the bus speed has been calibrated for several days during one month. The calibration varied by ±1.5%.

In the second method the SICK laser scanner data was used. The longitudinal distance from a corner of a building to the bus was measured with the SICK at two times, one second apart from each other. The distance divided by the 1 second gives the speed. From the accuracy of the SICK laser, the accuracy of the speed determination was estimated to be about ±1%. The two methods yielded results which differed by only 1%.

In summary:

Accuracy of speed calibration:	±1%
Stability of calibration over one month:	±1.5%

This accuracy and stability of the speed is very good, and was never the cause of a false warning or any other problem of the system.

2.3.2.2.3 Bus yaw rate

The manufacturer specifies a resolution of 0.025^{o}/sec and a bias of less than 2^{o}/sec. Our tests confirmed these numbers. For the most part these specifications were good enough for the SCWS as such. We found one case when a false reading of the yaw rate led to a false warning. For the analysis of driver behavior it would have been preferable to measure the change of yaw rate directly by instrumenting the steering wheel.

2.3.2.3 Range of laser scanner

We wanted to determine the maximum range that the laser scanner needs to cover in order to detect all the dangerous situations the bus is exposed to during normal operations. For this we created a density plot of the location of all the warnings, based on the warnings from all good runs. The density plots for the SamTrans and the PAT buses are shown in Figure 2-13**Error! Reference source not found.** and Figure 2-14 where the highest density is dark red and the lowest is dark blue.

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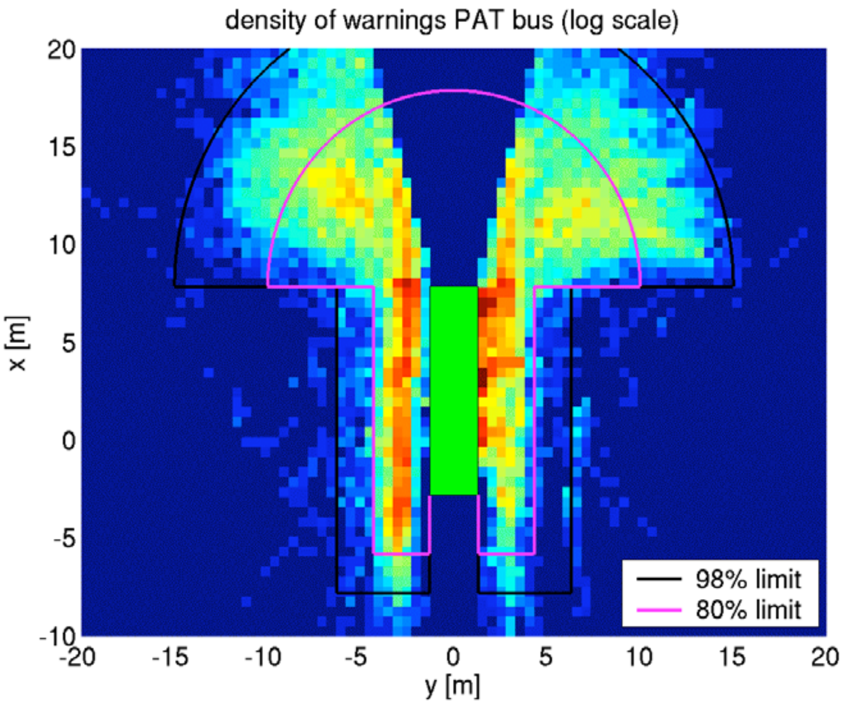


Figure 2-13 - Density (log scale) of warnings around the PAT bus

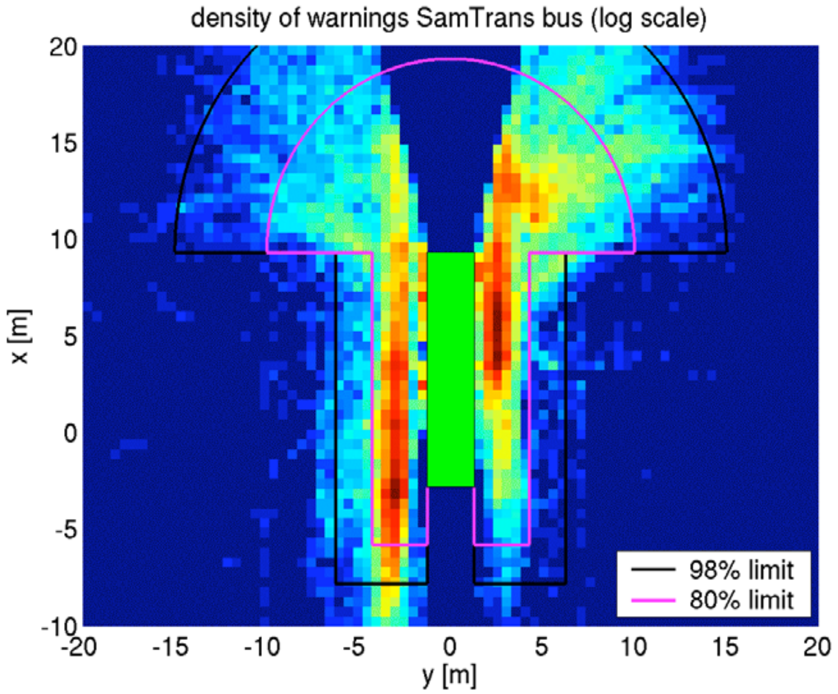


Figure 2-14 - Density (log scale) of warnings around the SamTrans bus

Most of the warnings are located alongside the bus:

- On the right side they are mostly pedestrians, which are moving towards the bus when the bus is coming to a stop.

- On the left side most of the warnings are caused by passing vehicles.
- For the PAT bus there is a high concentration of warnings in the middle of the bus adjacent to the right side.

The latter is the location of the laser scanner, and these warnings were generated when the laser scanner was dirty or retracted (see Section 3.3.6.2 for more discussion about these situations). The warnings in the front right or front left area of the bus are generated when the bus is turning and an object is in the path of the bus.

These figures also show two enveloping areas, which include 80% and 98% of all warnings, respectively. They can be described as rectangular boxes on the side of the bus extending 3 m (5 m) from the back and 3 m (5 m) to the side and a half circle in front with a radius of 10 m (15 m). The system covers the area of a half circle of 50 m radius for large objects (> 1 m as viewed from the scanner), which is much larger than the area indicated by the enveloping limits. For pedestrian sized objects, which are harder to detect and track, the coverage is approximately a half circle of 20 m radius, which still includes the enveloping area. We can therefore be quite confident that we did not miss warnings because of a lack of coverage.

The enveloped areas give an indication of what the coverage of a commercial system should be. It is desirable for the sensor to have a range somewhat greater than the indicated area, because this enables the detection and tracking of objects before they enter the area.

2.3.3 System Testing in a Controlled Environment

There are two main categories of warning system errors: false positive and false negative. A false positive is when an alarm is issued, but there is no danger. With a false negative, no alarm is issued, but a danger was present. It is much easier to find and analyze false positive alarms, because there are few alarms to begin with and usually there are a fair number of false ones among them. It is therefore feasible to review all alarms in one or several runs to determine if they are true or false.

In contrast, it is very hard to find false negative alarms in the data. One would have to watch many hours of data to find situations when an alarm should have been issued. There are several ways one can get around this problem. One can try to pick out these events with an algorithm, either by increasing the sensitivity of the current warning algorithm or using a completely different one. Another way is to stage collision events and investigate if the system responded properly to them.

A true warning is generated when the system works correctly and the warning is not a nuisance to the driver. Working correctly means that the system detected an object that actually exists, measured the object and bus state within the specified measurement errors and calculated the appropriate warning level for the given situation.

Collisions and near-collisions were staged in closed course testing. One set of these events was used to calibrate the system and another set to evaluate it.

2.3.3.1 Alert/Imminent warning

2.3.3.1.1 Testing protocol

Several cardboard boxes were set up in a parking lot as obstacles.

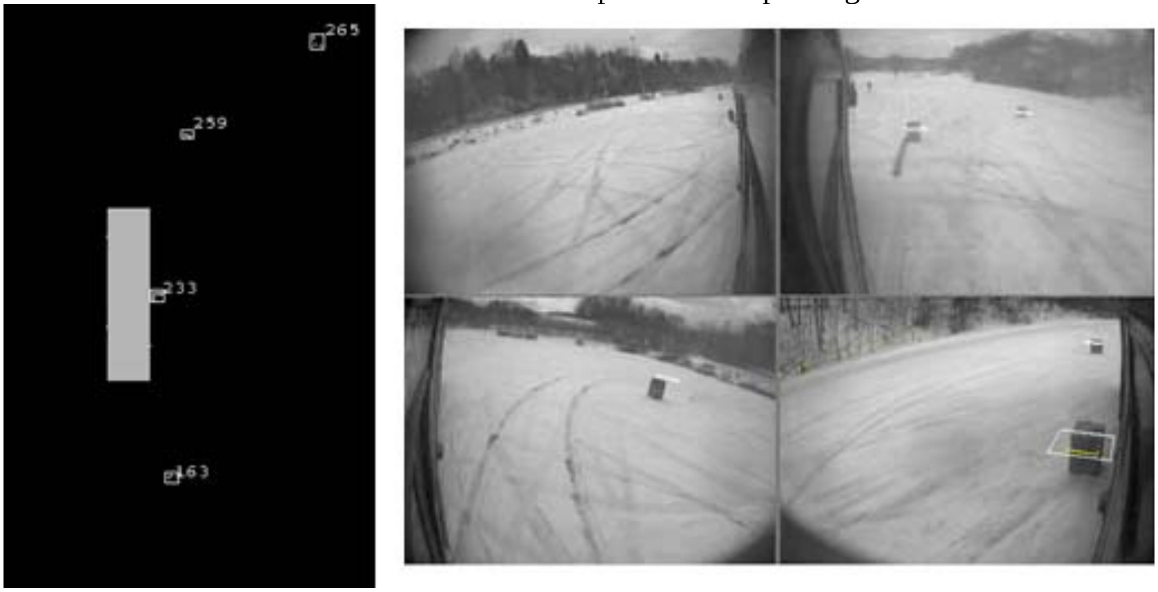


Figure 2-15 shows the first of the arrangements, with all boxes stationary. On the left is a birds-eye-view with the bus and the laser scanner data. On the right is the view from the four side cameras. The bus drove past the cardboard boxes, sometimes getting close to a collision and sometimes actually hitting them. In the second arrangement (Figure 2-16) one of the boxes was pulled parallel to the initial driving direction of the bus while the bus is making a sharp right turn.

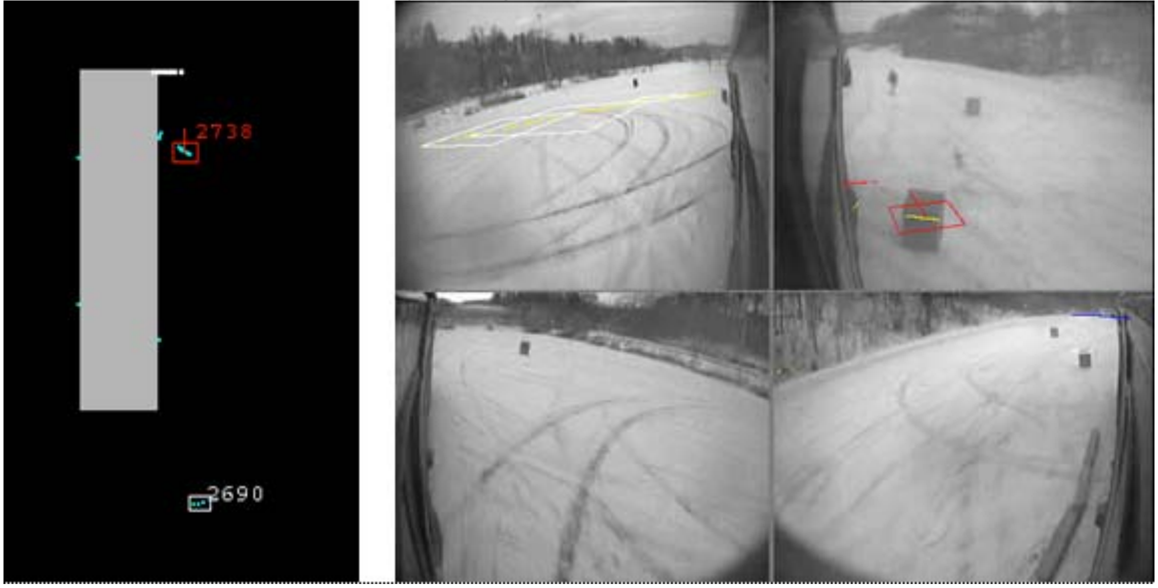


Figure 2-15 - Snapshot of the bus driving past four boxes

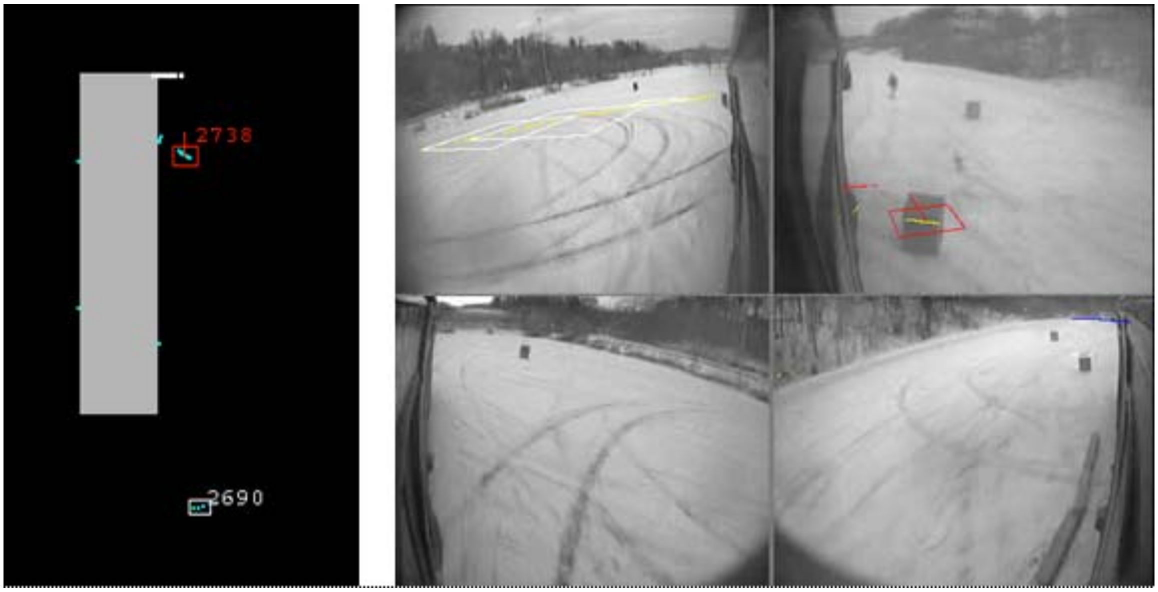


Figure 2-16 - One of the boxes is pulled parallel to the driving direction of the bus

In the next arrangement one of the boxes is pulled perpendicular to the initial driving direction of the bus. In some instances the box collided with the side of the bus, as happened in the scenario shown in Figure 2-17, and sometimes the front of the bus hit the box.

Figure 2-17 - The box in the front is pulled perpendicular to the bus

Whenever the bus hit an object, the system should have given an imminent warning before the collision occurred.

2.3.3.1.2 Calibration of Probability of Collision Graph

The areas in the probability-of-collision (POC) graph determine the warning levels displayed to the operator.

Figure 2-19 shows an example of a POC graph. For details on the warning generation and POC graphs see[x]. The areas were first calibrated using data collected in normal transit operation, with an emphasis on selecting the most dangerous situations (those with the highest POC values at each time step). All the POC curves of all objects (10 curves per object per second) for one good test run (totaling about 2 million curves) were accumulated in one distribution, shown in Figure 2-18.

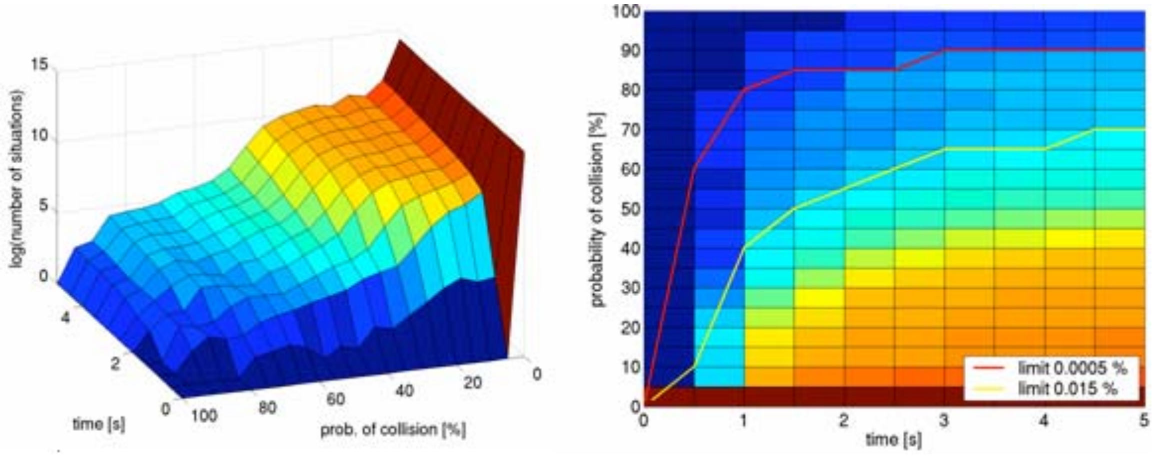
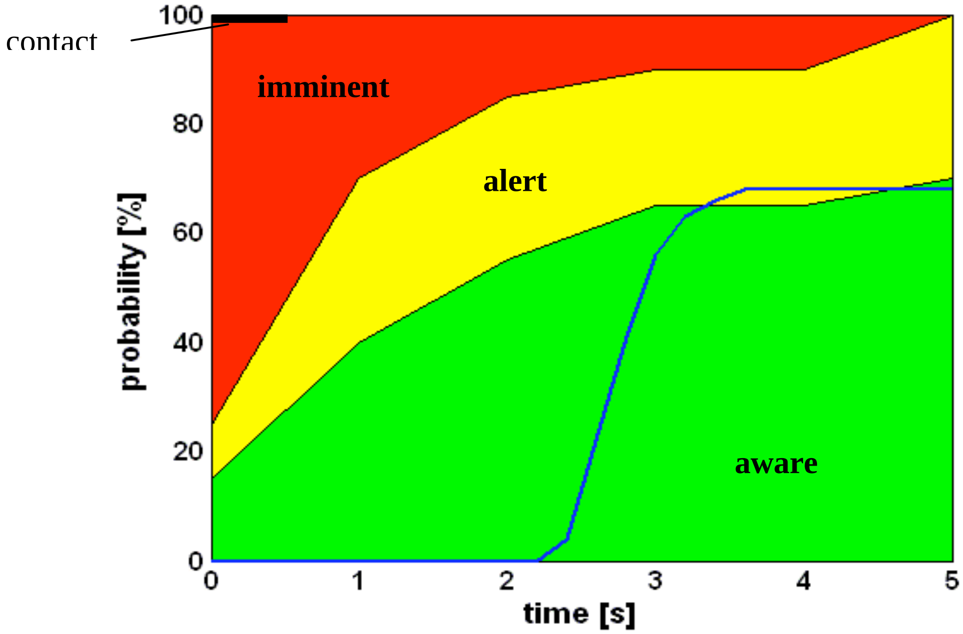


Figure 2-18 - The POC distribution of all curves of all objects from one run



The left plot in Figure 2-18 shows the accumulation (z-axis) of the POC (y-axis) vs. time (x-axis) plots for the entire test run, with a logarithmic z-scale. The right plot is a planar projection of the same data, with the colored fields representing the accumulated values. The limits for the 0.015 percentile (yellow line) and the 0.0005 percentile (red line) most dangerous situations are shown. We found that these boundaries for the "imminent warning" and "alert" areas of the POC graph gave the best results.

We modified these initial boundaries in two ways. First, we noticed that for times greater than 4 seconds the prediction of vehicle and object behavior becomes unreliable and therefore we shifted the POC boundaries to higher percentages for times greater than 4 seconds. Second, there were no collisions recorded in the data and therefore the calibration lacked an important set of situations. The closed course testing collisions and near-collisions were used to fill this gap. These situations are especially important to calibrate the graph for short times. The boundaries of the POC graph were chosen so that all the collisions are preceded by an imminent warning, but also so that situations that are not dangerous do not produce a warning. The final graph with warning areas defined for the medium sensitivity setting resulting from the calibration and an example of a POC curve is shown in
Figure 2-19.

Figure 2-19 - Medium sensitivity warning area graph with an example of a POC curve

2.3.3.1.3 Evaluation of the resulting Probability of Collision Graph

Seventeen staged runs were used for the calibration. After the calibration all of them gave correct alerts and imminent warnings, which of course is expected. Thirteen additional runs were selected to evaluate the calibration and look for false warnings:

1. Nine gave correct imminent warnings.
2. One gave a correct alert.
3. Three gave correct imminent warnings, but they came so close to the SICK laser scanner that the scanner retracted and the object was lost.

In the three scenarios when the laser scanner retracted (representing 23% of all warnings) the object was lost and no further alarms were issued, when in fact the imminent warning should have continued. These are correct imminent warnings that did not last long enough, since warnings should be given until there is no more danger. Since no false warnings were observed, we can only give an upper bound on the false warning rate. With a 90% confidence level, the false warning rate for these scenarios is less than 0.16. It needs to be mentioned that in a strict sense the scenarios are not typical collisions, because we asked the driver to hit the boxes. In real transit operations the driver will not try to hit objects intentionally. We can therefore not reliably calculate a false negative alarm rate. We can only note the fact that collisions can result in the retraction of the laser scanner and the subsequent loss of the object and cessation of the warning. There are several other ways the system can miss a warning:

- The system needs time to start up, so during this time no warnings can be issued.
- The system reboots for some reason.
- The laser scanner is retracted.
- The laser scanner is dirty.
- The bus is leaning and therefore the laser scanner does not point horizontally.
- Some objects do not reflect the laser light sufficiently. For example, we observed a situation when a person was wearing a dark outfit on a rainy day and was not seen by the scanner. It could be that wet clothing specularly reflected the laser light or the dark clothing absorbed it.

We also studied the duration of the warnings before a collision. The imminent warnings lasted 0.6 to 1.5 seconds and were preceded by alerts of 0.1 to 0.5 seconds duration. The shortest overall alarm was 0.7 seconds, 0.1 seconds of alert followed by 0.6 seconds of imminent warning. Alarms issued one second before a collision are not sufficiently early for the driver to react and avoid the collision. The reason that alarms could not have been issued earlier is that the driver made sudden directional changes to hit a cardboard box. Such movements can not be predicted by the system.

2.3.3.2 Contact Warning

Due to time restrictions we were not able to fully complete the development of the contact-warning algorithm, which is based on a probability-of-collision calculation. Further tests and refinements of the algorithm are necessary. According to the algorithm, a collision occurs when the probability of collision reaches 100% in the first 0.5 seconds (see small black area in
Figure 2-19).

Initial evaluation showed that this algorithm is too restrictive, since objects colliding with the bus at small velocities do not trigger a contact warning. The system always gives an object an uncertainty in position and velocity, so the probability-of-collision calculation will not give a result of 100% unless the velocity of the object is sufficiently large and aimed at the bus.

The rate of contact warnings is very low, about 0.4 warnings / hour on the right side and 0.1 warnings/hour on the left side. All the contact warnings we observed during normal operations were false positive warnings. The reasons were:

- The laser scanner was retracted but the system did not know about it. This produced many objects with false locations and velocities.
- The bus-door-open indicator did not work, so that people entering the bus triggered contact warnings. This trigger should have been vetoed by the bus-door-open indicator.

Figure 2-20 - A three-second image sequence of a person falling under the bus

2.3.3.3 Under the bus warning

We staged twelve situations when a person fell under the bus (example image sequence shown in Figure 2-20). The falls occurred at different locations on both sides of the bus. In some instances the person appeared between boxes, but in others he was the sole object in the area. The bus was stationary during these events for safety reasons.

2.3.3.3.1 Calibration of the under-the-bus warning algorithm

We used the data from these staged scenarios to test and calibrate the under-the-bus warning algorithm. We found that we needed to modify the tracking module (DATMO) to determine if an object went into occlusion or merged with another object. This information was passed to the warning algorithm so that it did not falsely think an object disappeared (and potentially was under the bus) when it in fact became occluded or merged with some other object. We also discovered that we should only consider objects that were detected for at least half a second in order to suppress alarms for spurious objects. Lastly, objects that are as far as 1.8 m from the bus when they disappear need to be considered. The image at 2 seconds in Figure 2-20 shows the person just before he disappears from the view of the laser scanner. The last part of the body to be seen is the head, more than a meter away from the bus. Sometimes the last part to be seen is an outstretched hand, even further away from the bus than the head.

2.3.3.3.2 Evaluation of the under-the-bus warning algorithm

After these modifications and tuning of parameters, all twelve staged events gave correct under-the-bus warnings.

There were not enough staged events to determine a reliable rate of false negative under-the-bus warnings. False negative warnings are possible when a person falls while being occluded by another object or the last part seen by the sensor is close to another object and merges with it. Another possibility is that a person falls under the bus at the front door when the door is open. The system excludes these situations because people routinely disappear from the view of the sensor at that location when they enter the bus.

The other events in the closed course testing when we did not stage a person falling under the bus are useful to investigate false positive under-the-bus warnings. These events involve collisions and near-collisions (see previous sections), which are very rare events under normal operational conditions and might trigger false positive warnings; e.g., an under-the-bus warning is given when an imminent warning should have been given. Among 23 situations we analyzed, we found four false positive under-the-bus warnings:

- One time the system was confused when a person picked up a cardboard box.
- One object seemed to disappear when it was far away from the laser scanner but still close to the bus. The object was too far from the sensor to produce a sufficient return.
- Two objects appeared to vanish when the laser scanner retracted.

Again, there were not enough situations to determine a false positive warning rate. For this we need to study data taken during normal transit operations.

2.3.3.3.3 False positive rate during normal operation

We studied all under-the-bus warnings from runs totaling 6 hours in California and 7 hours and 46 minutes in Pittsburgh. We found no correct under-the-bus warnings and 26 false ones, representing a rate of 1.9 false positive warnings per hour:

- Two times the object was lost because the laser scanner retracted.
- Twelve times the system was not able to interpret a cluttered scene correctly. The clutter consisted of stuff in the garage, vegetation, or a person carrying several bags.

- Two times the object was a dust cloud created by the bus tires. The dust cloud disappeared and triggered a warning.
- Ten times the door open/close recorder didn't work. A person entered the bus or the back doors closed and the system thought an object disappeared.

The fact that we did not observe any correct under-the-bus warning is no surprise, since people falling under the bus is an extremely rare event. The system would benefit from an additional sensor that can positively identify that something is underneath the bus.

2.3.4 Evaluation of the SCWS Test Results

The subsystems of the SCWS were calibrated and evaluated according to performance measures. The performance measure most directly affecting the bus operator is the true alarm rate. True or correct warning means that the system detected an object that actually exists, measured the object and bus state within the specified measurement errors and calculated the appropriate warning level for the given situation.

The range, field-of-view, resolution and accuracy of the basic sensors (laser scanner, speedometer, gyro, and laser line striper) were all adequate for the SCWS. The detection and tracking algorithm was accurate most of the time. Once in a while its velocity estimate of an object was not good enough, which caused some false warnings.

The false negative alarm rate (missed warnings) for alerts or imminent warnings is difficult to determine because it is time consuming to review large sets of data to find situations when warnings should have been given. Instead, we staged collisions to determine how many the system missed. We did not observe any missed warnings in these staged scenarios, which puts an upper limit of 16% on the ratio of missed warnings to correct warnings.

The false positive warning rates were 0.5 contact warnings / hour and 2 under-the-bus warnings / hour (both sides combined). These are still too high because either warning requires drastic actions from the bus driver, namely stopping the bus and investigating what happened. We therefore did not activate and display these warnings for the operational testing in public service.

2.4. Summary of FCWS and SCWS Test Results

2.4.1 Findings

Tests were carefully designed and conducted under controlled conditions in order to quantitatively calibrate and evaluate the performance of the ICWS. Because of the different characteristics of the FCWS and SCWS systems, the verification tests were conducted separately.

The verification tests for FCWS focused on engineering validation of obstacle detection functions and scenario-based verification of the collision warning system.

- The engineering validation concluded that the obstacle detection functions consistently provided good longitudinal range measurements, relative speed and acceleration estimation and prediction.
- The quality of the measurements of target lateral position, on the other hand, is not to the level expected, particularly when the objects are farther away. Additionally, delays associated with LIDAR processing pose significant issues.

Scenario-based testing was conducted to evaluate system performance for vehicle following, target cutting in and staged crashes. Test results showed that:

- Under the tested scenarios, the FCWS can correctly identify hazardous targets and generate warnings when the driver's action is needed.
- Errors in target lateral position estimates can potentially cause false detection of targets that may not be of threat and therefore result in false positive warnings.
- Time delays reduce the effectiveness of the collision warning system.

For the SCWS we first calibrated and validated the basic sensors and then the modules that analyze the raw data to obtain higher level measurements such as object velocity. We investigated if any of the limitations of these subsystems would later lead to either false positive or false negative warnings. The rate of false negative warnings was investigated in this section; the corresponding false positive rate was estimated with data collected during normal operation and is reported in Section 3.3.4. We investigated the rates of contact and under-the-bus warnings and determined the area that the sensors of the SCWS need to cover in order to see all the hazards. The primary findings from these analyses are:

- The range, field of view, resolution and accuracy of the basic sensors (laser scanner, speedometer, gyro, and laser line striper) were all adequate for the SCWS. The detection and tracking algorithm was accurate most of the time. Occasionally, its velocity estimate of an object was not good enough, which caused some false warnings.

- The false negative alarm rate (missed warnings) for alerts or imminent warnings was measured by staging collisions and counting how many the system missed. We did not observe any missed warnings in these staged scenarios, which puts an upper limit of 16% on the ratio of missed warnings to correct warnings.

- The false positive rates were 0.5 contact warnings / hour and 2 under-the-bus warnings / hour (both sides combined). These rates are still too high because either warning requires drastic actions from the bus driver, namely stopping the bus and investigating what happened. We therefore did not activate and display these warnings for the operational testing in public service

2.4.2 Recommendations

The testing results clearly point to the need for improvements of lateral position (or azimuth angle) measurements and reduction of delays for the FCWS. The team has concluded that a more robust approach to remedy the estimation errors and the delays is to employ video image processing to detect obstacles and their lateral position with respect to the subject vehicle and then, through sensor fusion with obstacle detection sensors such as radar or LIDAR, determine their threat levels. Other approaches may also include using the raw LIDAR/radar front end data directly for target tracking or advanced prediction filtering to reduce prediction errors and time delays.

For the SCWS we have following recommendations:

- The velocity determination should be improved. This can be done through the use of a better laser scanner (e.g. a multi-plane laser scanner) or improvements in the detection and tracking algorithm.
- The rate of 1.9 false positive under-the-bus warnings per hour is too high. An additional sensor is needed that directly detects objects under the bus.
- The contact warning algorithm should be completed and tested.

Additional testing under the controlled environment is recommended in order to understand bus driver response time to collision warning systems. The testing results will be critical to refine the performance requirements of ICWS, which will help to further define the technical specifications for sensing, tracking and warning algorithms.

3 Evaluation of ICWS in Revenue Service

In order to determine the effectiveness of the prototype integrated collision warning system and to verify the ICWS requirement specifications, field testing was conducted on two buses, one in San Mateo County, California and one in Pittsburgh, Pennsylvania. Both buses were equipped with the integrated frontal and side collision warning system. The instrumented vehicles were operated on SamTrans and PAT service routes by bus operators assigned through their regular bidding process. Since bus crashes are infrequent events, efforts were made, within the constraints of transit agency competing needs for resources, to gain as much on-road in-service driving time for each operator as possible. The testing and data analysis focused on assessing bus operator behavior and opinions prior to the introduction, compared with behavior and opinions after introduction of the collision warning system. Data were obtained for a limited number of operators, based on the availability of only two completely instrumented buses and the schedules of bus operator assignments.

The effectiveness of the frontal collision warning system was evaluated through comparisons of 'before-and-after' driving behavior, characterized by vehicle following time gap, brake pressure, longitudinal acceleration/deceleration, time to collision (TTC) and required deceleration. Cumulative frequency distributions for each key measure of driving behavior were generated and the data were analyzed by comparing days before the DVI was activated to subsequent days after it was activated.

The effectiveness of the side collision warning system was assessed by evaluating the frequency of alerts or imminent warnings and the steering behavior of the operators before and after the DVI was activated. This analysis was done to reveal if the operator avoids getting into situations that set off warnings and how the operator reacts to warnings when they are issued.

The field data were reviewed to identify simultaneous and near-simultaneous frontal and side warnings, to assess the frequency of occurrence of the conditions under which such warnings occurred and to thereby determine if a warning synthesizer might be useful.

The team also surveyed operators' responses to the integrated collision warning system to gather feedback from operators as to whether the developed ICWS was acceptable to operators and what changes they thought would be useful to implement. Ride-alongs were carried out to collect dynamic information regarding operators' opinions of warning timings and to view scenarios that operators were concerned with or were interested in. The findings from the surveys and ride-alongs are reported in Section 3.6

In the remainder of this chapter, Section 3.1 describes the field data collection conditions and procedures that were used in San Mateo County and Pittsburgh. The methods of analyzing the data and the results of the data analyses are reported in Sections 3.2 and 3.3, the former section focusing on the frontal system and the latter section focusing on the side system. The outlines of these sections are generally parallel, but the technical approaches were somewhat different because of the differences in the issues that were most important to the effectiveness of the two types of warnings. Section 3.4 addresses the hardware problems that were encountered, while Section 3.5 addresses the simultaneous frontal and side alerts and their implications for development of an integrated warning synthesizer. Finally, Section 3.6 describes the operator feedback obtained from surveys and revenue operation ride-alongs and Section 3.7 discusses conclusions drawn from the field testing.

3.1. Testing Procedures

Between June 2, 2004 and May 5, 2005, about 300 G bytes of objective data were collected from the bus operations in revenue service. This involved a total of 604 operational hours (when bus speed was greater than zero). Two transit buses were instrumented, one operated by SamTrans in the San Francisco Bay Area, the other operated by the Port Authority in Pittsburgh, Pennsylvania. Both buses were equipped with the ICWS capability, comprised of the FCWS and SCWS, as described in Section 1.5. The instrumentation on the two buses was very similar, but only the SamTrans bus was equipped with brake pressure and accelerometer sensors. The evaluations described in Sections 3.2 and 3.3 treat these systems separately, and then Section 3.4 shows how infrequently the systems generated warnings at the same time. The largely separate evaluations make sense here because the FCWS and SCWS are addressing different types of threats, which are detected by different sensors, and lead to different driver responses.

3.1.1 Field Testing Routes

In the San Francisco Bay Area, the service routes were spread throughout San Mateo County, with connections to the Daly City and Colma BART stations, the San Francisco Airport, several Caltrain stations, and the downtown areas of local suburban cities. The routes were mostly on local streets (one and two lane) and included some sections of freeway. These routes covered flat sections as well as some tight hill turns. The SamTrans bus usually went into service in the early afternoon and stayed in service until the late evening.

The Port Authority bus in Pittsburg was usually put in service for a morning and an afternoon run. They started at 7 am and 3 pm respectively and lasted for approximately four hours each. The routes were between the suburban Harmarville and downtown Pittsburgh through various towns in between. The routes included freeways, local streets, flat and steep roads.

3.1.2 Participants

Project team members worked with the transit agencies to arrange these buses on routes that contained a mixture of the driving conditions experienced in the service region. Bus operators were assigned to the buses by the transit agencies, so no screening of bus operators was undertaken. Although several dozen bus operators have driven the equipped buses, the majority of operators only drove the equipped buses occasionally, and did not accumulate enough days of driving to support comparisons of their driving behavior before and after the activation of the DVI. After careful screening, data from seven operators, summarized in Table 3-1, were selected for the analyses described in this section. These were the operators who had the most driving experience on the instrumented buses, including driving both before and after activation of the warning system DVI.

Table 3-1 - Summary of data available for seven bus operators

Operator	Days of Data “DVI Off”	Hours Driven “DVI Off”	Days of Data “DVI on”	Hours Driven “DVI on”
A	12	47	15	60
B	7	29	15	60
C	4	16	20	78
D	9	25	25	53
E	5	16	14	30
F	26	41	6	11
G	25	58	23	59

3.1.3 Schedule

The bus operators were assigned to drive the instrumented bus as part of their normal driving assignment bids, which minimized complications in the process of obtaining approval for use of human subjects in the testing. These bids, which are generally conducted on a quarterly basis, provide the means for assigning drivers to routes based on their personal preferences and seniority. Bus operators drove the bus with the DVI turned off for the first 2-4 weeks (time varied due to availability of researchers and system status) of each bid (approximately three months long) and then with the DVI turned on for the remainder of the bid. As this did not always go according to plan (due mostly to other transit agency needs competing for resources and operator vacation times), in order to maximize the data available for each operator efforts were made to keep operators for more than one bid at a time.

3.1.4 Weather

Data collected from these two sites included operations with rain, fog, wind, snow, ice and clear skies.

3.1.5 Training

Members of the evaluation team trained the bus operators. Each training session lasted approximately ten minutes and covered the following areas: how the project was funded, the project purpose, the purpose of the system and the field testing, the equipment used, and how the system works (including situations when false warnings might occur). The training period was short because the system was designed, based on earlier bus operator inputs, to be intuitive to understand and easy to learn. The operators had the opportunity to ask questions about anything that was not clear to them before they started to use the system. Based on the experience with these operators, the short training period would appear to be sufficient for a future deployable system.

Operators were left with a half page laminated quick reference card that had contact names and they were asked to report any problems they encountered to either a team member or to the dispatcher to pass on to the evaluation team.

The bus operators were able to adjust the brightness of the display as well as the sensitivity of the system. Both controls were explained to the operators and they were encouraged to experiment with the system. The operators were able to choose among three levels of sensitivity of the system, which altered the alert parameters in the warning algorithm. Increasing sensitivity results in earlier alarms, allowing more reaction time, but will also likely lead to an increase in the total number of alarms (including true, false and nuisance alarms).

3.1.6 Data Collection

The data were saved automatically and collected every two weeks, at which time they were checked for any system problems. After both FCWS and SCWS systems were working, the data for analysis were further down-selected by deleting non-consented and untrained operator data. The data for days when operators had driven for only one day here and there were also deleted. This still left us with substantial quantities of data to analyze, covering three SamTrans operators and four Port Authority Transit operators.

3.2. Evaluation of Frontal Collision Warning System (FCWS)

3.2.1 FCWS Measures of Effectiveness

Because it was not possible to collect enough data to show differences in crash frequency or severity based on whether the FCWS was activated, it was necessary to use surrogate measures of safety that describe the bus operator behavior. Indeed, no crashes were experienced on either of the instrumented buses throughout the field testing. The surrogate measures had to be chosen to be measurable by the available instrumentation and representative of the riskiness or conservatism of the operator’s driving. Considering the diversity of driving styles among the operators, it was judged most important to concentrate on changes in the driving measures of effectiveness (MOEs) for each operator, comparing their driving before and after activation of the DVI. The measures of effectiveness that have been used to evaluate the effects that the FCWS had on driving behavior are described below.

3.2.1.1 Vehicle following time gap

Vehicle following at smaller time gaps limits the ability of drivers to react to rapid decelerations of the forward vehicle. Safety could potentially be improved if the more aggressive operators increase their vehicle following time gaps or reduce the variability of the time gaps. To investigate this we compared periods of vehicle following before the FCWS DVI was activated to comparable periods after the system was activated. We investigated the data on a day-by-day basis to determine the changes in vehicle-following time gaps over time.

3.2.1.2 Brake pressure

A major concern for transit agencies is to have operators drive buses in a smooth manner. This is important so that passengers are not moved violently within the bus, so that they will be more comfortable and it will be less likely that standees will fall, as well as for reasons of fuel economy. The first metric evaluated here is the brake pressure applied by the operator, comparing days before and after the DVI was activated. This also provides an indication of whether the operator may be getting into more hazardous encounters that require him or her to make more aggressive corrective maneuvers.

3.2.1.3 Longitudinal deceleration

The longitudinal deceleration corresponds directly to the brake actions, and is an alternative to the brake pressure for addressing the same issues.

3.2.1.4 Small values of Time To Collision (TTC)

Time-to-collision is an often-used metric in developing and evaluating collision warning systems. TTC is defined as the time it would take for the bus to collide with the leading vehicle, assuming both vehicles maintain their current speeds. They are only in danger of colliding if the leading vehicle is going slower than the bus, so TTC is only relevant under this condition. This distinguishes it from the vehicle following time gap measure, which is relevant when both vehicles are traveling at about the same speed. Small values of TTC indicate potentially hazardous encounters, so it is important to understand whether the activation of the FCWS DVI reduces the frequency of occurrence of small TTC values.

3.2.1.5 Required deceleration parameter

The required deceleration parameter is the primary parameter used by the forward collision warning algorithm to determine whether to issue an alert to the operator and how urgent an alert to issue. It is important to evaluate the extent to which the activation of the DVI makes it less likely that the operator will drive in ways that would lead to a warning, hence the value of using the same MOE that is used to trigger the warnings. Reduced values of the required deceleration parameter would imply less of a need for the operator to decelerate at higher braking rates in order to avoid conflicts.

3.2.2 Data Processing Tools and Procedures

Data analysis software tools were developed and tested to select data of interest from the large amount of data collected on the integrated buses. Several data table files are generated for analysis, with each entry in the file composed of the bus state and target track states, including the “most significant time gap track”, or the “most significant TTC track”, or the “most significant ARQ track” (ARQ is the “required deceleration parameter” used to generate warnings to operators). The analysis focused on the cumulative distribution of time gap, brake pressure, bus acceleration, time to collision and required deceleration.

The data selection process is shown in Figure 3-1. First, the tool processes the data and generates the bus state and all the tracks in front of the bus. Then the bus speed threshold is set at 20 m/s to eliminate free-flowing highway traffic conditions (which are not of interest because they are handled adequately by existing commercially available collision warning systems), the tracks attributed to fog or rain are eliminated and marked in a fog file for later reference, and some general scenario thresholds are set, for example, the lateral distance to the chosen target is no greater than 2 meters. Lastly, the tracks are put into categories by sorting and are saved in different data files. For example, the time gap parameters of all tracks are calculated, those that meet the requirement of "time gap<5 seconds" are selected and compared, the one track with the minimum time gap (the most significant time gap track) is then stored in a file Gap.dat along with the bus state.

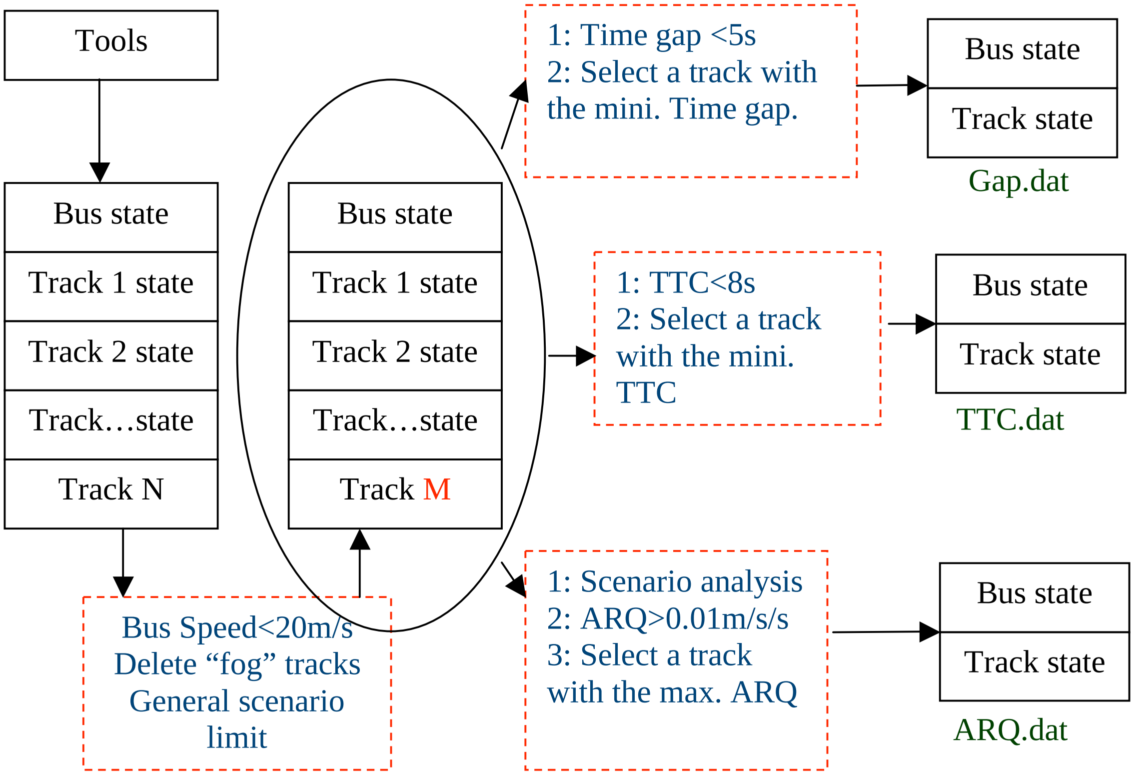


Figure 3-1 - Data sorting procedure

Below are example data selection criteria:

1) Bus speed is less than 20 m/s and more than 0.1 m/s. This eliminates free-flowing highway traffic conditions and stopped conditions, to focus attention primarily on urban and suburban arterial driving.
2) The bus is not turning violently (yaw rate <0.1 rad/s). Target vehicles must fall into the range of ±2 meters to the center of the bus front bumper (lateral distance). This eliminates the transient conditions when the bus is making a sharp right turn at a corner. The target vehicle condition is needed to focus on target vehicles that are in the same lane rather than an adjacent lane.
3) Target vehicles are moving in about the same direction as the bus (1-dr) < 0.1, where dr = sin(Heading of the bus) * sin(Heading of the vehicle) + cos(Heading of the bus) * cos(Heading of the vehicle). This focuses attention

on forward vehicles rather than vehicles that are crossing the path of the bus or vehicles approaching from the opposite direction.

4) Moving vehicles are selected. (Tracks that have a relative longitudinal distance to the bus of less than 1 meter, or 2 meters and relative speed to the bus that is within (-2.6 m/s, +2.6 m/s) range are excluded.) The excluded tracks tend to be artifacts of weather conditions such as rain or fog, as explained in Section 3.2.5.
5) The vehicle that has the least time gap is selected. This concentrates attention on the vehicle that is most likely to represent a threat condition to which the bus operator should be responding, rather than other vehicles of lesser concern.

The cumulative distribution functions of the variables: the time gap, the brake pressure, the TTC, the ARQ, and bus acceleration for each full day are then calculated and represented by one line in a graph. All the data on the RAID are processed and files are generated. As an example, the format of the time gap file is shown in Table 3-2.

Table 3-2 - Format of time gap data file

Column	**Name**	
1	Time Stamp	0.075s
2	File number	Dir
3	Brake Pressure (v)	Bus State
6	Bus Speed (m/s)	
7	Bus Heading (degree)	
8	Bus Acceleration (m/s/s)	
9	g	Tag
10	Track ID	Target State
11	Target Relative lateral distance (m)	
12	Target Relative longitudinal distance (m)	
13	Target Relative Speed (to the bus) (m/s)	
15	Target Acceleration (m/s/s)	
16	Time gap (s)	

3.2.3 Analyses of Driving Behavior

Considering that the buses were being driven under a wide range of operating conditions in real traffic, there were many sources of uncertainty in the data. More significantly, the conditions that are relevant to determining the safety implications of use of the FCWS are rarely occurring hazardous encounters, which cannot be identified by studying typical statistical measures such as means and standard deviations. Rather, attention here has been focused on the tails of the cumulative distributions of these measures of driving behavior, since that is where safety differences are likely to be found. The cumulative frequency distributions are much more revealing than probability density functions because of their smoothness and their direct indication of percentile values. Direct inspection of the tails of the cumulative distributions shows which values of the selected performance measures were experienced in the most dangerous 1% or 5% or 10% of driving conditions during the day. These provide much more important indicators of safety differences than means or standard deviations of any of the performance measures.

The data were analyzed using cumulative frequency distribution plots comparing days before the FCWS DVI was activated to subsequent days when it was activated. The first step was to run global analyses of the data, focusing on several key measures of driving behavior:

- car-following time gap
- brake pressure
- longitudinal acceleration/deceleration
- time to collision (TTC)
- required deceleration parameter (the warning criterion).

These measures are surrogate measures of driving safety, providing indications of behaviors that are more likely to lead to hazardous conditions. It was necessary to depend on these surrogate measures because the bus operators did not encounter any serious hazards during the field testing, leaving no crashes or “near misses” to compare. In part, this was a consequence of the fact that they were already very safe drivers, and in part it was a limitation of data being available from only two instrumented vehicles. If there were enough data available to show significant differences in the frequency of crashes or near misses before and after the activation of the DVI, more conventional data analysis approaches could have been applied.

The patterns of operator selection of warning sensitivity level are discussed for three of the operators in Section 3.2.3.6, on a daily average basis. These sensitivity levels were not correlated with the performance measures reported in the earlier sub-sections because that would have greatly complicated the analysis, although the data were all recorded and could be investigated in subsequent analyses. The primary concern here was to investigate the overall changes in driving behavior as the principal measures of effectiveness, regardless of which sensitivity settings the operators preferred to adopt.

As data were collected, they were processed and the characteristics of the runs were recorded for further reference. The maximum distance (by geometric coordinates, not accounting for indirect routing along streets) traveled from the depot and the maximum speed of the bus were also recorded to see if the bus had gone out for a run or just stayed around the garage for maintenance, in which case the data would not be used. The detailed results for the seven operators whose data were studied closely are shown Appendix C, but the results of the analyses of these data are described here. In each case, the strength of the conclusions from these analyses should be tempered by consideration of the limited number of bus operators involved (7).

3.2.3.1 Cumulative distributions of car-following time gap

In the cumulative distributions of driver behavior shown here, each line on a plot represents the data from one day of driving. The blue lines are for the days prior to activation of the DVI, and the red lines are for the days after the DVI was activated, so the contrast between blue and red lines represents the measured change in the driver's behavior. The detailed results for all operators are shown here for this first measure of effectiveness, but the details for the other measures are found in Appendix C.

When studying the cumulative distributions of car-following time gaps, the primary attention should be devoted to the lower tail of the distribution, representing the shortest time gaps. If the very short gaps occur more frequently, the driving style would be considered more aggressive and more likely to encounter a frontal collision hazard if the forward vehicle decelerates unexpectedly. In contrast, if very short gaps are less frequent (flatter start to the cdf plot), the driving style would be considered more conservative and less likely to encounter a frontal collision hazard.

The cumulative distributions of time gap in Figure 3-2 through Figure 3-8 show a large diversity of car-following behavior and of responses to the activation of the DVI among the seven bus operators. Of these operators, operator F was the most aggressive by an appreciable margin, and he appeared to use the forward collision warning system to drive slightly more aggressively (perhaps pushing the limits to try to operate on the boundary of triggering alerts).

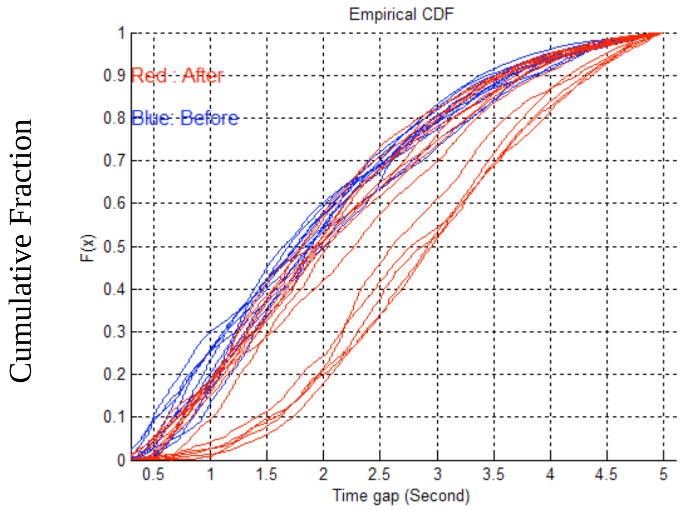


Figure 3-2 - Time gap cumulative distribution (Operator A)

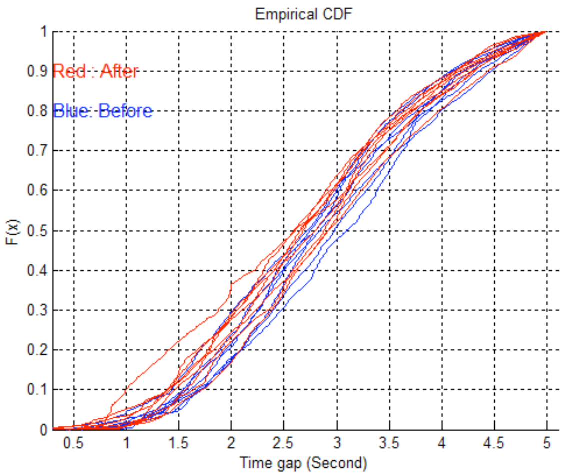


Figure 3-3 - Time gap cumulative distribution (Operator B)

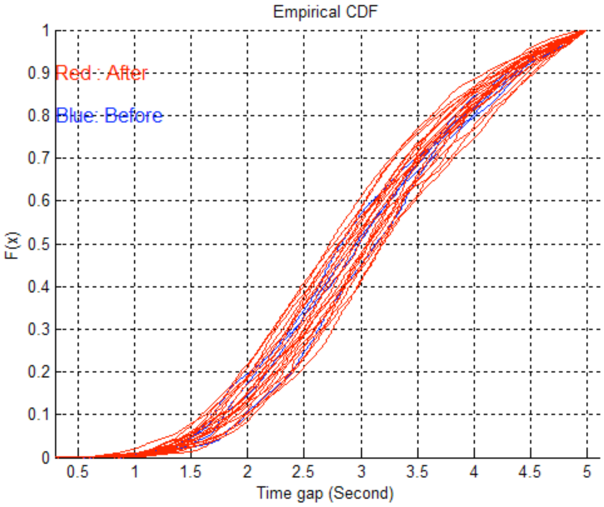


Figure 3-4 - Time gap cumulative distribution (Operator C)

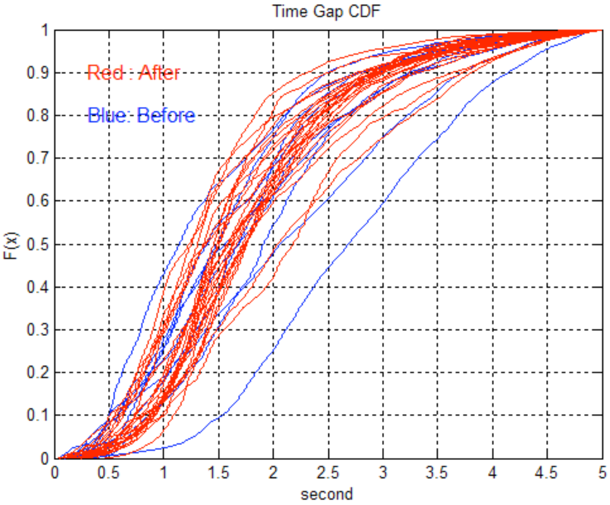


Figure 3-5 - Time gap cumulative distribution (Operator D)

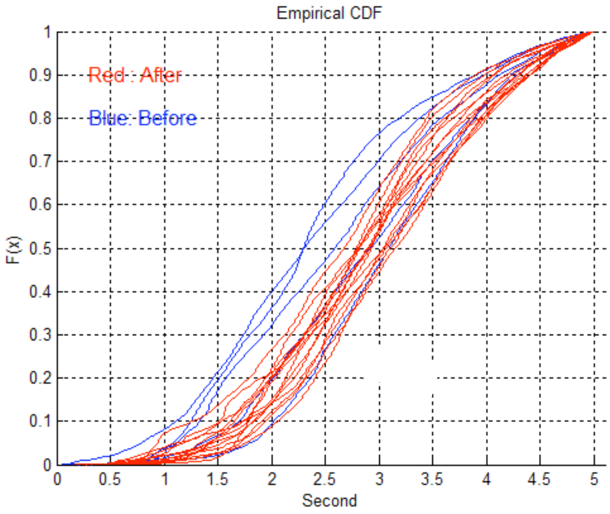


Figure 3-6 - Time gap cumulative distribution (Operator E)

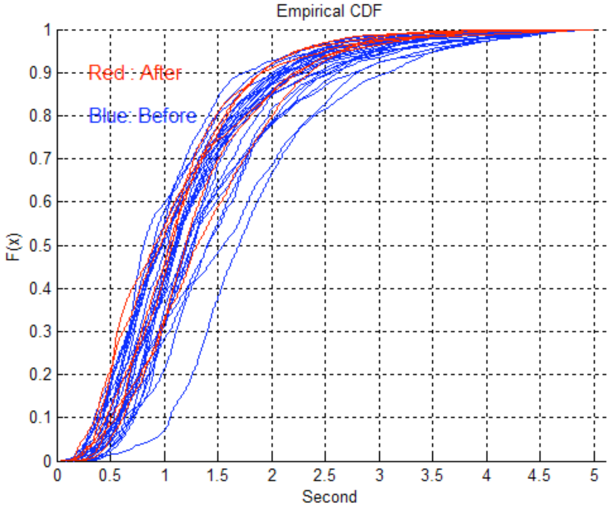


Figure 3-7 - Time gap cumulative distribution (Operator F)

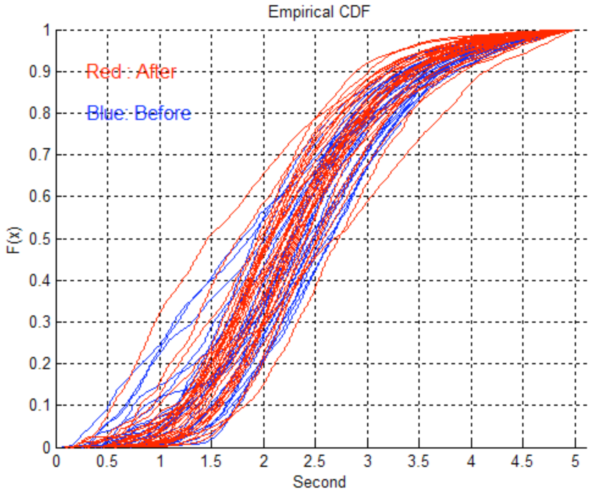


Figure 3-8 - Time gap cumulative distribution (Operator G)

Bus operators A and D were somewhat less aggressive than Operator F, but still more aggressive than the others. After the activation of the DVI, Operator A showed a distinctly bimodal distribution of behavior, driving somewhat more cautiously on some days than he had been prior to the DVI activation, but much more cautiously on other days. The most cautious behavior of Operator A occurred within a period slightly longer than one week, a few weeks after activation of the DVI. After a period of three weeks not driving the instrumented bus, his behavior returned to the "somewhat more cautious" pattern that he followed during his early use of the DVI.

Operator D was also rather inconsistent in his car following behavior, but became noticeably more consistent after activation of the DVI, even though he was not noticeably more conservative in his average selection of time gap. Bus operator G was the most inconsistent of the operators, but after activation of the DVI, he became more consistent and somewhat more conservative in his vehicle following behavior.

The data were not sorted based on conditions such as traffic density (which was not directly measurable), but rather each data set for analysis (each individual line) represented a full day of data. No patterns based on day of the week were discernible. When the data were examined for "learning curve" effects immediately after activation of the DVI, these effects were not evident. There were no discernible patterns in the evolution of driving behavior after DVI activation, other than the bimodal pattern discussed above for Operator A.

There are no "normative" data for vehicle following time gaps for transit bus operators, so there is no established baseline with which to compare the measured performance of these operators. Drivers are typically taught to drive with a 2-second gap, but it is notoriously difficult for drivers to perceive the time gap at which they are actually driving.

Bus operators C, B and E were the most cautious and consistent of the operators. Bus operator C was the most cautious and consistent of these. Bus operator E became noticeably more cautious after the activation of the DVI.

The numerical estimates of the lower tail percentiles of these cumulative distributions are shown as
Table C-1 in Appendix C. These indicate how large the differences are across the bus operator population when we consider the relative frequency of occurrence of very short time gaps, which could put the bus and its passengers into hazardous situations. The differences in the car-following behavior changes after activation of the DVI are also very noticeable, with the most cautious and most aggressive operators least influenced. Among the more "typical" bus operators, the aggressive ones were more likely to have their behavior modified by the activation of the warning system.

3.2.3.2 Cumulative distribution of brake pressure applications

The cumulative distributions of brake pressure applications are only available for Bus operators A, B and C because the brake pressure sensor was only available on the

SamTrans bus, but not on the PAT bus. A reduction in the frequency of occurrence of higher-pressure braking events (on the upper tail of the cumulative distribution) would indicate a shift to a smoother style of driving and one with less of a need to brake hard in response to forward disturbances, with a reduced likelihood of causing falls by standing passengers. This would be manifested as lower values of braking pressure at each of the cumulative percentiles.

Bus operator A showed an appreciable reduction in higher-pressure braking for some of his days of driving, as evident in Appendix C Figure C-8. It was difficult to discern differences in the braking responses of the cautious Operator B, and it appeared that the very cautious Operator C had a slightly increased frequency of harder braking events after the activation of the warning system, perhaps associated with over-reactions to alerts from the new system. The upper tail percentile values for these cumulative distribution functions are shown in Table C-2. Considering that data were only available for these three operators, it is not possible to draw strong conclusions regarding braking differences

3.2.3.3 Cumulative distribution of accelerations

The acceleration distributions were only available for Bus operators A-C because accelerometer measurements were only available on the SamTrans bus, not on the PAT bus. In this case, we are interested in the lower tails of the distributions, corresponding to the hardest braking maneuvers (largest negative values of acceleration). If the hard braking maneuvers are occurring more frequently, the driving style would be considered more aggressive and more in need of frontal warnings to avoid hazardous encounters. This more aggressive style would be manifested as larger negative values for the lower percentiles of the acceleration cumulative distribution.

These distributions are very similar to the shapes of the brake pressure distributions since there is a direct relationship between the brake pressure and the deceleration of the bus. Bus operator A shows the greatest reduction of harder decelerations after the activation of the DVI, but he was also the most aggressive operator in the “before” cases. Bus operator B had the most consistent deceleration behavior, while Operator C was in the middle. It is worth noting that some of the “after DVI” days for Operator A showed noticeably less frequent occurrences of harder decelerations than was typical for the other two operators, whose car following behavior was generally more conservative. Estimates of the lower tails of these distributions are shown below.

Table C-3. Considering that data were only available for these three operators, it is not possible to draw strong conclusions regarding braking differences.

3.2.3.4 Cumulative distributions of Time to Collision (TTC)

Data for the TTC distributions were available for all seven operators, and are shown in Appendix C Figure C-14 through Figure C-20. The important portions of these distributions are the lower tails, which correspond to the potentially hazardous conditions that could lead to crashes or to the need for the operator to decelerate hard. In other words, if there is a higher frequency of occurrence of small TTC values (or the TTC values corresponding to the lower percentiles are smaller), the driving would be considered more hazardous.

The differences across bus operators in the TTC distributions were much less than the differences in the other measures that were evaluated previously, and in most cases it was difficult to discern the changes between the before and after cases. Somewhat surprisingly, the most cautious operator, Operator C, showed somewhat smaller TTC values after the system was activated than before, indicating that perhaps the system gave him more confidence about following more closely than he would have done otherwise under comparably dynamic conditions (recalling that his steady car-following time gaps did not change). While his "before" values were larger than those for most of the other operators, his "after" values were very similar to those of the other operators.

Just as surprisingly, the most aggressive operator, Operator F, showed the largest increase in TTC values after the system was activated, and indeed his TTC values after activation were the largest among all the operators even though his car-following time gaps were the smallest. This indicates that he was following other vehicles closely but also responding quickly to the slowing of forward vehicles that can lead to lower (potentially more hazardous) values of TTC, and was using the collision warning system as an aid to "push the envelope" of his driving behavior, following even more closely than before. Operator G, the one with the largest day-to-day variations in driving style, also showed a noticeable increase in TTC values after the system was activated.

3.2.3.5 Cumulative distributions of required deceleration parameter (Arq)

The required deceleration parameter is the primary parameter used by the forward collision warning algorithm to determine whether to issue an alert to the operator and how urgent an alert to issue. Larger values of this parameter indicate the need for the operator to decelerate at higher braking rates in order to avoid conflicts, and are therefore considered undesirable from the perspective of safety. The concentration is therefore on the upper tail of the distribution of required deceleration, and safer driving is represented by smaller values of this parameter at each percentile. The cumulative distribution plots for the seven operators are shown in Figure C-21 through Figure C-27 in Appendix C and the upper tails of these distributions are described in Table C-5.

These results indicate that the activation of the forward collision warning system had no discernible effect on Operators C and G, and only modest effects on the other operators. Operator D appeared to show slightly higher values of the required deceleration parameter after system activation than before, implying somewhat riskier driving, but he was initially one of the most cautious operators based on this performance measure. All the other operators showed reductions in the value of required deceleration, and the reduction was largest for Operator A, who started out with the highest value of this performance measure.

The overall effect of the warning system activation was to reduce the diversity of driving performance across the seven operators and to produce a modest decrease in the occurrence of larger values of the warning criterion, the required deceleration parameter.

3.2.3.6 Operator selection of sensitivity level

The number of alarms (both imminent warnings and alerts) is related to the sensitivity level that the bus operator selects. If the sensitivity level is set high we can expect more imminent warnings and alerts. Figure 3-9 through Figure 3-11 shows the number of warnings (red lines), alerts (yellow lines) and the average sensitivity setting (blue line) per day for Operators A, B and C respectively. Note that the operators were free to select whatever sensitivity setting they preferred at any time, so the observed sensitivity settings represent their expressed preferences for each day of driving.

From these plots we see that all three operators have worked at all three levels of the sensitivity setting. We also note that for Operator A there was a general trend of a reduction of both warnings and alerts over the period of the study, with a parallel trend toward selecting reduced sensitivity. It is also quite noticeable that on the first day with the system turned on Operator A had nearly double the number of imminent warnings than for any other day. This suggests that on the first day of operation this operator experimented with the system.

Figure 3-9 through Figure 3-11 also show variations between the imminent warnings and alerts received by the three different operators, with Operators B and C generally getting many more alerts than warnings, while Operator A received more of a mixture, with sometimes more warnings than alerts and sometimes more alerts than warnings. The variability of these results gives a strong indication of the importance of providing the operator with the flexibility to adjust the system sensitivity level. Even within the relatively homogeneous (compared to the driving population in general) set of these three operators, the need for the three sensitivity levels is evident from these results. Operator A gravitated toward the lowest sensitivity setting, leading to very infrequent alerts by the end of his period of driving the instrumented bus, while Operator B went in the opposite direction and Operator C was between the other two in preferences.

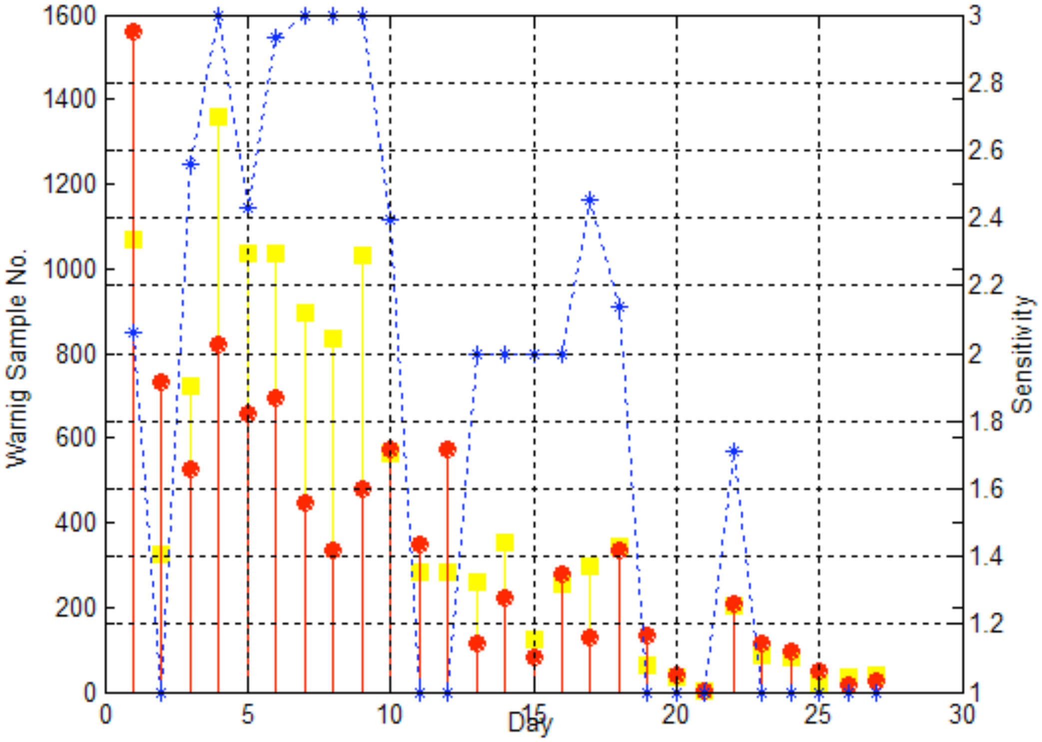


Figure 3-9 - Post-activation evolution of sensitivity versus warnings/alerts (Op A)

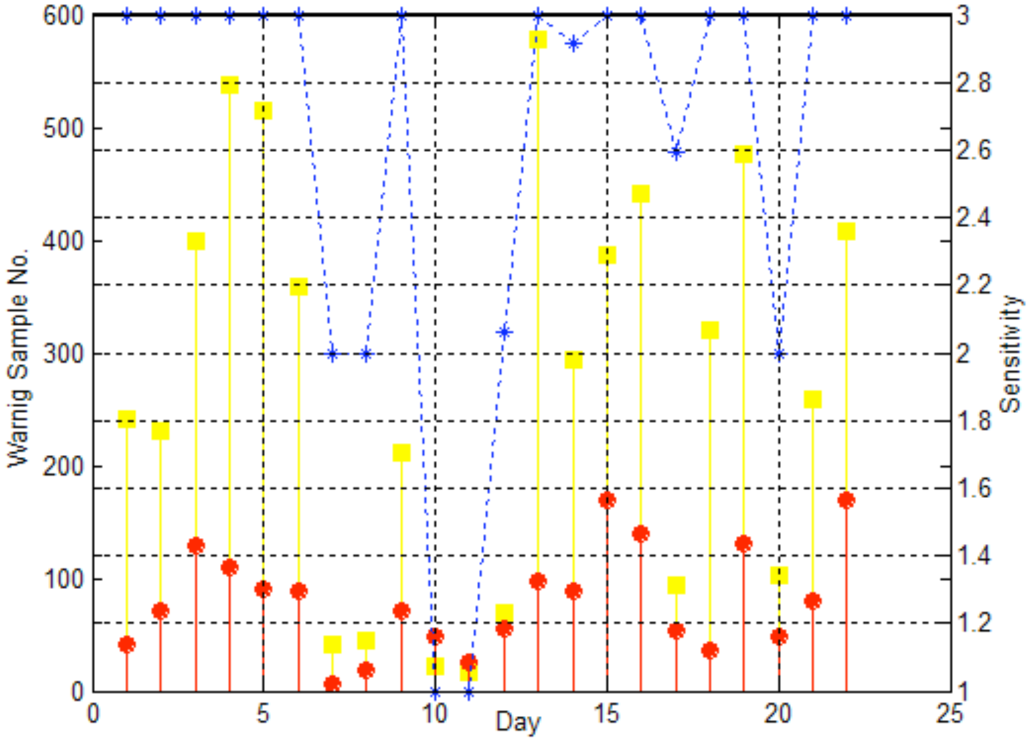


Figure 3-10 - Post-activation evolution of sensitivity versus warnings/alerts (Op B)

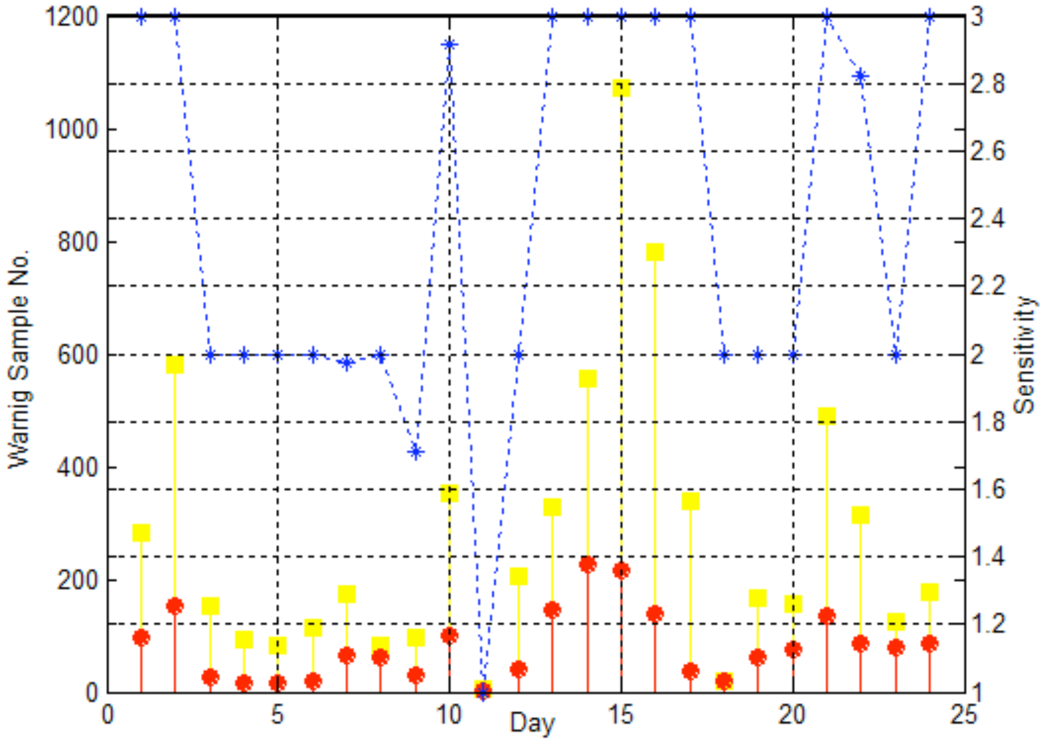


Figure 3-11 - Post-activation evolution of sensitivity versus warnings/alerts (Op C)

3.2.4 FCWS Technical Issues

The entire ICWS that was tested in revenue service was a prototype system, implemented using hardware and software that have not yet been refined to meet all of the requirements of a deployed system. Furthermore, the system included extra data acquisition hardware and software to make it possible to collect independent information about operating conditions (mainly video cameras) and to save all of the data for subsequent review and analysis. These elements would not be present on a fully operational deployed system, but they added complexity to the experimental ICWS implementation.

Because of the prototype character of the system, it is important to consider carefully the issues involved in determining which parts of the FCWS worked how well. Issues involving the host computer system should be of little concern at this stage because a deployable system would have to be based on a different type of computer that is less vulnerable to environmental disturbances, especially vibrations. On the other hand, the ranging sensors and inertial sensors were very similar to what one would expect to have in a deployable system, so their limitations need to be considered more seriously. The ranging sensor is the most important element of the system. Its ability to identify the location and motions of targets was identified in the controlled environment testing of Chapter 2. The other primary consideration for the ranging sensor is the ambient weather conditions, which are addressed here.

The SamTrans bus FCWS performance was studied under fog and rain conditions. During the initial testing of the ICWS in Pittsburgh, when the system was exposed to more severe weather conditions than those of the Bay Area, the LIDARs experienced more false detections. Subsequently, a subroutine was developed to match the pattern of the false targets and eliminate the target tracks that were believed to be attributable to fog and light rain and snow. Figure 3-12 shows the range-range rate plot of real targets (in red) and the false tracks caused by fog, rain and snow that are recognized by the algorithm subroutine (in blue) (12/10/2004). The improved algorithm rejects tracks that have a relative longitudinal distance to the bus of less than 1 meter, or around 2 meters but with a relative speed to the bus that is within (-2.6 m/s, +2.6 m/s) and have not been identified as vehicles.

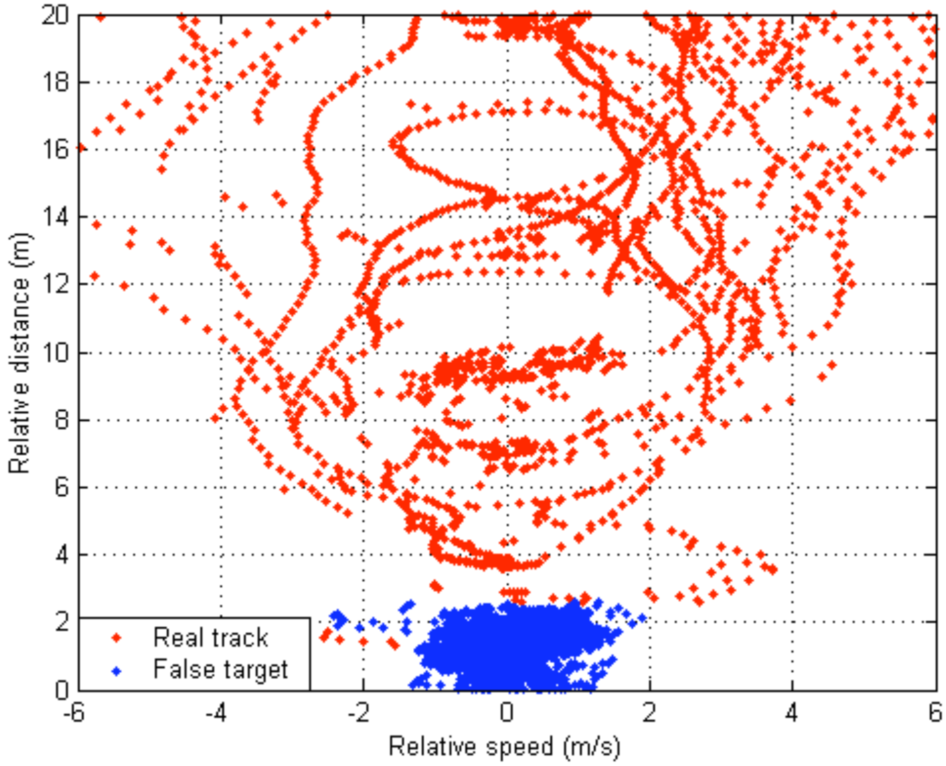


Figure 3-12 - Range and range rate of target tracks and tracks rejected

There is a trade-off in selecting the threshold for eliminating false targets. If the threshold is not set high enough, there can still be some warnings induced by rain, fog and snow. However, if the threshold is set too high, there will be risks associated with real tracks being discarded as false targets, or false targets being recognized as real tracks. An example is also shown in Figure 3-12, in which a few red dots appearing at the lower left corner were actually false targets. Although the percentage of errors is very low (as seen in Figure 3-9) and varies as the circumstances change, these false targets could trigger high level but short duration warnings as listed in Table 3-3.

Table 3-3 - Warnings triggered by mixed true and false targets

```
Time                           Warning Type
05:29:14.194-05:29:14.194      Level 7 Fog
05:43:04.519-05:43:08.419      True warning
06:16:50.569-06:16:50.644      True warning
06:19:28.669-06:19:30.319      True warning
06:24:24.244-06:24:24.394      True warning
06:29:25.669-06:29:25.744      Level 7 Fog
.........................
06:34:37.744-06:34:38.119      True warning
06:35:02.644-06:35:02.644      Level 2 Fog
06:35:03.019-06:35:03.019      Level 7 Fog
06:36:12.469-06:36:12.469      Level 3 Fog
06:36:19.969-06:36:24.544      True warning
06:36:56.044-06:36:56.044      Level 7 Fog
06:43:21.319-06:43:21.544      Level 7 Fog
.........................
08:17:00.469-08:17:01.744      True warning
```

The system has also been designed to deal with very severe weather conditions, in which LIDARs can not function properly. When the windshield wiper is turned on, indicating that the weather is getting bad, the system automatically switches from the LIDARs to the radar sensors (Eaton-Vorad EVT-300). The test data show that the system is now capable of working under harsh weather conditions, although the performance is somewhat degraded due to the less desirable azimuth angle resolution of the radar.

The more general issue of the rate of false positives (or false alerts) was not addressed explicitly in the analysis of the data because the engineering data recorded on the vehicles cannot reveal which forward collision alerts were false and which were true. That can only be done by detailed review of the video data recorded for each alert, with the data analyst making a judgment regarding the validity of each alert after studying the videos. Such a review could be conducted in the future using the existing data set, but it was not achievable within the resource constraints of this project.

3.2.5 Summary of Key Findings about Driving with FCWS

The analyses of the five key driving measures of effectiveness have produced several useful insights:

- The introduction of the warning system appeared to lead to more consistency of driving behavior across the sample of operators. In general, the driving behavior changes were in a favorable (safer) direction. However, the test period was not long enough to establish how durable the changes would be in the long term, and there was no opportunity to evaluate carry-over effects on the behavior of operators after they ceased driving the buses equipped with the warning systems.

- The largest differences between individual bus operators can be seen in the distribution of short time gaps that they use in car following. These show most dramatically which operators are most cautious and most aggressive.

- The most cautious bus operators also tend to be most consistent in their behavior from day to day, and in most cases their behavior was least affected by the introduction of the forward collision warning.
- The operators whose behavior was most inconsistent before the introduction of the warning system became noticeably more consistent after the warning system was activated.
- Different bus operators adapted to the introduction of the warning system in different ways, indicating that the effects across a more diverse driving population are likely to be even more diverse.
- Different bus operators showed different preferences in selection of warning sensitivity level, even within a very small sample of operators, indicating the importance of adjustable sensitivity.
- In general, the driving behavior changes were in a favorable (safer) direction. However, the test period was not long enough to establish how durable the changes would be in the long term, and there was no opportunity to evaluate carry-over effects on the behavior of operators after they ceased driving the buses equipped with the warning systems.
- The LIDAR sensors are vulnerable to generating false targets at short range in adverse weather conditions (precipitation), indicating the need for alternative sensors or for modifying the warning logic to disregard the false targets.

3.3. Evaluation of Side Collision Warning System (SCWS)

3.3.1 SCWS Measures of Effectiveness

3.3.1.1 Change in warning rate

One MOE of the side component of the CWS is the warning rate, the number of alerts or imminent warnings per hour. If the system makes the driving behavior safer, one expects the warning rates to decrease when the DVI is switched on. It is helpful to distinguish two different changes of driving behaviors. The first is a proactive change; the operator avoids getting into situations that set off warnings. The second is a reactive change; the operator reacts to warnings when they are issued. In the first case, warnings of all duration are reduced, while in the second only warnings lasting longer than the driver reaction time will be reduced.

3.3.1.2 Change in steering behavior

The second MOE for the side system is the steering behavior of the driver when the DVI is switched on. We will attempt to see how it is different during critical situations compared to when the DVI is off. When the driver is warned about a danger on the side of the bus, one would expect the driver to attempt to decrease the danger by steering the bus away from it, so we will focus on the steering during the 5 seconds after the system detected the danger.

3.3.2 Data Processing Tools and Procedures

In Section 3.1 we described the routes, schedule, participants, training and data collection. In the next sections we explain how we selected specific runs from the data and analyzed them.

3.3.2.1 Selection of runs

The selection of the runs for the analysis is critical to ensure that the results are meaningful and unbiased. First, we selected operators who drove several runs on the same route when the DVI was switched off and when the DVI was switched on. Next, we checked the integrity of the data of each run. All the systems had to work, as indicated by the presence and correct size of the respective data files. In several runs the laser scanner was either retracted or dirty for an extended period of time, so these runs were rejected. We also checked the alert rate and the distance traveled by the bus, and if they were very different from the average run, we investigated the reason. Examples of reasons are failure of the odometer, partially retracted laser scanner and corrupted data files. Runs with these errors were also eliminated from the data base.

3.3.2.2 Analysis of runs

To avoid the introduction of biases through the analysis, we reproduced all the warnings from the raw sensor data. Our biggest concern was that during the time the DVI was on, the operators switched the sensitivity levels. Those runs have to be compared to the "DVI-off"-runs, when the sensitivity level was fixed. This can only be done by rerunning the warning algorithm with the same sensitivity settings for all runs. Our other concern was that possibly some other parameters or software versions were different between the runs. In these cases, the warnings we get in the analysis would not be exactly the same as the ones displayed to the operator. This will result in a dilution of the effect we try to show; i.e., it will be harder to see a change in operator behavior, but it will not bias the data in a way that produces a change in operator behavior where there is none. If the operator behavior did not change, we will see the same rate of warnings and the same steering behavior with DVI on and DVI off.

As mentioned in the previous section, runs in which the laser scanners were retracted or dirty for extended times were eliminated from the dataset, but this still left some runs when the scanners were retracted or dirty for short times. The signature in the data for retraction or dirt is that the scanner sees its housing or the dirt, which appear as objects at a distance of a few centimeters. We developed an algorithm based on this signature to mark the data so that warnings created during times when the scanner was retracted or dirty were not counted.

If several warnings occurred at the same time or within less than one second of each other they are considered one warning. This eliminates counting several warnings in cluttered scenes, which the operator will perceive as one warning.

3.3.2.3 Run statistics

The total amount of data used in this analysis is 263 hours or 6989 km of driving. A more detailed breakdown is shown in Table 3-4, and the warning rates are shown in Table 3-5.

Table 3-4 - Durations and distances of driving used for the MOE analysis

		SamTrans	PAT	Sum
DVI on	duration [h]	44	86	130
	distance [km]	1160	2477	3587
DVI off	duration [h]	37	94	133
	distance [km]	1071	2331	3402

Table 3-5 - Warning rate for different side warning levels, by side and transit agency

Side	Warning rate	SamTrans	PAT
right	Alerts / h	22.7	18.2
	Imminents / h	5.6	7.3
left	Alerts/h	18.8	24
	Imminents / h	7.5	8.1

In the next section we compare the rates of occurrence of warnings of similar durations. Figure 3-13 shows the probability density function of alert duration (The distribution of imminent warning durations looks basically the same). The left graph shows the data in fine bins for up to 5 seconds. Most of the warnings are of very short duration, and 75% are less than 0.5 seconds long. To obtain more samples in each bin for the later comparison we increased the size of the bins to 0.5 seconds, as shown in the right graph. The last bin includes all the warnings lasting more than 1.5 seconds.

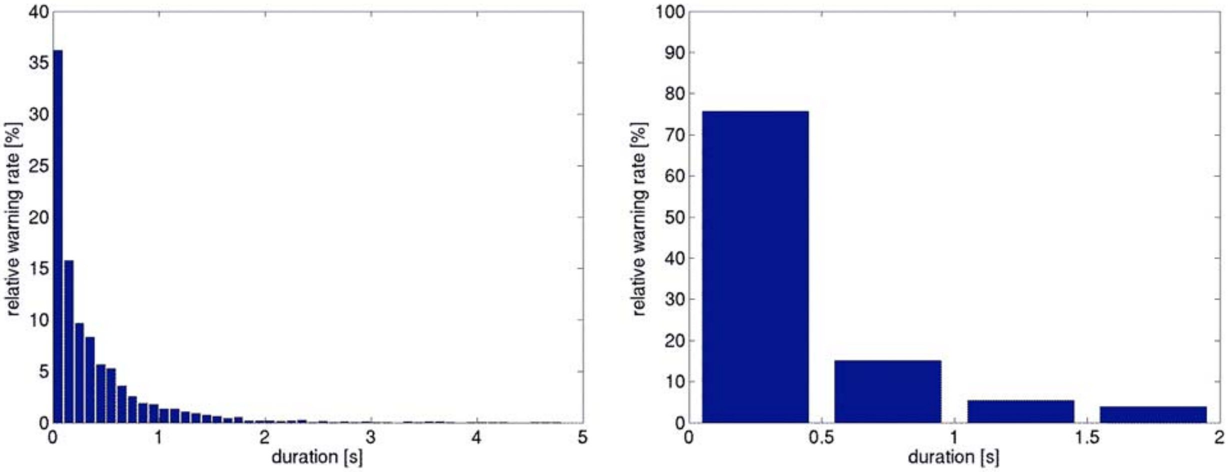


Figure 3-13 – Probability distribution of side warning durations

The warnings lasting more than 1.5 seconds are of greatest interest, since they last longer than the typical reaction time of an operator.

3.3.3 Analyses of Driving Behavior

3.3.3.1 Change in warning rate with DVI activation

The objective of this test is to find statistically significant changes in the warning rates due to the SCWS. We distinguish between alerts and imminent warnings and between four different ranges of warning duration.

We compare the rate of warnings when the DVI was switched off with the rate of warnings when the DVI was on for each side of the bus, using the ratio on/off and the difference on-off. For each result, we calculated the error assuming that the distribution of the absolute number of warnings is a Poisson distribution. Then the error on the absolute number of warnings is simply the square root of the absolute number and one gets the error of any derived quantity (rate, ratio, or difference) through standard error propagation. It needs to be mentioned that the Poisson distribution is only an approximation to the real distribution of the warnings. For example, it sometimes happens that the bus drives very close beside some vegetation, which can create many warnings in a short time. It is therefore likely that the errors shown in the graphs underestimate the real errors.

We did the calculations separately for the SamTrans and PAT data, but did not find a significant difference between the two data sets. The results agreed with each other within their statistical errors. We therefore combined both data sets to get a larger data sample. The conclusions are valid for both. Figure 3-14 shows the ratios and differences for the right side of the bus.

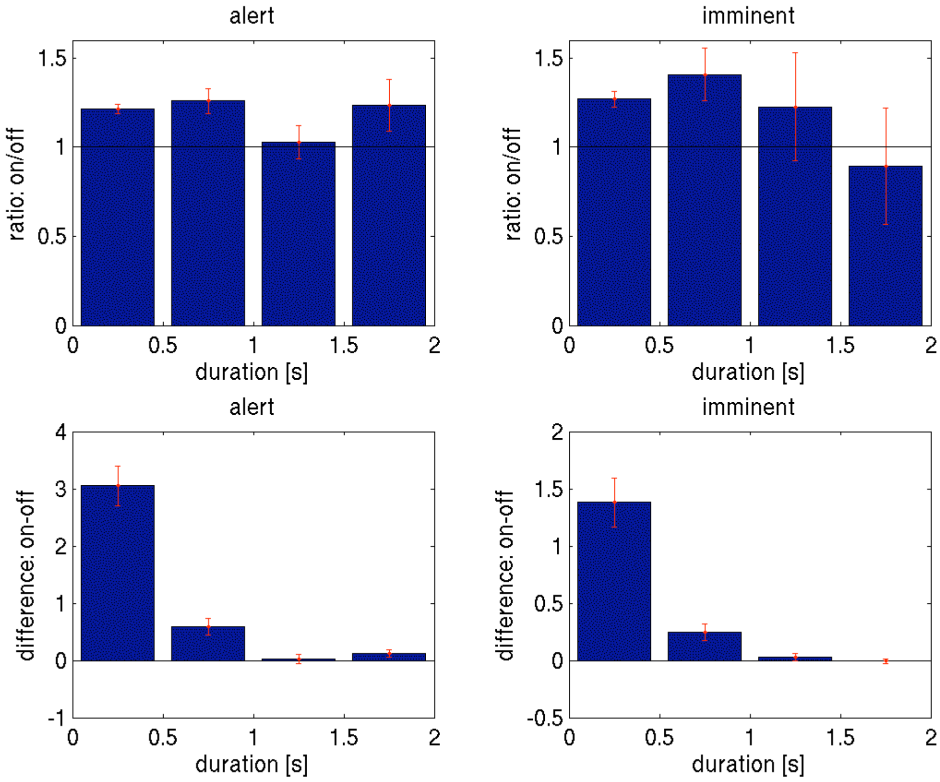


Figure 3-14 - Ratios/differences of the alert/imminent warning rates for the right side

One can see a sizable increase of alert rate (about 20%) and imminent warning rate (about 25%) after the DVI was activated. The statistical errors on the warnings lasting more than 1 second are large enough that these rates are also consistent with the hypothesis of no change based on activation of the DVI. The first conclusion to draw from these data is that we can not see an improvement in operator behavior or reaction to warnings.

A possible explanation for the increase in warnings is that the operators are using the system to get closer to the edge of the road (e.g., the guard rail), trying to stay right on the warning boundary. This hypothesis is consistent with the anecdotal evidence of one operator reporting that he used the system in this manner.

There are other possible explanations, including an undetected system failure or degradation of sensors. It is also plausible that the amount of traffic, traffic behavior, or amount of vegetation changes with the seasons. The periods when the DVI was on or off were arranged sequentially and covered different seasons, which then introduced possible biases. Examples of seasonal changes are less pedestrian traffic during summer break, less pedestrian traffic in the winter because of bad weather, and varying amounts of foliage during the year. Another explanation is that the system may have degraded the operator behavior.

Figure 3-15 shows the ratios and differences for the left side of the bus:

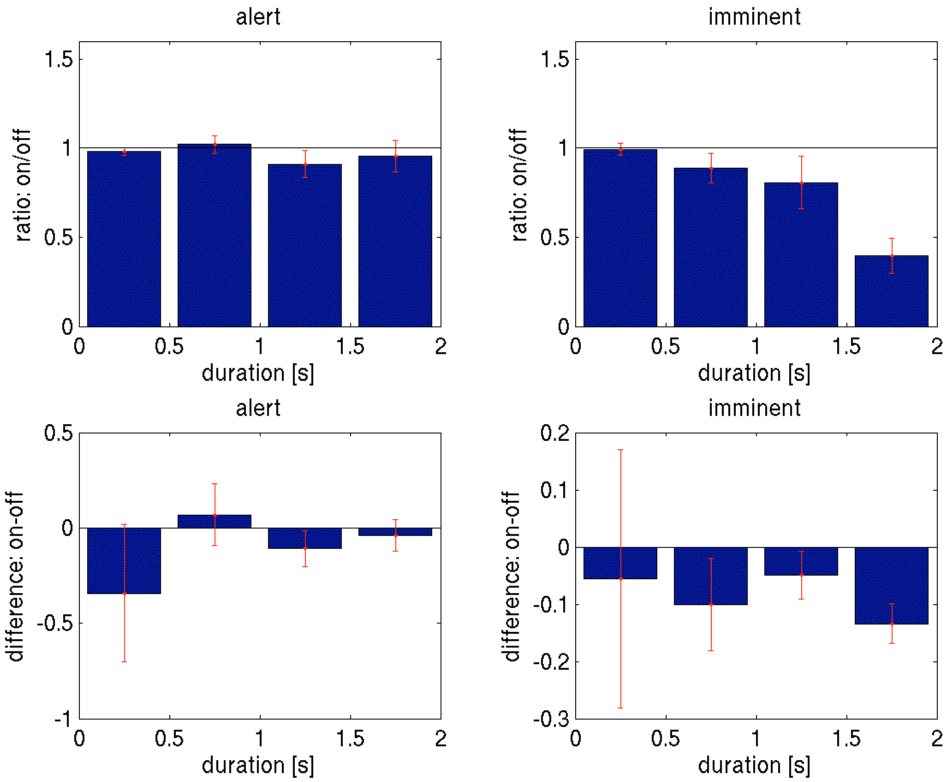


Figure 3-15 - Ratios/differences of the alert/imminent warning rates for the left side

These results show a reduction of alerts and imminent warning rates. For imminent warnings lasting more than 1.5 seconds the reduction is statistically significant, but for all other cases the data are also consistent with no change. The 60% reduction of imminent warnings lasting more than 1.5 is a strong effect.

As mentioned earlier, a reduction of rates across all durations points towards a change in overall operator behavior, whereas a drop in the warnings lasting more than 1.5 seconds points towards a reaction of the operator to warnings. The data indicate the latter, meaning that the operator reacts to imminent warnings that were issued and therefore the imminent warnings lasting more than 1.5 seconds are significantly reduced.

The key findings of the warning rate analysis are as follows. We did not find a reduction in the warning rate on the right side, but rather it increased for warnings of short duration. The reason for that could be that the drivers used the system in an unintended way such as driving closer to the road boundary. Other possible explanations are seasonal changes or undetected problems with the system. For the left side we saw a dramatic (60%) reduction in the number of imminent warnings lasting more than 1.5 seconds. This is an indication that the drivers reacted to warnings and reduced the danger of the situations.

3.3.3.2 Change in steering behavior

The objective of this test is to see if there is a change in the steering behavior of the driver due to the SCWS.

We examined the steering behavior right after a warning was issued. Figure 3-16 shows the yaw rate for 5 seconds after the warning for several warning events on the left side. The green curves are single events, and the red one is their average.

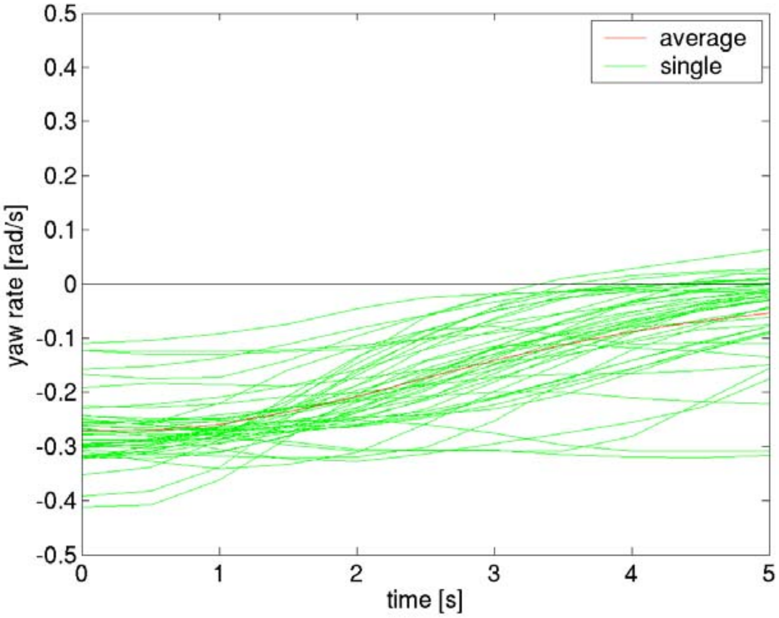


Figure 3-16 - Yaw rate after a warning was issued

In order to collect a set of warning events similar to each other and with the initial steering to the left we used the following selection criteria:

1. The events were all from one driver.
2. The trigger warnings were imminent warnings on the left side.
3. The initial yaw rate was less than -0.1 rad/s.
4. The initial yaw acceleration was close to zero (between ± 0.02 rad/s^2).

The average of the curves is indicated in the figure as a red line. We compared the average from events when the DVI was on with the average from events when the DVI was off. Both are shown in the right graph of Figure 3-17 together with their difference, and the equivalent data for the right side are shown in the left graph. For the blue curve the DVI was on and for the green curve the DVI was off. The red line is the difference between the two curves, which is a measure of the driver reaction to the warning.

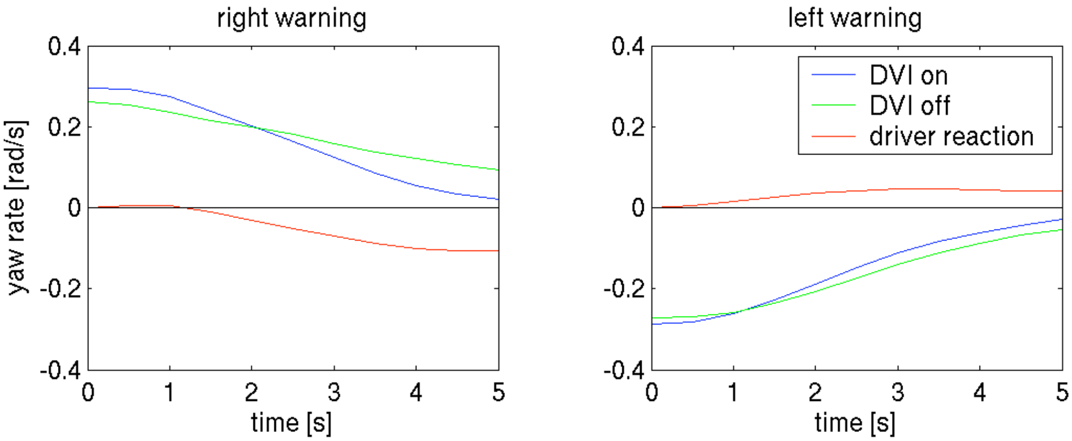


Figure 3-17 - The average yaw rate after an imminent warning

If we had a large enough sample and no factors other than whether the DVI was on or off would play a role, then the two curves would have the exact same value at time t = 0 s. Because we do not have a very large sample the two curves are somewhat different at t = 0 s. We neglect this difference in the graph and all the "driver reaction" curves (red) start at zero. In both graphs the driver reaction is fairly smooth and very small for the first 1 to 1.5 seconds (the typical reaction time).

The driver reaction to left warnings is a positive yaw rate. Initially the bus driver is steering to the left. Beginning when the system detects the danger, the driver starts to straighten the driving direction. The positive yaw rate of the driver reaction indicates that the driver straightens the steering faster when the DVI is on, i.e. the driver steers away from the objects that caused the warning more quickly.

One expects that the graph for the right side would look similar to the one for the left side, except that the directions are reversed; i.e., the yaw rates have opposite signs. Indeed, this is the case, as one can see by comparing the left and right graphs of Figure 3-17. We can conclude the same for the right as we did for the left side: The driver reaction we observe indicates that the driver steers away from the danger more quickly when the DVI is switched on. One difference between the right and left graphs is that for the right side the driver reaction is stronger.

In order to estimate the significance of the previously mentioned results we took two random sets of events when the DVI was off and analyzed them in the same manner as we did the DVI on and DVI off sets. The resulting "driver reaction" is a measure of the fluctuations; it would be zero if there were no fluctuations:

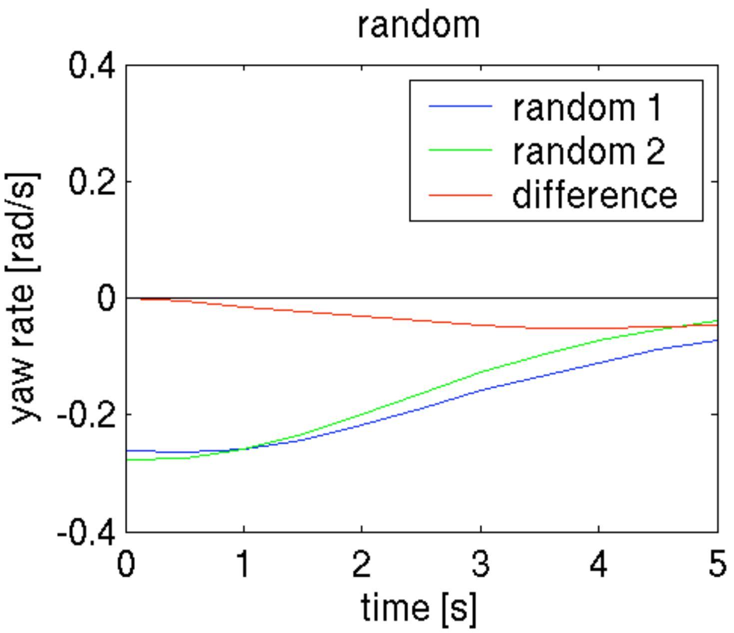


Figure 3-18 - Measure of the fluctuations.

Figure 3-18 shows the estimate of the fluctuation. It is of similar magnitude to the driver reaction on the left side (Figure 3-17 right graph) and of smaller magnitude than the driver reaction on the right side (Figure 3-17 left graph).

We did the same analysis for alerts instead of imminent warnings and found weaker "driver reactions". We also analyzed different drivers, but for those we had many fewer events and therefore the random fluctuations were bigger.

The key finding of the steering behavior analysis is that we see an indication that given a warning on either side, the driver reacts more quickly by steering earlier away from the object. The magnitude of the steering correction seen after a warning on the left side was of similar magnitude than random changes in steering. The magnitudes seen on the right side were of greater magnitude than random changes in steering.

3.3.4 False Positive Rate during Normal Operation

In Section 3.6.1, the operators state that although the collision warning system is acceptable to them, they still would like a lower false warning rate (Section 3.6.2). The false warning rates which are discussed below should therefore be considered in the context of an acceptable system, while recognizing that a reduction in the false warning rate is desirable.

We reviewed all alerts and imminent warnings in two runs and determined if they were true or false. One of the runs took place in California and the other in Pennsylvania, and together they were five hours long. We wanted to gather enough data to ensure that we observed the main categories of false warnings. Collecting at least 30 warnings ensured an upper limit of 10%; i.e., false warning categories which were not observed have a rate of less than 10% (90% confidence level). Table 3-6 shows the absolute number of warnings, the relative number for each category (percentage of the total number of warnings), and the warning rates, for the left and right sides.

Table 3-6 - True and false positive warnings.

	absolute				relative [%]				rate [1/hour]			
	alert		imminent		alert		imminent		alert		imminent	
	right	left	right	left	right	left	right	left	right	left	right	left
True	60	94	15	9	59	71	47	26	12.0	18.8	3.0	1.8
Vegetation	10	3	2	0	10	2	6	0	2.0	0.6	0.4	0.0
false velocity	21	28	10	20	21	21	31	57	4.2	5.6	2.0	4.0
no velocity	0	2	1	0	0	2	3	0	0.0	0.4	0.2	0.0
ground return	10	4	3	3	10	3	9	9	2.0	0.8	0.6	0.6
Other	1	2	1	3	1	2	3	9	0.2	0.4	0.2	0.6
Sum	102	133	32	35	100	100	100	100	20.4	26.6	6.4	7.0

The most common situations that cause true warnings are vehicles passing and fixed objects in the path of a turning bus. On the right side there are additional true warnings caused by pedestrians entering the bus or walking towards the bus when the bus has not yet come to a full stop.

A majority of the alerts are true alerts, whereas a majority of the imminent warnings are false positives. The most common reason for false imminent warnings is that the velocity was incorrect, but as explained below this kind of error is not very serious.

3.3.4.1 Vegetation

The system can not distinguish between vegetation (grass, bushes, and trees) and other fixed objects, but the threat posed by vegetation is much less than other objects because a bus can come in contact with grass, leaves or small branches without being damaged. A warning triggered by vegetation can often be considered a nuisance warning. This is the least serious kind of system error because the system functions correctly, but the warning is considered a nuisance. Figure 3-19 shows a situation when the bus comes close to a bush and the ICWS triggers an imminent warning. On the right side the four images from the four side cameras (see Figure 2-5) are shown. The bush can be seen in the upper right image, overlaid with a red box, indicating an imminent warning for that object. The red object box can also be seen in the birds-eye-view of the situation on the left. Notice that part of the bush extends over the curb. If an object is off the curb the warning algorithm will give it a higher probability of collision than if it is on the curb.

3.3.4.2 False velocity

The velocities of the objects are determined by the DATMO algorithm. The description of the algorithm and the detailed characterization of its performance can be found in the document FTA-PA-26-7006-04.1 “Integrated Collision Warning System Final Technical Report”[xi]. Figure 2-12 shows the error distribution of the velocity in the x- and y-direction from that report.

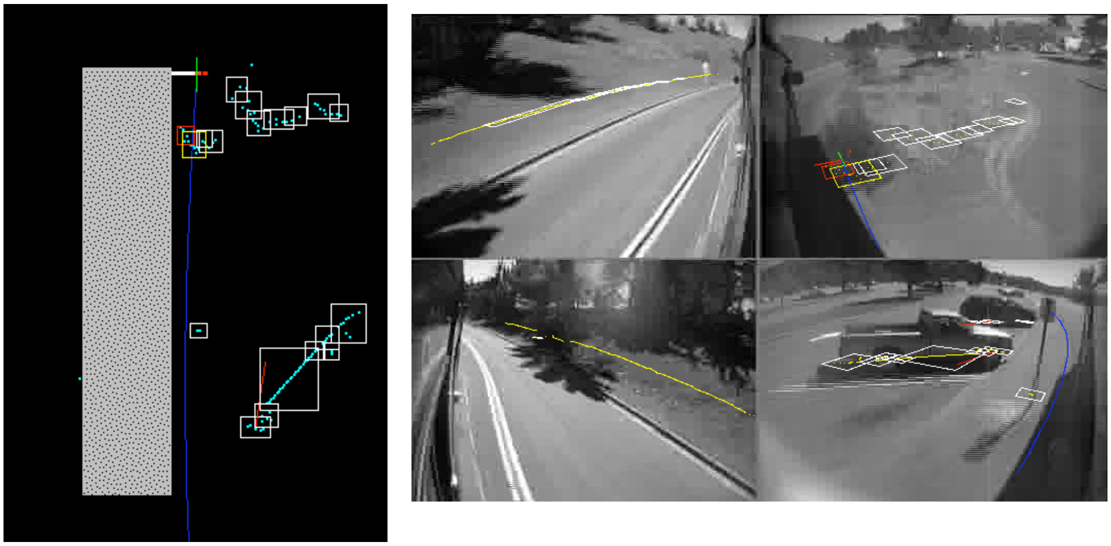


Figure 3-19 - Overhanging bush is close enough to trigger an imminent warning

The distribution is characterized by a Gaussian shape plus some additional outliers. The false velocities which give false warnings are from the tail of the Gaussian distribution or are outliers. An example of a case when a slightly incorrect velocity leads to an alert is shown in Figure 3-20. The vehicle can be seen in the lower left image with a yellow box on it, indicating an alert. The yellow box also appears in the birds-eye-view display.

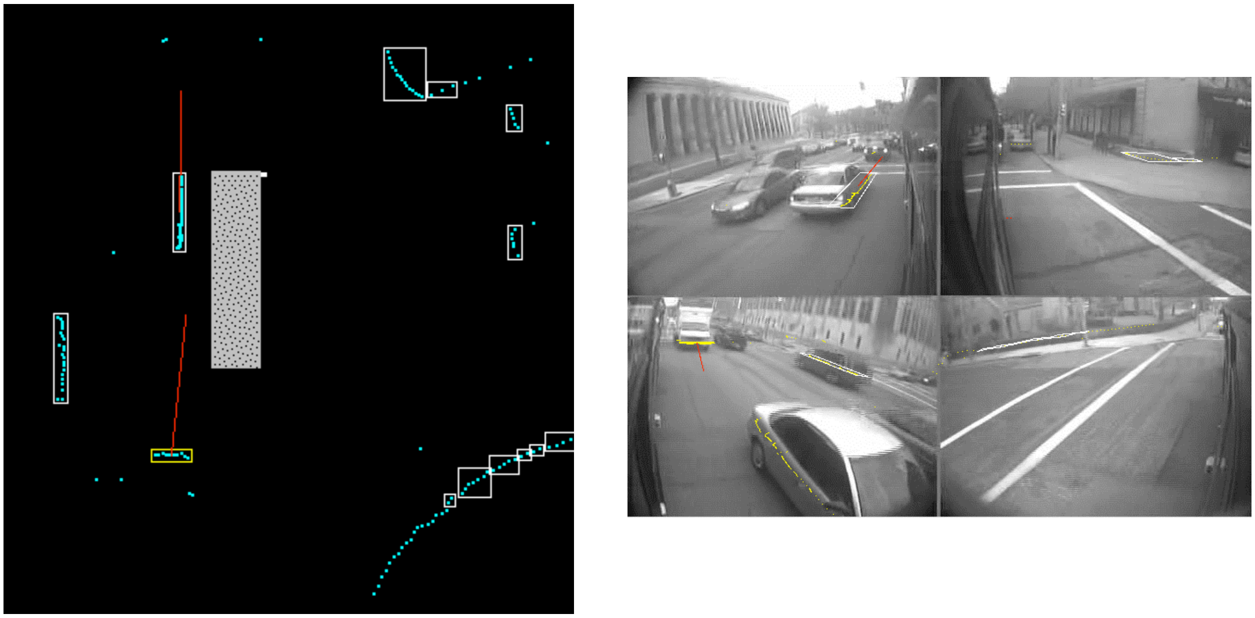


Figure 3-20 - The velocity of the vehicle is slightly off, leading to an alert

The incorrect velocity increases the probability of collision by enough to cross the warning threshold. It needs to be mentioned that this kind of error is not very serious because the danger level was only slightly overestimated. In most of the cases when an imminent warning was issued because of a false velocity (such as Figure 3-19) the correct warning level would have been an alert.

3.3.4.3 No velocity information

DATMO needs about 0.5 seconds to determine the velocity of an object after its initial detection. During that time the system sets the velocity of the object to zero. In some cases this can lead to a false warning, especially if the object is in the path of the bus and moving away from the bus. This error is of medium seriousness because an object is present but the threat level is misjudged.

It is possible to avoid these false warnings by waiting the 0.5 seconds until the velocity of the object has been established, but this would introduce latency and therefore false negative warnings.

3.3.4.4 Ground return

The laser scanners will see the ground if the bus rolls or pitches or if the ground in the vicinity of the bus slopes upwards with respect to the plane the bus stands on. Depending on the location of the ground seen by the sensor the system might issue a warning, as shown for example in Figure 3-21.

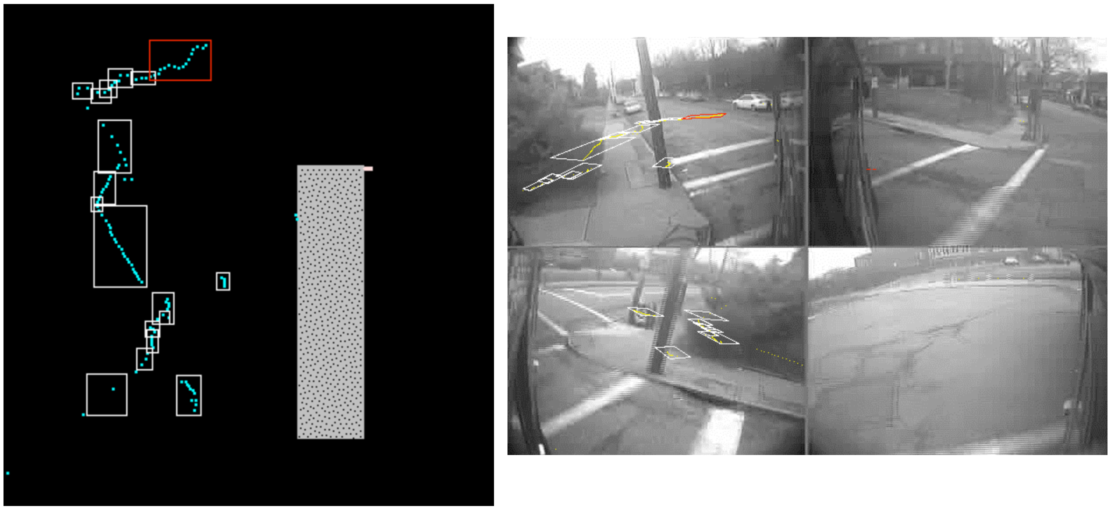


Figure 3-21 - Ground returns seen as an object in the left front of the bus (red box)

In this case the bus is turning left. The laser scanner sees the ground and the system thinks an object is directly in the path of the bus and issues an imminent warning. In the left upper image the ground return is indicated as a red (imminent warning) box and in the birds-eye-view display it is the red box in the upper left corner. This is the most serious error, because a warning is issued when there is no threat whatsoever.

3.3.4.5 Other reasons for false positives

There are many other reasons for false positive warnings, which can vary greatly in their frequency from run to run. For example, in some runs a malfunction of the retraction mechanism misaligned the laser scanner and resulted in hundreds of false warnings. Some of the reasons were easily eliminated after their discovery, but they are listed here for completeness.

Retraction malfunction: When the laser scanner is retracted, a switch should signal this fact to the system. In some cases the switch malfunctioned and the sensor was retracted without the system knowing about it.

Dirt on the scanner: Dirt on the laser scanner appears as an object very close to the bus. This problem can be solved by discarding all scanner data points very close to the scanner itself.

Scanner sees the bus: The laser scanner can see parts of the bus if the scanner is slightly misaligned or if some parts of the bus protrude, such as an open door or a wheel when the bus is turning. This problem can be solved by excluding returns from certain areas, but this has the side effect that these areas are now blind spots.

Error in DATMO: There are many ways that the DATMO algorithm can make mistakes. The most common one was already mentioned above, this being the incorrect estimation of the velocity of an object.

Splashes: Splashes of water can be seen by the scanner and trigger a warning (see Section 3.3.6.2.6 on weather effects).

Noise in turn rate: The turn rate of the bus is measured by a gyroscope, which has some noise, so there is a small chance that it gives an erroneous value. Very few cases were observed when these errors led to a false warning.

Dust: A cloud of dust can be produced by the wheels, appearing as an object to the system.

3.3.5 Reduction of Nuisance Alarms through Curb Detection

In an earlier document [xii] we reported that the warning rate can be reduced by detecting the position of the curb. If a person or an object is on the sidewalk, the likelihood of a collision is smaller, because the person or object is more likely to remain on the sidewalk. If one takes this into account, the number of warnings on the right side of the bus can be reduced by 30%. The warning rates displayed in Table 3-6 already include this 30% reduction.

3.3.6 SCWS Technical Issues

In this section we discuss various things that could cause a degradation of the system performance. Foremost is the effect of weather, but dust or dirt can also have an effect on the performance of the system. We first investigate the influence of the weather on the full system and then consider the degradation and failures of system components.

The National Climatic Data Center (NCDC) Web site (http://cdo.ncdc.noaa.gov/ulcd/ULCD) offers hourly and daily climate data gathered by automated weather stations located at regional airports. These data are unedited; therefore the data have yet to pass quality assurance measures. We retrieved the weather data for the Pittsburgh Allegheny Airport (airport code AGC), the closest airport to the common routes of the bus. For each run of at least one hour duration we calculated the average precipitation rate (inches per hour) and average temperature (Fahrenheit).

Of 339 good runs the distribution of precipitation was as shown in Figure 3-22. Good runs mean that all the systems had to work, as indicated by the presence and correct size of the respective data files. Almost 90% of all runs (301 runs) had no precipitation. The highest rainfall was 0.16 inches per hour.

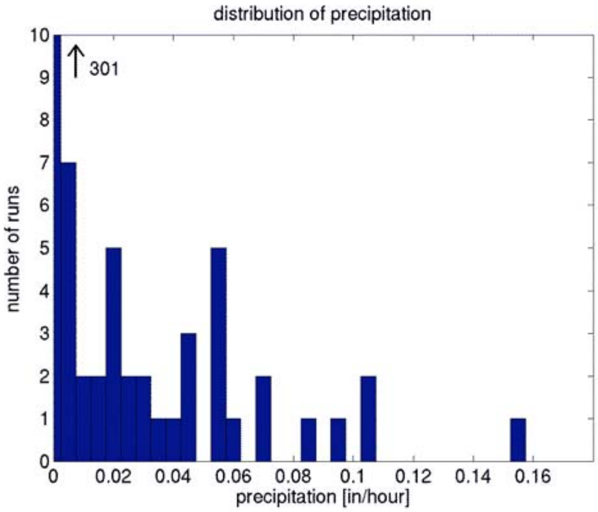


Figure 3-22 - Distribution of precipitation

The distribution of average temperatures can be seen in Figure 3-23. The lowest temperature during a run was 3^{o} F and the highest 85^{o} F. The mean temperature for all runs was 47^{o} F and the mode of the distribution was 55^{o} F.

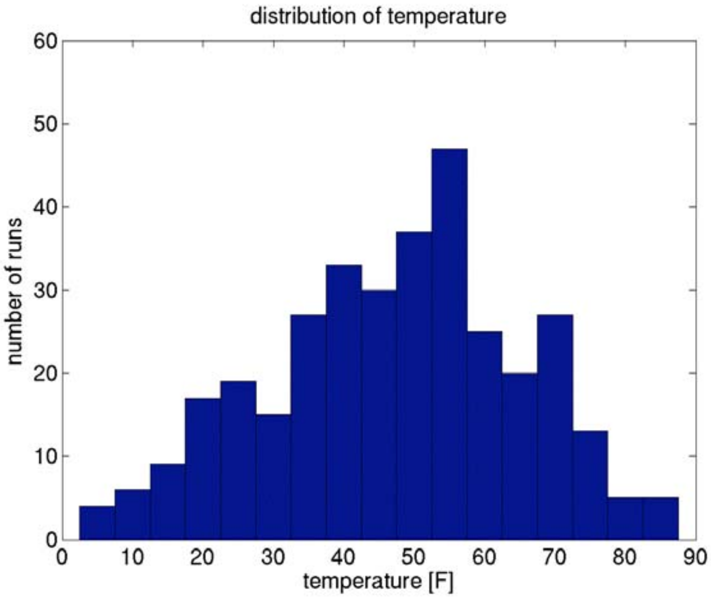


Figure 3-23 - Distribution of average daily temperature

The weather can affect the SCWS by corrupting a sub system or degrading the performance of the sensors. We first consider the overall performance of the system to see if there is a correlation between performance and weather, and then examine in detail how the weather affects subsystems.

3.3.6.1 Performance of system in different weather conditions

For the analysis in this section we used runs when all the systems worked, as indicated by the presence and correct size of the respective data files. These include runs when the laser scanner was retracted or dirty.

If the weather inhibits the detection of objects, the alert rate will be reduced, but if the weather creates ghost objects, the alert rate will be increased. We counted the number of alerts per hour, without taking into account the duration of the alert. It is difficult to imagine how weather could change the distribution of warning duration without a change in the warning rate; e.g., warnings from short-lived ghost objects would give more short warnings, but the warning rate would also be increased. On the other hand, a reduction in warning rate could happen without a change in the distribution of warning duration. The alert rate is therefore a better measure of performance than the alert duration. The rate of imminent warnings could also have been used, but there are many more samples for alerts. Figure 3-24 shows the distribution of alert rate, not including a few runs that had an alert rate of more than 250 per hour.

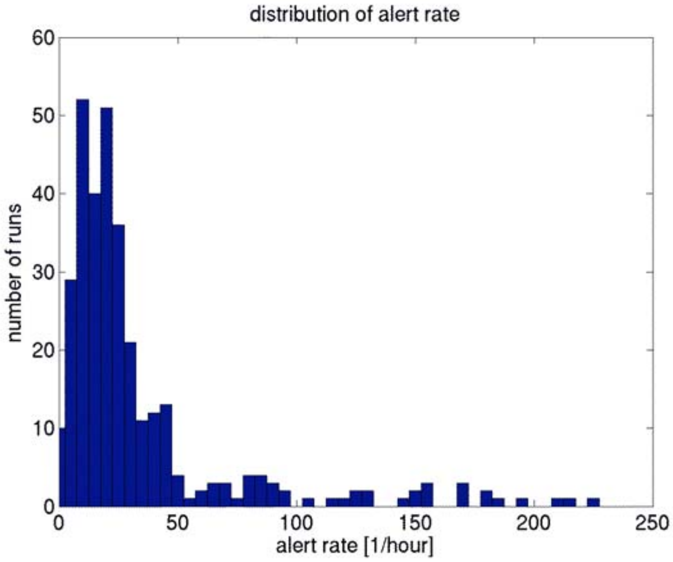


Figure 3-24 - Distribution of alert rate

The distribution is characterized by a curve that peaks at 15 alerts/hour, comes back to almost zero for 50 alerts / hour and then has a long tail. If a run has more than 50 alerts / hour we can suspect that something is wrong with that run.

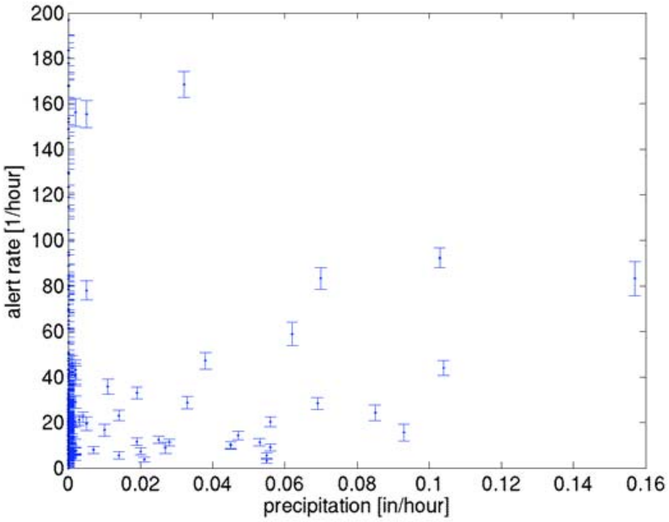


Figure 3-25 - Alert rate versus precipitation

Figure 3-25 shows the alert rate versus precipitation. Each point has an error bar which is calculated as:

$$\delta alert = \frac{\sqrt{alerts}}{duration}$$

The few runs with more than 200 alerts/hour have no precipitation. At first sight one might suspect that the alert rate increases and therefore the performance of the system decreases with an increase in precipitation. But a closer analysis shows that a statistically significant effect can not be found. The correlation coefficient between precipitation and alert rate is -0.03 (-0.1 if runs with no precipitation are excluded). It should also be mentioned that the scatter of the data points is greater than one would expect from their statistical errors.

Next we examine the relationship between ambient temperature and the alert rate.

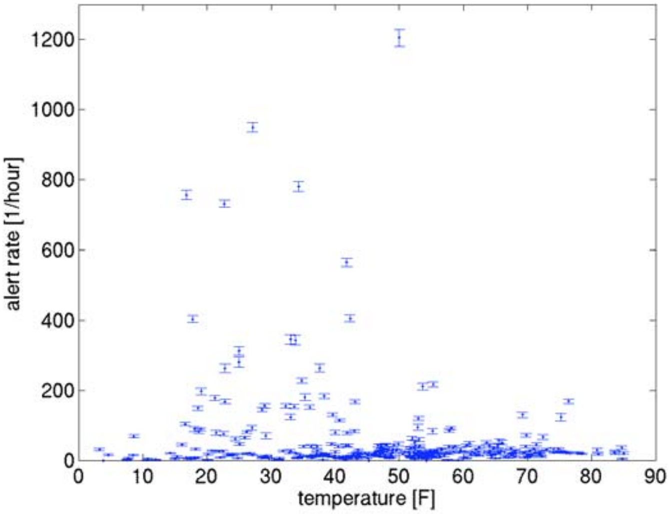


Figure 3-26 - Alert rate versus temperature

The error bars shown in Figure 3-26 are calculated as before. The one significant thing one can see in the plot is that the temperatures for runs with very high alert rates are all less than 50^o F. The mean alert rate for runs when the temperature was over 50^o F was 30.4 alerts/hour and the mean alert rate for runs when the temperature was 50^o F or less was 75.1 alerts per hour. The reasons for this are explained below. Otherwise there is no significant correlation between the alert rate and temperature; the correlation coefficient is -0.18.

3.3.6.2 Degradations and failures of system components

During the course of running the warning system on the bus we experienced some failures which later turned out to be weather related. We also examined the runs with a very high alert rate to see if weather conditions were among the reasons.

3.3.6.2.1 Curb detector

The effect of temperature and water on the curb detector was discussed in a previous project report[xiii]. A heater had to be installed in the laser box to reduce the temperature range and we had to take extra measures to water-proof the camera.

3.3.6.2.2 Cameras

Some of the cameras mounted on the side of the bus degraded and then failed because water was able to get into the housing. Moisture condensed on the inner side of the entrance window and caused the image to be foggy. We did some extra waterproofing and later the manufacturer came out with an improved design of the camera. At night the ambient light was often not sufficient to see details of the surroundings. Fog or rain also reduced visibility.

3.3.6.2.3 Retraction mechanism

The retraction mechanism failed a few times due to corrosion. If the laser scanner does not extend properly, the system cannot work properly. We observed the failures in the Pittsburgh bus in the winter time, when the bus was exposed to salt, but no such failures happened on the bus in California.

3.3.6.2.4 Computer

In the beginning the specified temperature range for the computers was 0^o C to 50^o C (32^o F to 122^o F). The computers for the side components of the warning system were close enough to the cabin of the bus to remain within this range during operations. However, at one point the bus was left outside during a cold spell and when the bus started the computer was too cold to work. We replaced some of the computer boards and achieved a temperature range of -40^o C to 70^o C (-40^o F to 158^o F).

3.3.6.2.5 DVI

The visibility of the DVI lights is affected by the ambient lighting. At night the DVI lights stand out more than during the day. The brightness control can be used by the operator to adjust the lights to compensate for the ambient light. However, when the sun is close to the field-of-view in which the DVI is located, the glare is too strong and the DVI light can no longer be seen by the operator. (See also Appendix D on operator feedback).

3.3.6.2.6 SICK laser scanner

We observed several situations when the performance of the laser scanner was affected by weather:

Direct sunshine from a certain direction can confuse the sensor and it shuts down. Only rebooting the sensor restores its functions.

Water splashes from the front tires can be so strong that they appear as objects very close to the bus. These objects often trigger a warning and because they are so close to the laser scanner the retraction is also triggered. In Figure 3-27 one can see the development of such a splash, indicated by a circle in the middle image. The outline of the bus is on the left in grey.

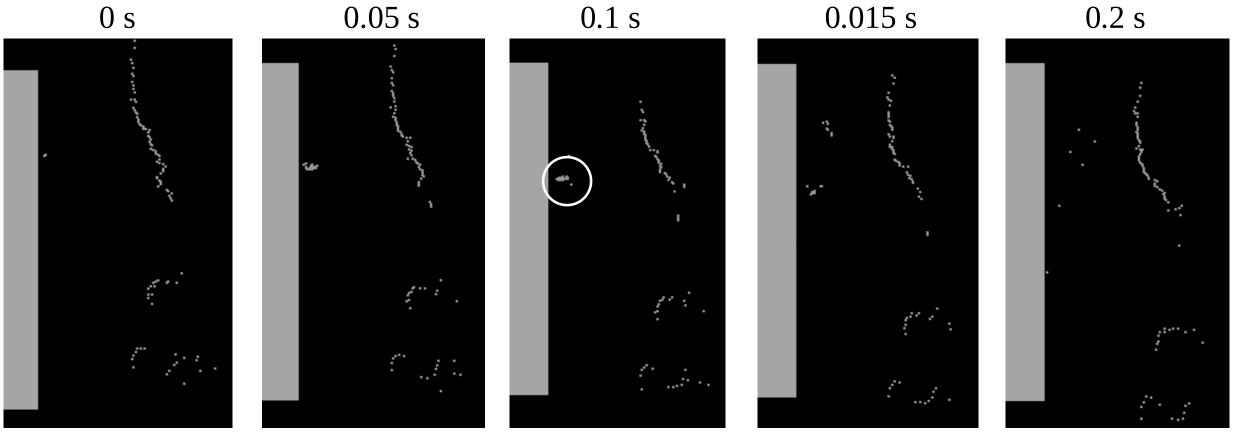


Figure 3-27 - Example of a splash of water appearing on the right side of the bus

The splashes are seen by the sensor for only about 0.2 seconds, but this is enough to be registered as an object and to trigger an alert. In this particular case the splash also came close enough to the laser scanner to initiate a retraction. We also simulated splashes with a garden hose and observed the same thing, namely that splashes can be seen by the sensor as objects.

Dirt can build up on the window of the scanner and obscure its view. This happened often during the winter months in Pittsburgh when a significant amount of salt accumulated on the sensor. The problem was aggravated during cold weather because the bus wash can not be operated in freezing temperatures and therefore the dirt remains for several days.

Dust can be thrown into the air by the tires of the bus and appear as an object for a short time.

Rain can cause a few erroneous returns. Those were not observed in the field testing data we collected with the buses, but we observed it in a test when we used a garden hose to simulate strong rainfall.

Fog did not cause any degradation of the laser scanner performance. We examined data when fog had reduced the visibility to 100 m and saw no effect.

3.3.7 Summary of Key Findings about Driving with SCWS

We used two measures of effectiveness, the change in the warning rate and the change in steering behavior following a warning.

In the warning rate analysis, we did not find a reduction in the warning rate on the right side; in fact it increased for warnings of short duration. The reason for that could be that the drivers used the system in an unintended way such as driving closer to the road boundary. Other possible explanations are seasonal changes or undetected problems with the system. For the left side we saw a dramatic (60%) reduction in the number of imminent warnings lasting more than 1.5 seconds. This is an indication that the drivers reacted to warnings and reduced the danger of the situations.

In the steering behavior analysis we found that the driver reacts more quickly to a dangerous situation, changing the steering faster away from the object that caused the warning. This evidence is stronger for the right side than for the left side. The effects on the left side are of similar magnitude to ones seen from random changes, but the ones on the right side are of greater magnitude than random changes.

In future evaluations of SCWS one should pay particular attention to the scheduling of the data taking in order to avoid any possible bias of the data due to seasonal or other changes. It is also advisable to measure the changes in steering directly from the steering wheel, so that sudden changes in response to side warnings can be captured more accurately.

From operator feedback (Sections 3.6.1 and 3.6.2) we found that the current false positive warning rate gives acceptable performance, but a further reduction in false warning rates is desirable. Our analysis showed that of the alerts and imminent warnings around 65% and 35% respectively are correct. Most of the false warnings, especially the imminent ones, were not very serious; the danger levels were only slightly overestimated because the object velocity estimation was somewhat off. Vegetation, ground return, no object velocity and a few other very rarely occurring reasons also caused false warnings. Improved laser scanners, which should soon be commercially available, and improved tracking and classification algorithms will be able to significantly reduce the false warning rate.

The biggest technical concern we had was the laser scanner. It performed very well during most of the data taking, but in some circumstances there were problems. Direct sunlight can blind the sensor and water splashes, dust, or dirt can create false objects. Corrosion degraded the retraction mechanism in some instances and prevented the scanner from extending to its correct position. As the laser scanner was originally designed for indoor use, it was not surprising that there were some issues during outdoor operation. In the near future laser scanners that are specifically designed for automotive use should become commercially available.

3.4. Key Hardware Problems

The ICWS developed for this program was a research prototype system that was not hardened for commercial use. The main purpose of this system was to demonstrate a proof of concept for an advanced ICWS. As such, the frequency of failures was much higher than would be acceptable for a commercial system. The key problem areas are summarized below, with the resulting corrective actions identified.

- **Data Disks failing** - We switched to notebook drives for the data disks due to their ability to withstand greater vibration and shock. Data disks are only used to record research data and would not be used in a commercial system

- **System Disks failing** - These were also switched to notebook drives. For unknown reasons, the California ICWS was harder on the drives than the Pittsburgh ICWS. In California, we switched to using flash drives.
- **Flaky CPUs** - The CPU used for the SCWS was chosen because it was fast enough to run the SCWS software algorithms, but it had memory problems. Of the five originally purchased for this project, only two passed extensive memory testing. This is not normally a problem for computers. By the time the commercial prototype is designed, there should be many more CPU's to choose from which are fast enough to run the software algorithms.
- **Network Problems** - The industrial quality network switches on both buses degraded in performance. We replaced them with consumer grade switches with no further problems.
- **Corrosion of Laser scanner retraction mechanism –** During the winter, there was corrosion in the Pittsburgh ICWS retraction mechanism and some parts needed to be replaced. Another time, the switch which indicates that the scanner is extended failed. A commercial system would use a smaller laser scanner that would not need to be retractable.

As can be seen, none of these issues should be show-stoppers in developing and fielding a commercial prototype system.

3.5. Collision Warning System Integration Issue: Simultaneous Warnings

The physical and logical interactions between the FCWS and SCWS were very limited in the experimental implementation, apart from the combined DVI. A serial communication link between the FCWS and SCWS exchanged the following information:

- GPS data – latitude, longitude, altitude, time, vehicle speed
- Speed measurement from vehicle data bus
- Warning message sent to DVI

The DVI incorporated displays of both FCWS and SCWS warnings within the same unit, as explained in Section 1.5.4. The physical connection between these warnings is less significant than the issue of possible confusion if the warning logic permits multiple warnings to be issued simultaneously.

Because the integrated collision warning system was capable of issuing multiple simultaneous alarms it was important to understand if the operators were being overloaded and/or potentially confused by the system issuing both frontal and side warnings within short time periods. It was first necessary to determine how frequently the simultaneous (and near simultaneous) alarms occurred. We also wanted to understand the conditions under which simultaneous alarms occurred, to contribute to a decision about the value of a warning synthesizer and what rules should govern it.

3.5.1 Warning Integration Issues

3.5.1.1 ICWS Simultaneous warnings

Table 3-7 shows the rates of simultaneous warnings per hour of bus operation. Two warnings are considered simultaneous if the time interval between them is less than a given threshold. The table shows threshold values of 0 s, 0.5 s, and 1 s, based on data from all good runs.

Table 3-7 - Rates of simultaneous warnings per hour

time interval to be considered simultaneous [s]	0	0.5	1
front and right [1/h]	0.14	0.21	0.26
front and left [1/h]	0.38	0.56	0.69
left and right [1/h]	0.45	1.07	1.46

The rate of simultaneous warnings is quite low. The highest rate is just under 1.5 per hour for left and right side warnings within 1 s of each other. The lowest is 0.14 per hour or one every 7 hours for front and right warnings at exactly the same time. It is instructive to compare these simultaneous rates with the individual front, right, and left warning rates themselves, which are shown in Table 3-8, (again based on data from all good runs). The percentage of warnings that are simultaneous (0 second threshold) with another side and the average duration of warnings are shown in columns 3 – 6.

Table 3-8 - Warning rates for the front, right and left side

	Warning rate [1/h]	Fraction of simultaneous warnings			average duration [s]
		front	right	left	
front	10.8	N/A	1.30%	3.52%	1.24
right	49.8	0.28%	N/A	0.90%	0.37
left	56.7	0.67%	0.79%	N/A	0.38

The fraction of simultaneous warnings is about 1% or less for most cases, except that the fraction of front warnings which are issued simultaneous with a left warning is 3.52%. This percentage is higher than one would expect if the left and front warnings were uncorrelated. The expected percentages that would be simultaneous (0 second threshold) with another side if the warnings were uncorrelated are shown in Table 3-9, where the cases in which the uncorrelated percentages are less than the measured ones are highlighted.

Table 3-9 - The percentages of warnings that would be simultaneous if uncorrelated

	Fraction of simultaneous warnings		
	front	right	left
front	N/A	2.22%	2.54%
right	0.48%	N/A	1.18%
left	0.48%	1.03%	N/A

The uncorrelated expected percentages are calculated in the following way. If side 1 (2) has a warning rate of r_1 (r_2) and an average warning duration of d_1 (d_2), then the percentage of side 1 warnings that are simultaneous with side 2 is

$$p = \frac{r_2 \cdot (d_1 + d_2)}{3600s}$$

The warning rates (in 1/h) and the durations (in seconds) for each side (front, right, left) were listed in Table 3-8.

The fact that the observed fraction of front warnings that are issued simultaneously with a left warning exceeds the expected fraction (and likewise left warnings issued simultaneously with front warnings, see yellow highlight in Table 3-9) shows that front and left warnings are somewhat correlated. One possible explanation for this weak correlation is that in some instances the two systems may see the same object and warn on the same object.

3.5.1.2 Recommendations regarding Warning Synthesizer

The original plans for the project included the development of a warning synthesizer to manage the display of warning information to the bus operator. Through this type of tight integration of the frontal and side warning systems, priorities would be established to determine which of multiple simultaneous warnings was considered most urgent to display to the operator in order to minimize the possibility of distraction by a less urgent warning. In the course of discussions among the project team, legitimate concerns were raised about the risks associated with suppressing a warning in order to give priority to a different warning. If the suppressed warning turned out to be based on a hazard that was serious enough to lead to a crash, there could be adverse liability implications for everybody involved in the development and implementation of the warning system and synthesizer.

If both the frontal and side warnings were perfectly reliable, the warning synthesizer concept could, in theory, be technically viable. This would require high confidence in the validity of all the warnings, or at least the ability of the sensors and warning algorithms to assign confidence estimates to each warning (so that a low-confidence warning would not suppress a higher-confidence warning). However, once one considers any significant frequency of false positive warnings it becomes possible for a false positive warning to lead to the suppression of a true positive warning. In this worst-case scenario, the operator’s attention would be drawn away from a real hazard to deal with the false alarm, which could mean that the warning system would actually increase the probability of a crash rather than reducing it. So, until the false positives are reduced to extremely rare occurrences, use of a synthesizer to suppress warnings should not be considered seriously.

The analysis of Section 3.5.1.1 also shows that simultaneous or near-simultaneous warnings are already very rare occurrences in real bus operations, which calls into question the need for a synthesizer to reduce the potential for operator confusion or distraction.

3.6. Operator Feedback

Feedback about the performance of the ICWS was obtained from the bus operators who drove with the system, as well as from safety officers of a variety of transit properties. The bus operator feedback was obtained by means of a questionnaire administered to the operators near the end of their period of driving with the system and ride-alongs by a member of the research team, observing the operators' use of the system under a range of lighting and weather conditions and questioning them about their use and impressions of the system. The feedback from the safety officers was obtained as part of a demonstration for an APTA System Safety Meeting.

Nine responses from six SamTrans bus operators were obtained to the questionnaire shown in Appendix E. The ride-alongs were conducted with three SamTrans operators after they had completed the questionnaire and with one Port Authority operator who did not complete a questionnaire. A comprehensive description of the results that were obtained is found in Appendix D, the highlights of which are summarized here.

3.6.1 Operator Acceptance of the System

The primary goal of gathering operator feedback was to determine whether the prototype ICWS was acceptable to operators. Feedback from the operators suggests that a majority of the operators found the collision warning system very acceptable. It was also notable that even the least satisfied operator said that he would keep the system on when asked about turning it off.

Situations when operators felt the system was most useful included driving during poor visibility conditions, when fatigued, for vehicles cutting-in and when exiting and entering bus stops, where it aids in the detection of street furniture, pedestrians and other vehicles. They thought that it was helpful in conveying to them an appropriate sense of urgency regarding hazards in their driving environment, helping them to improve their safety and avoid collisions. They also thought that it could be useful for training and for use by rookie drivers when they start driving in daily revenue service.

The operators said that the very limited level of training they received was appropriate, but the researcher who rode along with them had the impression that some re-training regarding the system capabilities and limitations would have been beneficial.

3.6.2 Operator Suggested Changes

The most prominent concerns expressed by the operators involved the frequency of false alerts and the related issue of apparent inconsistency of conditions that would or would not generate an alert. The concern about inconsistency was probably related to some instances of unreliability in the prototype system that they were using, which was not always completely functional. There was also a concern that the alerts would sometimes lead them to look in the wrong place for a hazard, which is probably related to the false alerts.

After the operators gained experience with the system, they recognized it as an aid but not something on which they should become dependent. This led to a recommendation that when other operators are introduced to the system they be urged to not expect to become dependent upon it.

The operators were interested in having the system capabilities extended in a couple of ways. They were most interested in having it assist them in judging side clearance when making tight turns in close proximity to parked cars and street furniture, especially at low speeds. They were also interested in creep detection, to help them avoid inadvertently creeping forward when a traffic signal changes from red to green but the vehicles stopped ahead of them are not yet moving.

The ride-alongs also revealed that the operators were not always aware of some of the alerts that were given, particularly if they were busy or the displays were not in their direct line of sight at the time. This could be addressed by adding an audible alert to the current visual alert, but that is a controversial feature that is strongly opposed by some of the operators even though it is favored by some of the other operators.

3.6.3 Agencies' Feedback

Twelve people completed a survey questionnaire as part of their participation at the APTA System Safety Meeting in San Carlos, CA (SamTrans headquarters) in December 2004. The respondents represented nine transit agencies, one consultant and two people from APTA, all of whom had a 10 to 15-minute demonstration of the system. The main elements of favorable feedback from these representatives regarded the potential of the system for improving safety and driver training and their perception of limited false alerts. The main concerns involved the liability implications of the recording and storage of vehicle data by the system, the timeliness and accuracy of the warnings to the drivers, and the costs of the system. When asked if they wanted the FCWS, SCWS or both, almost everybody said both (except for one who wanted a rear collision warning system). Most representatives indicated a willingness to pay $3 K to $5 K for a production system

3.7. Conclusions Regarding ICWS in Revenue Service

The field testing of the ICWS by transit bus operators in revenue service provided extremely useful "real world" experience to support future enhancements to the system. The extensive database of engineering data and video imagery has been mined to extract information that sheds light on the strengths and limitations of the prototype system under a wide range of realistic operating conditions, which could not be obtained from merely testing on a test track.

The field data collection and analysis on the usage of the collision warning systems in revenue service by bus operators at two major transit properties have provided important insights into a variety of important issues. These include issues of driver behavior in general, as well as issues specific to driver use of collision warning systems. The database developed in this project contains an unprecedented comprehensive characterization of urban and suburban transit bus operating conditions and driving behavior, including both engineering data and video.

3.7.1 Benefits of the System

- The activation of the collision warning system generally led to changes in bus operator behavior, but these changes were relatively subtle rather than dramatic.
- The general trends in bus operator behavior after activation of the frontal warning system were:
    - Increased consistency of driving behavior, especially for the drivers who were least consistent before;
    - More cautious or conservative driving, at larger car following gaps and with reduced braking severity;
    - Largest effects on most aggressive drivers, but negligible effect on drivers who were most cautious from the start.
- Changes in driver behavior were less evident for the side collision warnings than for the frontal collision warnings. Nevertheless, one can still draw the following tentative conclusions:
    - The driver takes corrective actions due to imminent warnings
    - Some data imply that drivers may use the system in unintended ways, such as using it to drive closer to the edge of the road.
- The bus operators responded favorably to the system and thought that it was useful to them and helped improve their driving.
- The transit agency representatives expressed interest in having both frontal and side collision warning systems, and said that they would be willing to pay \$3 K to \$5 K for a production system.

3.7.2 Issues that Need Further Attention

- Weather conditions can adversely affect the performance of sensors, especially those based on optical systems, so that the warning system is likely to be impaired or even disabled in adverse weather unless specific countermeasures are taken to keep the sensors clean or to augment them with other sensor modalities (such as millimeter wave radar or video image processing).
- It is desirable to further reduce the number of false warnings. This can be done by improving the ability of the sensors to detect, classify and track target objects, so that false and nuisance alerts can be eliminated, without missing alerts for any of the genuinely hazardous conditions.

3.7.3 Remarks on Other Findings

- Even though bus operators are better trained and more homogenous in their driving behavior than the driving population as a whole, there is still a wide diversity in their driving styles and preferences. This confirms the importance of providing the operator with the ability to adjust the sensitivity of the warning system. This is a case in which “one size fits all” does not appear to be a viable approach.
- Despite the extensive scope of the field data collection, it was still not sufficient to address all issues of interest. The limitations of the data included:

- Not enough driving time or mileage to experience crashes or near misses, so that changes in their frequency or severity could not be measured directly;
- Not enough different bus operators to draw statistically significant conclusions over the total population of bus operators;
- Not enough driving time by each bus operator to show clear trends associated with long-term familiarity with the system or carry-over effects after driving with, and then without, the warning system;
- Very few examples were observed of frontal and side alerts in close proximity to each other, providing little evidence regarding the suitability of a warning synthesizer;
- The yaw-rate sensor was not responsive enough to measure sudden changes in steering, limiting the ability to detect driver reactions to side warnings;
- The constraints on data collection time, operator scheduling and number of buses did not allow elimination of confounding effects such as seasonal changes.

3.7.4 Recommendations

- There is a need for additional testing, involving more bus operators and longer periods of driving, in order to overcome the observed limitations in this initial testing. This is likely to be time consuming because of the practical constraints associated with how operators are assigned to buses and bus routes unless a larger number of buses can be instrumented to provide more scheduling flexibility.
- There is a need for additional work on refinement of the obstacle detection sensors and the signal processing to improve the ability of the sensor systems to distinguish between hazardous and non-hazardous conditions, thereby reducing the frequency of false alerts and missed detections.

4 Conclusions and Recommendations

4.1. Conclusions

Substantial work was accomplished under the ICWS project as a whole, including development of system requirement specifications, development of two prototype systems, verification tests under controlled conditions and field testing in revenue transit service. The prototype development efforts were reported in the Integrated Collision Warning System Final Technical Report, FTA-PA-26-7006-04.1. This report provides the results of the system verification tests and field tests.

The detailed test track verification tests were designed to replicate key elements of real-world transit operating scenarios, showing the ability of the prototype ICWS to issue warnings in specific, controlled test conditions. This allowed the team to document the performance of the sensors and to understand the error characteristics of current systems, and the specific relevance of the sensor limitations to transit operating conditions. The test targets were designed to replicate typical urban street objects including stationary objects such as trees, poles, traffic signs, and parked cars; and moving objects including pedestrians, bicycles, and other cars. These types of targets are unique to a transit urban operating environment – a highway environment has far fewer stationary objects and fewer types of moving objects.

The verification of subsystems focused on the ability of the sensors to track relevant objects, to detect and predict motions of those objects, and to perform appropriate threat assessments. The verification tests also documented limitations of existing systems in data processing and data fusion.

The verification tests of the FCWS and SCWS elements of the ICWS were conducted separately due to differences in their respective system characteristics. Currently available FCW systems are not ideally suited to transit operational requirements, but are closer to meeting those requirements than currently available SCW systems. More work is needed on the threat assessment algorithms for both subsystems to develop an ICWS that is suitable for a typical transit operational environment in terms of accurate threat detection and driver acceptance.

The verification tests for the FCW system showed that the obstacle detection function provided adequate longitudinal measurements, but the quality of the measurements of the lateral distance to targets in front of the bus still needed improvements. Test results showed that, under the tested scenarios, the FCWS could correctly identify hazardous targets and generate warnings when driver action was needed. However, errors in lateral position measurements could potentially cause false detections of targets that were not threats, thereby resulting in false positive warnings. Time delays in the sensing and signal processing functions also reduced the effectiveness of the collision warning system.

Tests under controlled conditions showed that the SCWS had no missed warnings or false negatives under specific staged crash scenarios. The rate of false positive imminent warnings or alerts was similar to the rate of correct positives. This rate of false positive warnings was acceptable to drivers, but they would like to have it reduced. Tests also showed that the false positive warning rates for both contact and under-the-bus incidents were unacceptably high, so the warnings for these two conditions were not activated for the operational testing in public service. Analysis of field test data showed that of the warnings issued by the SCWS, about 2/3 of the alerts and 1/3 of the imminent warnings were correct warnings. Most of the incorrect imminent warnings were caused by incorrect velocity estimates. Curb detection reduced the nuisance alarms on the right side by 30%. The analysis also showed that the remaining false positive warnings were caused by a variety of reasons including vegetation, no velocity, and ground returns.

Two buses instrumented with the prototype ICWS were tested in revenue service in the San Francisco Bay Area and Pittsburgh. Data for a total of seven bus operators were analyzed, dealing with issues of driver behavior in general, as well as issues specific to the collision warning systems. The database developed in this project contains detailed information on urban and suburban transit bus operating conditions and driving behavior, including both engineering data and video. The data analysis compared drivers' behavior during the period when the ICWS was turned on with the baseline 'before' data (when the systems were active and collecting data, but not issuing any alerts or warnings).

The following lessons were learned from these operations in real-world conditions:

- The existing commercially available collision warning systems, which were developed for highway applications, are not suitable for transit operations in urban and suburban environments. Data collected using instrumented buses in revenue service showed that the transit operation environment involves complex conditions that existing commercial CWS are not designed for.

- The advanced ICWS addresses many of the problems the existing CWS did not address. However, improvements are still needed to overcome the limited ability of the sensors to detect, classify and track target objects, so that false and nuisance alerts can be further reduced, without missing alerts for any of the genuinely hazardous conditions. The verification tests indicated that the sensing approaches used for both frontal and side collision warning systems need improvement. Specifically, the FCWS required additional sensing means and sensor fusion to determine the lateral positions of obstacles relative to the vehicle path and their threat levels and to compensate for sensor and processing delays and errors. The SCWS may also need to employ additional sensing means and improved algorithms to classify objects as vegetation or ground, and to improve velocity measurements. For both under-the-bus warnings and contact warnings the false warning rates need to be reduced. To warn drivers of a pedestrian falling underneath the bus, additional sensors need to detect the presence of an object under the bus.

- Weather conditions can adversely affect the performance of sensors, especially those based on optical systems, so that the warning system is likely to be disabled in adverse weather unless specific countermeasures are taken to keep the sensors clean or to augment them with other sensor modalities (such as millimeter wave radar). Some commercially available heavy truck systems address this issue by using Doppler and pulse radar.

- There is a clear need for integrated design of the Driver Vehicle Interface (DVI) for FCWS and SCWS in order to make sure that both warnings are intuitive and effective for the drivers. Very few examples of frontal and side alerts occurred in close proximity to each other during the field tests, so no conclusive recommendation could be made as to whether a message arbitration system would be useful for prioritizing the warnings.

- Continuous sensor coverage can potentially enhance safety benefits, but at the same time increase the cost of the system. Fusing frontal and side obstacle detection sensing information may not provide significant improvements in system performance; however, sharing some sensor information may help to reduce the need for redundant sensors.

- Whether the two systems need to be physically integrated will depend in part on whether the integrated system will be significantly different in cost or performance from independent ones. In discussions with transit operators and bus manufacturer/suppliers, operators generally prefer to have an integrated FCWS and SCWS unless the cost of the integrated system becomes close to the combined cost of two independent systems. In that case, some would like to see frontal and side collision warnings systems become independent options that they can choose based on their needs and the costs.

- Regardless of whether the frontal and side collision warning systems are physically integrated, there would be value in terms of cost savings and reliability to integrating these systems with the transit bus electronics through standard electronic interfaces (such as the J-buses).

- The FCWS tended to produce changes in driver behavior, leading in a generally safer direction (longer car following time gaps and gentler braking). The effects were strongest for the operators who were initially the most aggressive and the most inconsistent, but negligible for the operators who were initially the most cautious and consistent. For the SCWS, increased steering away from a threat and a decrease in imminent warnings of long duration on the left side point to safer driving due to the system, but these changes were subtle. The number of warnings of short duration on the right side increased, which could be a consequence of the operators using the SCWS in unintended ways, such as using it to drive closer to the guardrails.

4.2. Recommendations

Based on studies conducted under this project, the ICWS team would like to recommend the following areas to be further studied and developed in order for ICWS to be advanced toward operational use in a transit environment.

4.2.1 Driving Simulator Studies

A driver training simulator is a very effective tool to study driver behaviors under conditions that are rare during field operational tests, such as actual crashes or "near-miss" scenarios. Specifically, a simulator instrumented with the ICWS could become an effective tool for investigating drivers' responses to imminent crash scenarios, with and without the collision warning system, under undistracted and distracted situations, for determining the most effective display techniques and for evaluating strategies for integrating frontal and side collision warnings. Additionally, use of the simulator would enable different operators to be exposed to exactly the same situations, which would allow better understanding of the effectiveness of true and nuisance warnings. During the ICWS project, the FCWS system has been partially integrated with the SamTrans FAAC simulator. We recommend completing the integration of the FCWS and SCWS functions with this simulator and using it to conduct human factors studies of the ICWS. The objectives of the human factors studies using the simulator are to better understand the effectiveness of CWS and to provide design parameters for system improvements.

4.2.2 Further Improvements of FCWS and SCWS

The test results documented in this report point to the needs for additional sensing and threat assessment to identify obstacles within the vehicle path for the frontal collision warning, and improved algorithms to classify objects as vegetation or ground and to improve velocity measurements for the side collision warning. Some of these sensor and threat assessment alternatives, e.g., vision-based obstacle detection and lane detection, have been developed or partially developed under the current ICWS project. These additional sensors are recommended in order to enhance the robustness and reliability of the system in the urban and suburban environment. When these additional sensor options are considered, sensor fusion is needed in order to achieve integrated system design and desired performance.

4.2.3 Need for Larger Scale Field Operational Tests

Although the field testing under this project has produced a substantial amount of data, it is evident that there were not enough driving time and bus operators included to draw statistically significant conclusions about the overall population of bus operators nor to show clear trends of long-term effects of using the warning system or carry-over effects after driving with and then without the warning system. There is a need for a larger-scale field operational test that involves more bus operators and longer periods of driving in order to address the above issues and to increase the opportunities for bus operators to respond to the warning system under imminent crash situations, thereby to fully assess the effectiveness of the collision warning system.

4.2.4 Outreach to Transit Agencies for ICWS

The market for transit ICWS still needs to be developed. Transit operating agencies need to be educated about the benefits of ICWS, including potential reductions of both the occurrence of crashes and incidents due to hard braking, with consequent reduced liability-related costs. The APTA bus and rail safety committee also suggested that the transit ICWS be considered as a potential training tool, with which transit safety personnel can collect field data on bus operators and advise them about the areas in which they need to improve.

In order to expand the market size and offer greater benefits of transit ICWS, the transit industry has recommended expanding the market for these systems to delivery truck fleets such as express mail and small package carriers, which frequently travel in urban/ suburban areas.

4.2.5 Improve Cost and Performance of Laser Scanner

The most expensive components of the prototype ICWS system are the wide-field-of-view LIDARs (side laser scanners). In the ICWS prototype these sensors cost over $15,000, without including the additional cost to mount them in retractable assemblies, which is prohibitively expensive for a commercial CWS. A laser scanner manufacturer is currently designing systems specifically for the automotive industry, which could lead to a sensor that is significantly cheaper and at the same time has improved performance. With this new laser scanner it should be possible to significantly reduce the false alarm rate. A much more detailed discussion of this issue is contained in the ICWS Final Technical Report. This new laser scanner should be evaluated for use in the ICWS as soon as it is commercially available.

4.2.6 Add a Dedicated Under-the-bus Sensor

The current SCWS algorithms employ an inferred under-bus object logic, which looks for the disappearance of an object around the wheel wells of the transit bus. This did not perform adequately in verification testing because it was spoofed by occlusions, multiple moving objects in the same vicinity, and the inability to resolve people boarding the bus from someone slipping near the doorway under the bus, since both objects disappear within the same vicinity. A dedicated direct sensor system would be more effective.

4.2.7 Perform Additional Data Analysis

A considerable amount of data has been collected by the ICWS project. The volume is so great that many interesting secondary analyses have not been feasible due to time and resource limitations in the ICWS project.

4.2.8 Refine the SCWS Measures of Effectiveness

The bus driver can mitigate dangerous situations by subtle changes, e.g., slight changes in steering increase the distance to other vehicles on the side. These subtle changes are difficult to detect and therefore it is challenging to evaluate the effectiveness of the SCWS. In future tests the evaluation techniques need to be refined and the instrumentation improved; in particular, a steering wheel encoder should be employed to directly measure steering behavior.

4.2.9 Recommendation Summary

In conclusion, in addition to the development of requirement specifications and prototype ICWS systems, substantial knowledge and lessons have been gained through the verification and field tests and by interacting with transit operators and manufacturers under this project. We believe that the ICWS technologies developed in this project have great potential for improving safety of transit operations and potentially have larger implications when applied to other vehicle platforms for urban/suburban operations. The foundation work done by this project could contribute to the success of a larger field operational test. The verification testing done as part of this project has provided a detailed quantitative assessment of what can and cannot be done with currently available sensor, threat assessment, and data fusion capabilities to meet typical transit operating requirements. Further development and deployment of transit ICWS technology should be pursued in the new Integrated Vehicle Based Safety System (IVBSS) initiative.

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[vii] Carnegie Mellon University Robotics Institute and California PATH Program, Integrated Collision Warning System Final Technical Report, FTA-PA-26-7006-04.1, 40 (December 2004): Section 1.11.

[viii] Carnegie Mellon University Robotics Institute and California PATH Program, Integrated Collision Warning System Final Technical Report, FTA-PA-26-7006-04.1, (December 2004): Section 1.3.2.

[ix] Carnegie Mellon University Robotics Institute and California PATH Program, Integrated Collision Warning System Final Technical Report, FTA-PA-26-7006-04.1, (December 2004): Section 9.4.

[x] Mertz, C. “A 2D collision warning framework based on a Monte Carlo approach,” Proceedings of ITS America's 14th Annual Meeting and Exposition (April 2004).

[xi] Carnegie Mellon University Robotics Institute and California PATH Program, Integrated Collision Warning System Final Technical Report, FTA-PA-26-7006-04.1, (December 2004).

[xii] Carnegie Mellon University Robotics Institute and California PATH Program, Integrated Collision Warning System Final Technical Report, FTA-PA-26-7006-04.1, Section 1.19.4 (December 2004).

[xiii] Carnegie Mellon University Robotics Institute and California PATH Program, Integrated Collision Warning System Final Technical Report, FTA-PA-26-7006-04.1, 40 (December 2004).

Appendix A DVI Improvement Testing

A.1 Introduction

The driver vehicle interface (DVI) provides a means by which the driver can communicate with the system. The DVI can be thought of as a decision aid in that it provides the driver with information that they incorporate into their decision making process. For a collision warning system it is therefore important that information be presented in a way that is easy to decipher, quick to disseminate and supports subsequent decision-making and action.

The DVI design implemented on the ICWS field testing buses integrates the forward and side warning stimuli into a unified display (Figure A-1). The forward portion was designed with specific care to utilize multiple levels of warning for both the side and forward components. This practice has been suggested and successfully deployed in other intelligent vehicle research (e.g., Graham & Hirst[xiv], Wilson et al[xv], Dingus et al[xvi] and Steinfeld & Tan[xvii]). The side warnings were developed specifically for this platform and application. This display involves two LED assemblies, one mounted on the left A-pillar and the other mounted on the center window pillar.

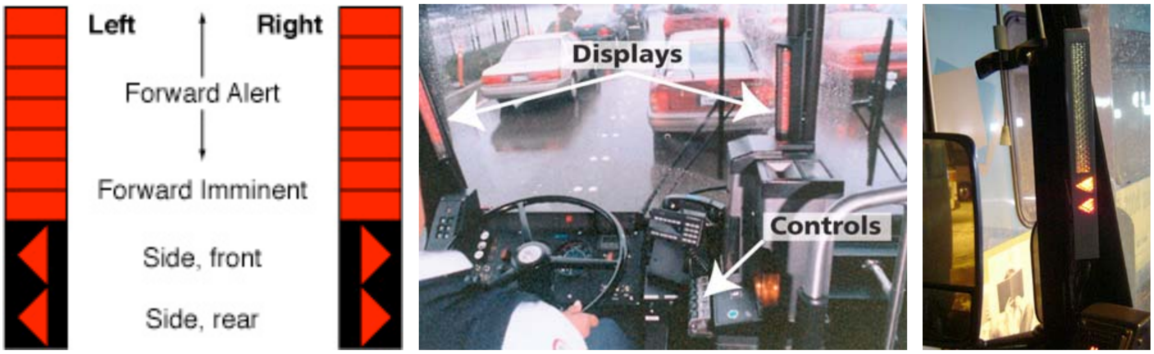

Figure A-1 - Integrated DVI

The forward LEDs grow downwards with threat level and “aim” at threat direction. The triangles point towards the relevant mirrors. Bars are mounted on the pillars of the driver’s forward window.

When viewing the DVI the physical “location” of the driver with respect to the spatial representations of the LEDs is in the middle of the two DVI bars, between the lowermost forward LED and the “Side, front” LEDs. The bars are designed for the window pillars immediately in front of the driver, thus providing a peripheral display that does not obscure the driver’s external view of the road scene. The placement also supports rapid checking of the side mirrors – an action much more frequent in transit operations than in regular passenger vehicle operation. Digital DVI outputs are refreshed every 75ms.

The goal of the DVI Improvement set of experiments was to determine whether the existing collision warning system (DVI) could be improved by adding a visual motion component to the forward warning part of the display. The study was conducted by members of the Visual Detection Lab (VDL), University of California, Berkeley. The study used a comparison between quantitative measures of the driver's ability to recognize and respond to a motion-enhanced warning signal (MEWS) and a warning signal in which a driver is alerted to a collision solely by illumination of a warning light without any motion enhancements (to be referred to as a non-MEWS). To quantify the driver's ability to recognize each of these signals, we use a statistic measuring the time required to respond to each of the signals. As a secondary goal, the study measured the extent to which the warning signals (both MEWS and non-MEWS) distract the driver from performing a lane-keeping task. Note, that the displays used for the field testing of this project utilized a non-MEWS warning signal as this work was undertaken concurrent to the field testing. Two studies were conducted in this testing, the first set was conducted with two VDL personnel as subjects and the second set was conducted using three bus operators.

A.2 Experimental Set-up

Each experiment consisted of eight runs, each consisting of 50 trials lasting at most ten seconds, during which either a MEWS or non-MEWS presentation occurred. The subject calls for the beginning of a trial by pressing a button. To prevent the subject from anticipating when a warning signal might occur, we randomize the time interval between the subject-controlled start of the trail and the presentation of the warning signal. We prevent the warning signal from occurring during the first 250 msec following the initiation of the trial. The end of an individual trial is indicated by a beep generated when the warning signal is presented and the subject selects a side. If the stimulus is not presented before the final second of the trial, the trial is ended with a beep, allowing for the possibility that there will be some trials during which no warning signal is displayed. Thus, the data collected during an experiment consist of the determination of the side on which the warning signal was presented, the time required to make this determination, and the measurement of error in performing the distraction task.

Figure A-2 - Set-up for DVI experiment

A.3 Results

Two factors affect the relationship between the response times to MEWS and non-MEWS stimuli. The settings for both the intensity of the LEDs within the DVI and the time interval between igniting successive LEDs in MEWS stimuli influence whether response time is faster for MEWS or non-MEWS stimuli. Figure A-3 depicts histograms of the response time for stimuli in which the intensity of the LEDS was set at its maximum. The interval between consecutive ignitions of the LEDs was 20 msec, requiring 100 msec to light the full display. For this set of parameters, the mean response time was faster for the non-MEWS stimuli by about 20 msec for both subjects. The differences between the means of these distributions were significant for both subjects ($P<0.005$). Thus, at this level of light intensity, reduction in response time associated with a moving signal is insufficient to make up for the additional time required to sequentially ignite the LEDs.

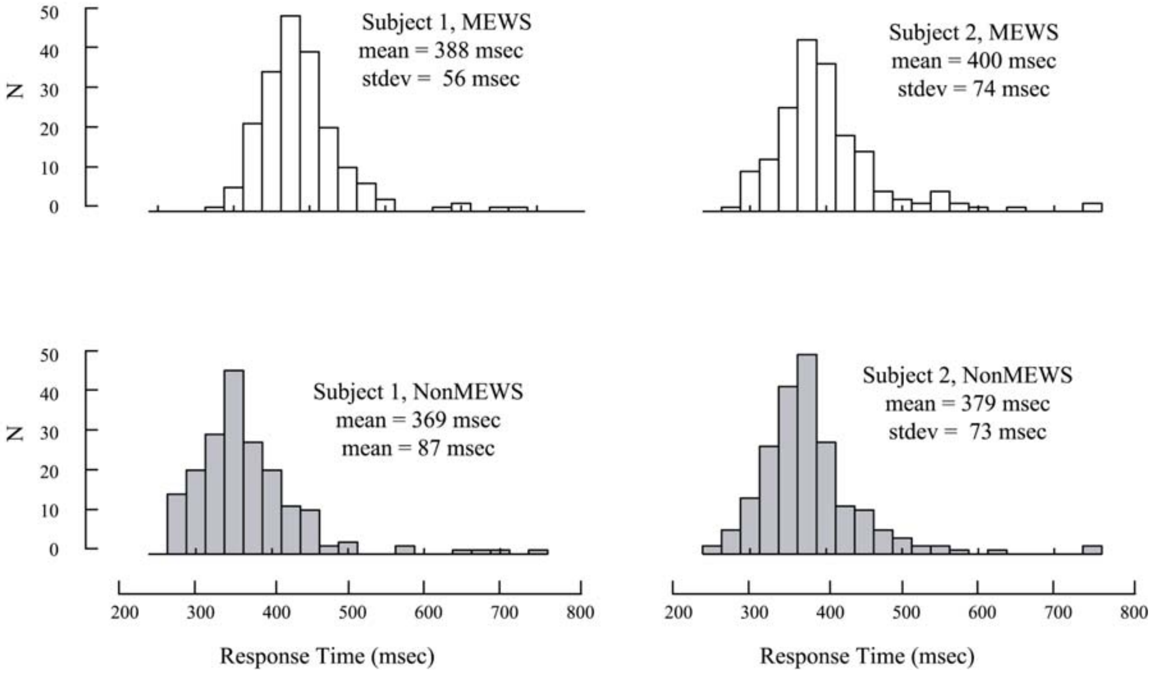

Figure A-3 - Histograms of response time to a high intensity signal (20 msec step)

Previous experiments in the laboratory signal have indicated that the reduction in response time associated with moving signals is enhanced at lower levels of light intensity. To examine whether the light level had any effect on response time, we reduced the intensity setting for the DVI to its lowest level. The histograms from these experiments are shown in Figure A-4. As expected, at the lower levels of light intensity the response times for both MEWS and non-MEWS stimuli were longer than at the higher intensity level (compare mean times in Figure A-3 and Figure A-4). The response times to non-MEWS stimuli, however, were still approximately 20 msec faster than the response times to MEWS stimuli. Again the difference between the means of these distributions was statistically significant (P<0.005). At this lower level of light intensity, the response time for the moving signal is still insufficient to make up for the additional time required to sequentially ignite the LEDs.

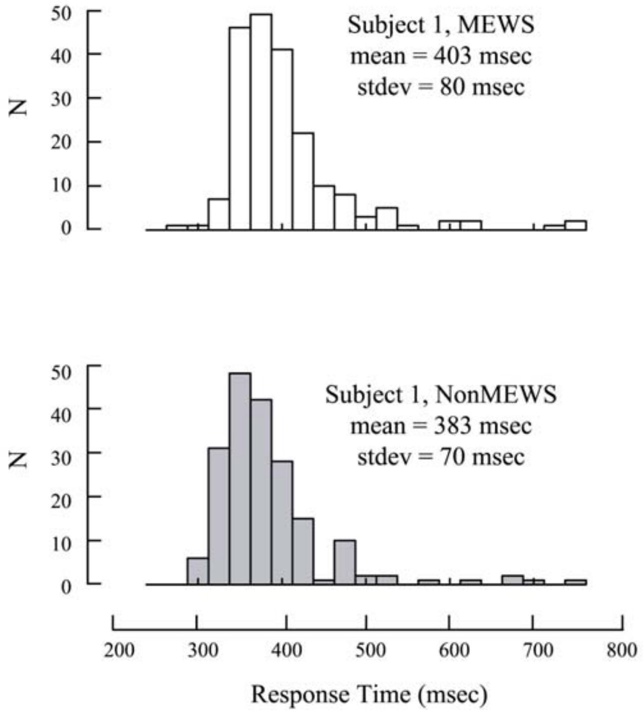

Figure A-4 - Histograms of response time to a low intensity signal (20 msec step)

Although the 20 msec intervals between successive illuminations of the LEDs provide a strong impression of motion, it seems that it is still too slow to reduce the response time relative to the simultaneous ignition of all of the LEDs in the non-MEWS stimuli. The histograms presented in Figure A-5 show the effects of reducing the successive ignition time to 10 msec. For this combination of ignition time and light level, the mean response times for the MEWS stimuli were smaller (3 msec for subject 1, 20 msec for subject 2). However, the difference between the mean for both subjects was not statistically significant. The probability of the null hypothesis that the response times for MEWS and non-MEWS stimuli came from the same distribution were 0.16 and 0.41 for subjects 1 and 2, respectively. Whereas for the 20 msec interval stimuli the response times were faster for the non-MEWS stimuli, for the 10 msec interval the response times to MEWS stimuli were no longer significantly slower.

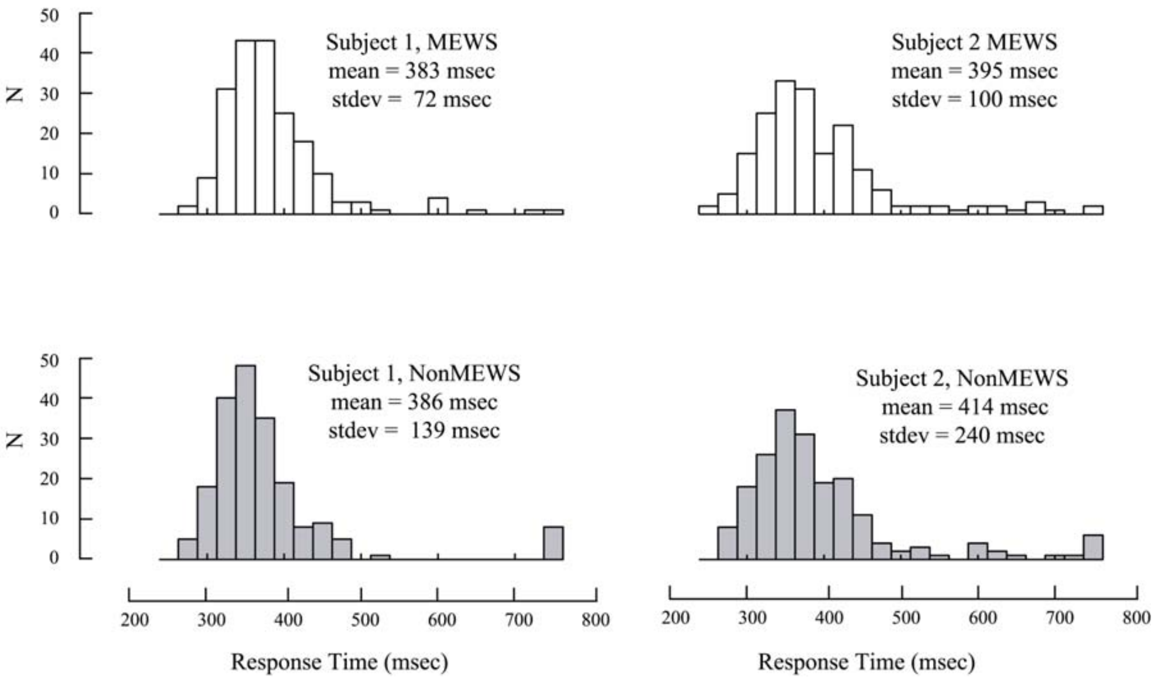

Figure A-5 - Histograms of response times to a low intensity signal (10 msec step)

To assess whether the warning signals distracted the subject in the lane-keeping task, we calculated the root-mean-square (RMS) error between the reference signal (the center of the lane) and the position of the subject-controlled cursor. We then compared the error over two 1 sec time windows, the first which was centered 1.5 sec before the subject pressed a button indicating an occurrence while the second was centered on the pressing of the button. In Figure A-6 the red and blue solid lines indicate the error averaged over 200 presentations, while the dashed lines indicate half of the standard deviation added to and subtracted from the mean signal. The presence of the warning signal appears to have little effect on the RMS error signal, as in both cases the means do not change significantly. This suggests that the warning signal does not distract the subject in performing the lane-keeping task.

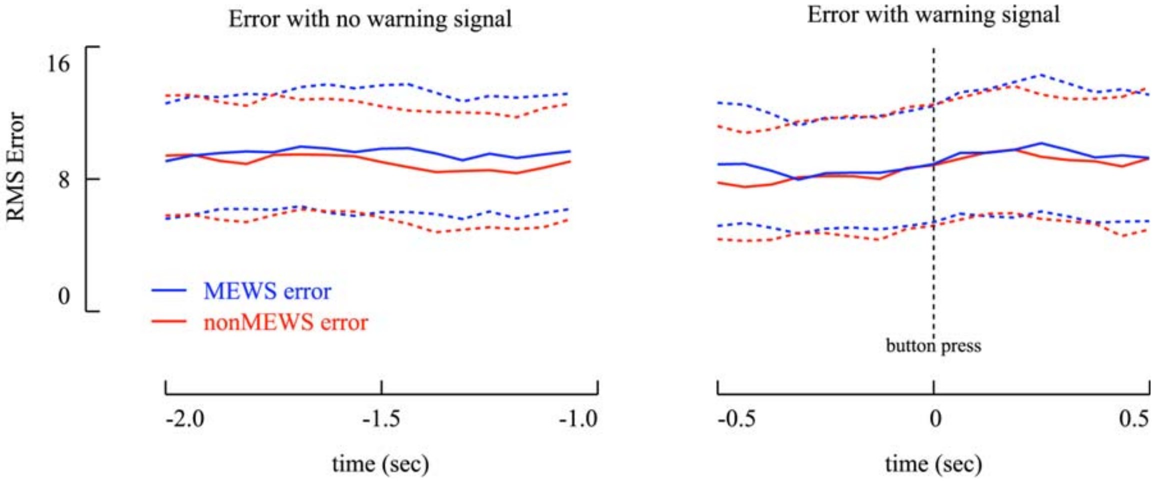

Figure A-6 - RMS Error in Lane Keeping Task

At the sponsor's request the tests were repeated using three SamTrans bus drivers as test subjects (hereafter referred to as Test Subject 1, 2, and 3). The tests were conducted at the SamTrans facility in San Mateo (next door to San Francisco International Airport). The test setup and procedure were identical to those already described. For these tests, DVI light intensity was set to medium intensity and the MEWS step interval was set to 20 ms. Response time histograms for each test subject are shown in Figure A-7 through Figure A-9. NonMEWS mean response times were from 107 to 146 msec faster for the NonMEWS than for the MEWS stimuli. For all of the drivers, the lesser mean reaction time for the NonMEWS case compared to the MEWS case was found to be statistically significant at the .005 confidence level.

Figure A-10 through Figure A-12 shows for each driver the RMS error for the lane-keeping task, which was run concurrently with the detection task (red corresponds to MEWS RMS error, blue to NonMEWS RMS error). For each driver, the RMS error for the one-second period centered 1.5 seconds before the button push is not significantly different from the RMS error centered on the button push itself. From this we can conclude that the warning signals did not distract the drivers from the lane-keeping task.

These results are consistent with those obtained previously in the Visual Detection Laboratory (VDL), in that:

- Test subjects' lane-keeping performance was unaffected by the presence of either signal. This was the primary question the study sought to answer.
- The test subjects responded more quickly to the NonMEWS signal than to the MEWS signal;

We note, however, that the reaction times of the bus drivers were substantially longer than those for the VDL test subjects, as indicated in Table A-1. The most likely explanation for the longer reaction times is that the VDL test subjects were all lab personnel who have extensive experience taking psychophysical tests of this kind, whereas this was the bus drivers' first exposure to such tests. Longer reaction times (and greater variability performance) are therefore to be expected.

Table A-1 - Overall Mean Reaction Times (msec)

	MEWS	**NonMEWS**	**Difference**
VDL Subjects	394	374	25
Bus Drivers	646	516	130
Difference	252	142	

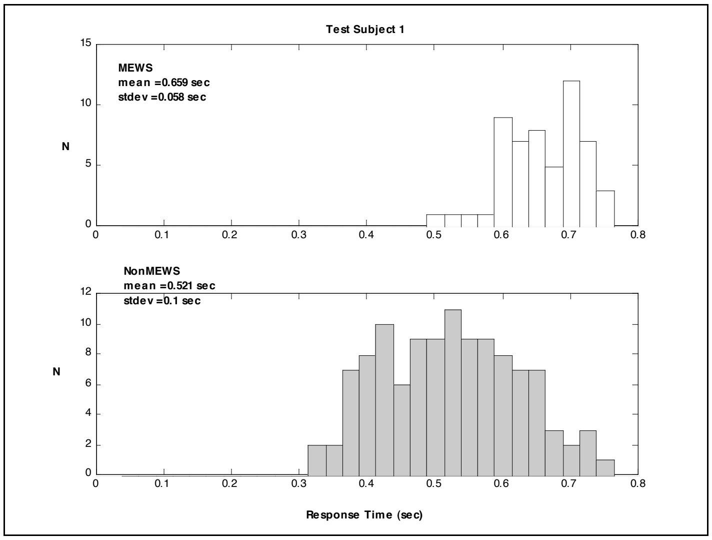

Figure A-7 - Test subject 1 - Response Time

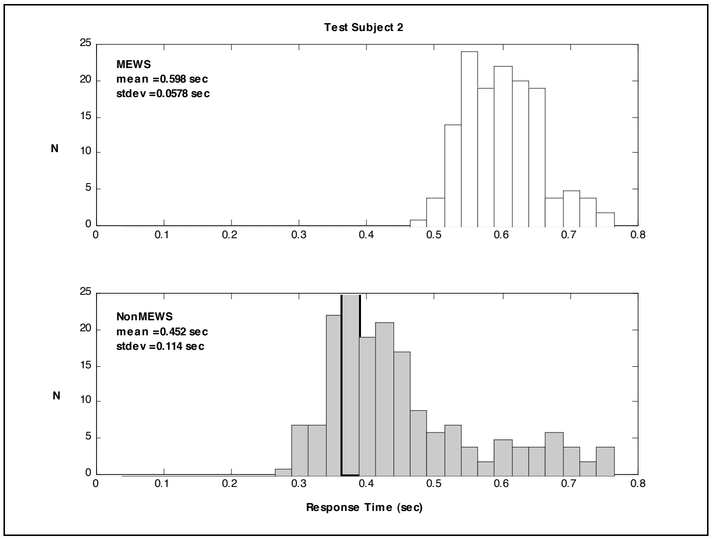

Figure A-8 - Test subject 2 - Response Time

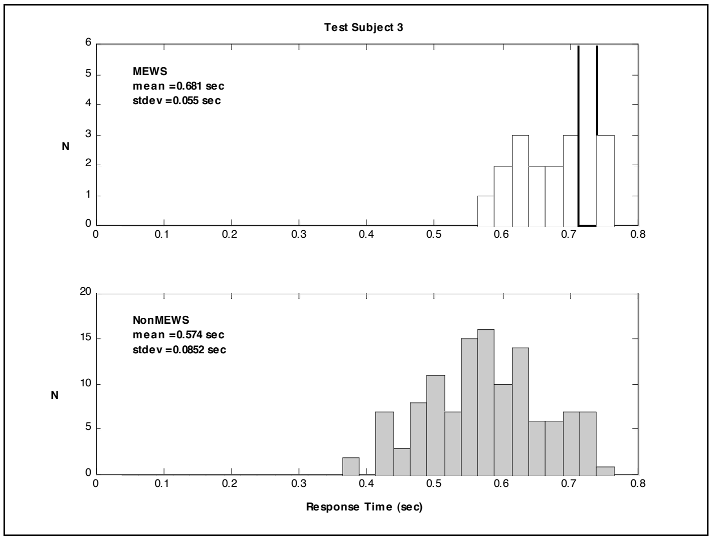

Figure A-9 - Test subject 3 - Response Time

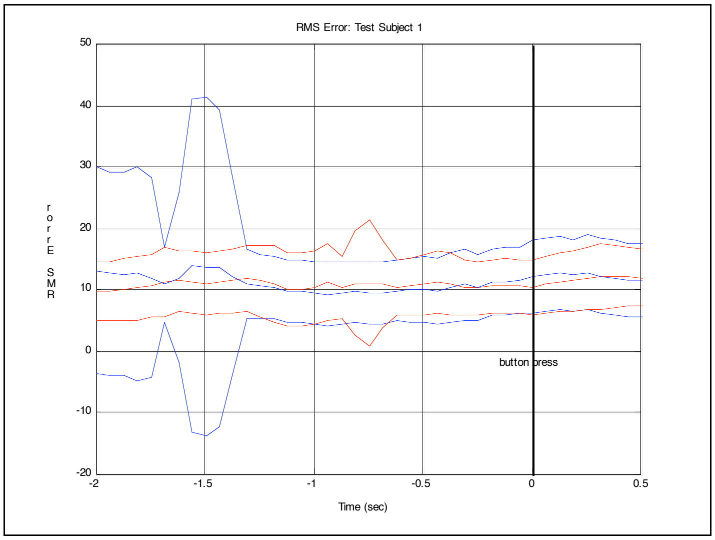

Figure A-10 - Test subject 1 – RMS Error

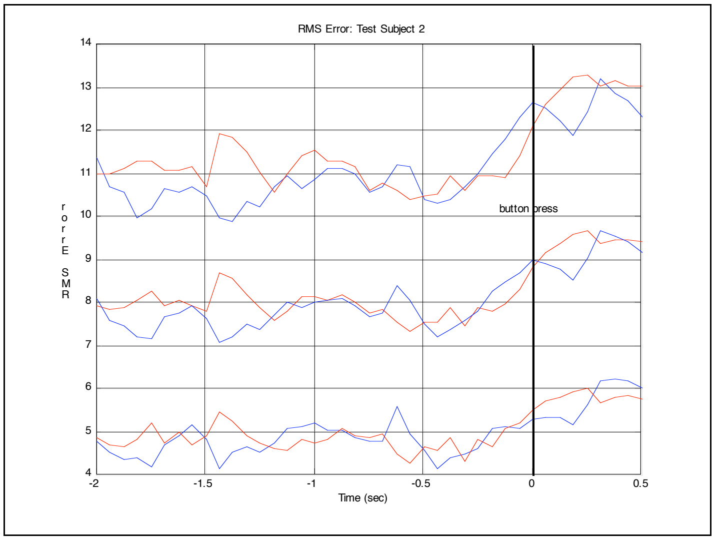

Figure A-11 - Test subject 2 – RMS Error

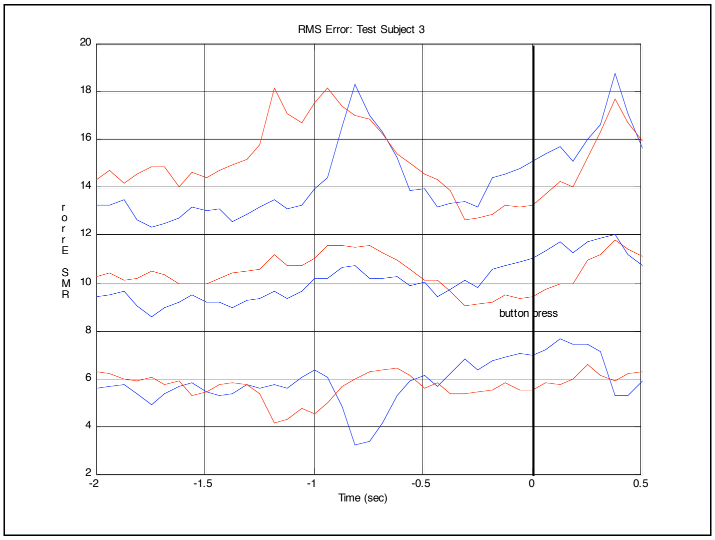

Figure A-12 - Test subject 3 – RMS Error

Somewhat more problematic, however, is the fact that for both sets of test subjects, reactions times for the NonMEWS signal were shorter than for the MEWS signal. This is at variance both with the known physiology of the visual system as well as other, similar experiments performed in the laboratory. Though this does not affect the primary conclusion of the test (lane-keeping performance is unaffected by the presence of either signal), it would be worth investigating further. Uncovering the explanation for it could lead to signaling schemes resulting in faster reaction times, thus giving drivers an additional edge in avoiding rear end collisions.

A.4 Conclusion

By delaying some elements of the DVI warning signal by as much as 50 msec, one can actually accelerate the speed with which the signal is seen, albeit by a small and not statistically significant amount. The effect was observed in both subjects tested. It seems to occur because of a few abnormally long reaction times, perhaps 5% of the total number of trials, as opposed to a slowing of all reactions times. In fact, the median response times for MEWS and non-MEWS stimuli shows the opposite relationship. The condition required for this to occur is when the signal intensity has been reduced to its 'low' level. We think that MEWS signaling thus deserves a closer look and urge consideration of its incorporation into system design for the DVI. The low intensity condition under which it occurs is comparable to 'worst case' viewing which can occur during eye movements, blinks, lapses of attention and other events.

[xiv] Graham, R and S. Hirst, "The effect of a collision avoidance system on drivers' braking responses," *Proceedings of the 4th Annual Meeting of IVHS America, Washington, DC: IVHS America*, (1994): 743 - 749.

[xv] Wilson, T., W. Butler, D. McGehee, and T. Dingus, "IVHS countermeasures for rear-end collisions, driver warning system performance guidelines," *Proceedings of the 1996 Annual Meeting of ITS America,* (1996): 949 - 957,

[xvi] Dingus, T., S. Jahns, A. Horowitz, and R. Knipling, "Human factors design issues for crash avoidance systems," in W. Barfield & T. Dingus (Eds.), *Human Factors in Intelligent Transportation Systems*, Lawrence Erlbaum Associates, Inc., (1998): 55 - 93.

[xvii] Steinfeld, A. and H-S. Tan, "Development of a driver assist interface for snowplows using iterative design," *Transportation Human Factors, Vol. 2*, no. 3, (2000): 247 - 264.

Appendix B Data Analysis for Verification Tests for Chapter Two

To understand the results in depth, it is necessary to refer to the technical report[xviii] on tracking algorithms and the terminology defined there. Basically, a firm target track built while the bus is moving corresponds to a target (static or moving relative to the ground) recognized by the bus using the algorithm. In principle, for each firm track built, there is a target position and speed in both lateral and longitudinal directions. Since LIDAR cannot distinguish lateral movement of a target due to its scanning property, only longitudinal speed and position are used.

It is noted that all the lateral positions are converted to the ground coordinate system as in Figure 2-1.

B.1 Terminology for Verification Test Data Analysis

Target: A target may be any object detected by an obstacle detection sensor, here the LIDAR system. Targets are classified as one of three types: static, moving and stationary. A static target corresponds to a static object, which is not moving from the instant of detection by LIDAR. A moving object is moving and continuously moving for some time. If a moving target later stopped moving, it would be considered stationary. Although there is a slight difference between static and stationary, we are not going to distinguish them here.

Firm track: According to the report referenced above, for multiple target tracking, a new track begins to build in the system as soon as the LIDAR detects a target. A track becomes a firm track only if it satisfies certain conditions for a certain period of time. Intuitively, a firm track is considered by the system to represent a “real target”, which may be a false target of course. Only firm tracks are used for threat assessment and could possibly lead to warning generation. Each firm track has several parameters: estimation and prediction (based on LIDAR measurement) of lateral and longitudinal positions, speed, and acceleration with respect to the bus. The estimation and prediction algorithms can be found in the report referenced above.

Arq: A critical quantity equivalent to the deceleration that would be required by the bus to avoid hitting the target, mainly determined by inter-vehicle distance, relative speed and acceleration. It is used for threat assessment and warning generation. Only if *Arq* is greater than a certain threshold value for a certain minimum period of time (e.g., 200 ms), will a warning be issued. The level of warning depends on the magnitude of *Arq*.

Speed ground truth: This is obtained from the calibrated fifth wheel measurement attached to the forward moving target vehicle.

Relative distance ground truth: This is obtained from the string pot connecting the forward moving target vehicle and the bus.

LHS (RHS) - Left (Right) hand side;

For each scenario, some of the following parameters and criteria will be used for evaluation, depending on the question to be addressed:

Static Target(s):

- If static targets are caught by firm tracks?
- Relative lateral position error if static target has been caught in a firm track;
- Relative longitudinal position error if static target has been caught in a firm track;
- Persistence of tracking.

Moving Target(s):

- If moving targets are caught by firm tracks?
- Relative lateral position and speed errors if moving target has been caught in a firm track;
- Relative longitudinal position and speed errors if moving target has been caught in a firm track;
- Persistence of tracking.

The error of a parameter is defined with respect to the ground truth. For a static target, this is its true location, for a moving vehicle, ground speed comes from the fifth wheel measurement; and for relative distance, it is from the string pot measurement.

B.2 Sensor Verification and Calibration Tests

B.2.1 Inter-vehicle Distance Measurement Error

This scenario mainly concentrates on measuring relative distance and relative speed of the forward moving target (a vehicle in this case).

Discussion: From Figure B-1, the target track is reasonably consistent. The lateral tracking (top plot) needs to consider the width of the front vehicle, which is about 2.5 m. Figure B-2 shows the relative distance tracking error compared to that measured by the string pot. It can be observed that maximum tracking error appeared during the deceleration to stop, which was about 2 m. During the cruise phase, the tracking error was within 1.0 m. The relative speed error shown in Figure B-3 is also consistent with Figure B-19 for scenario 1. These measurements and estimations are reasonably accurate for threat assessment.

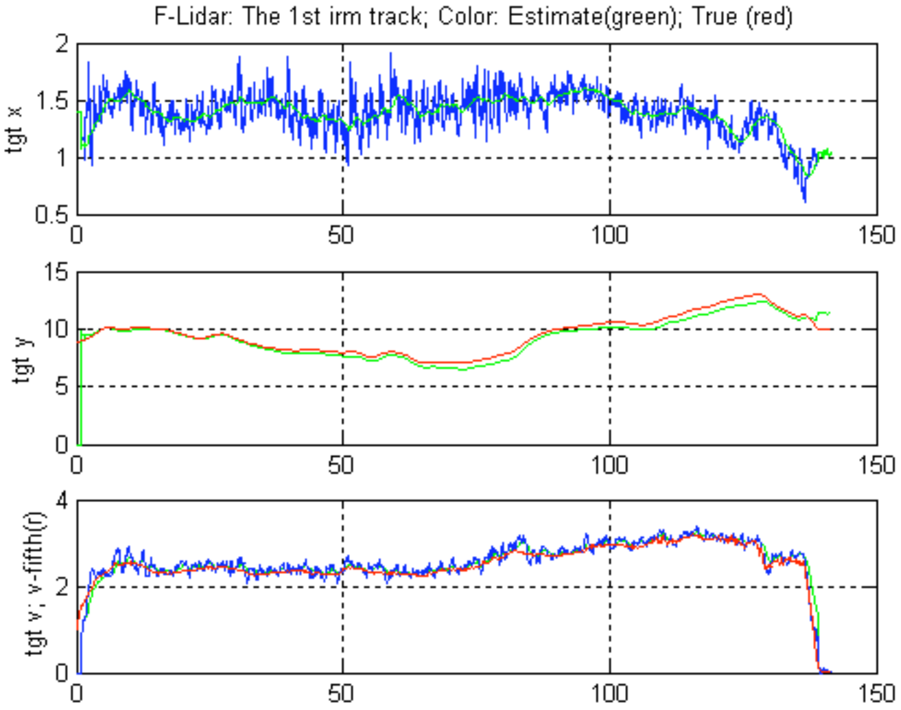

Figure B-1 - Lateral and longitudinal position and relative speed for Scenario 2

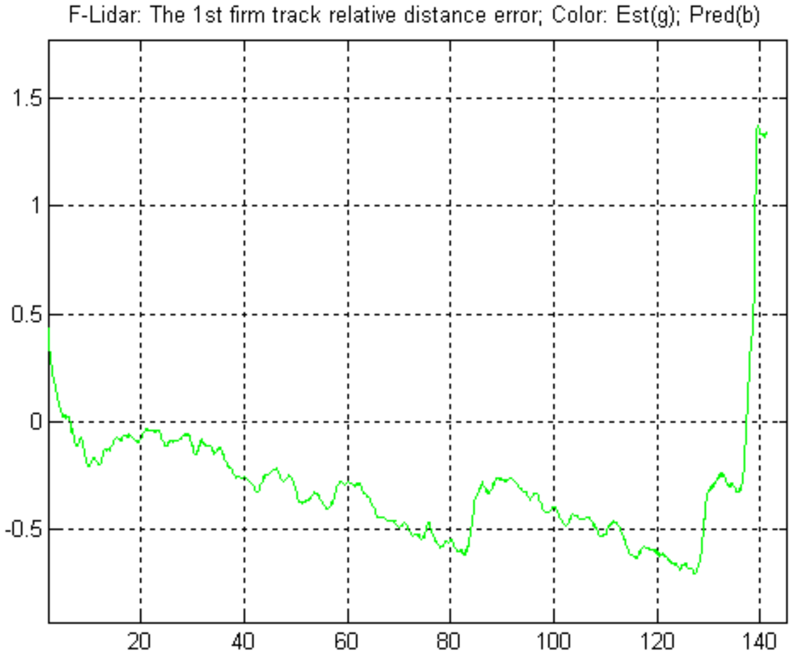

Figure B-2 - Relative distance tracking error [m]; Estimate and prediction are equal

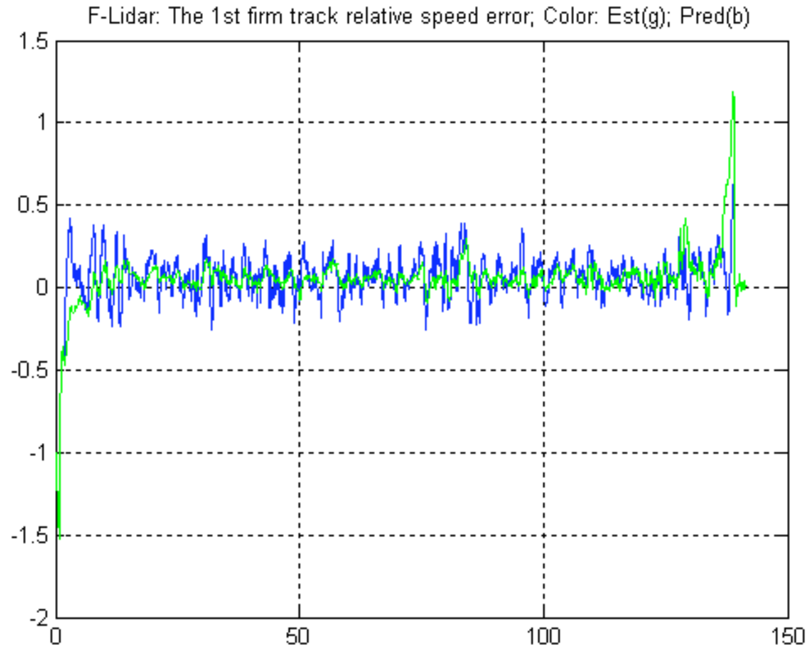

Figure B-3 - Relative speed tracking error with estimation and prediction

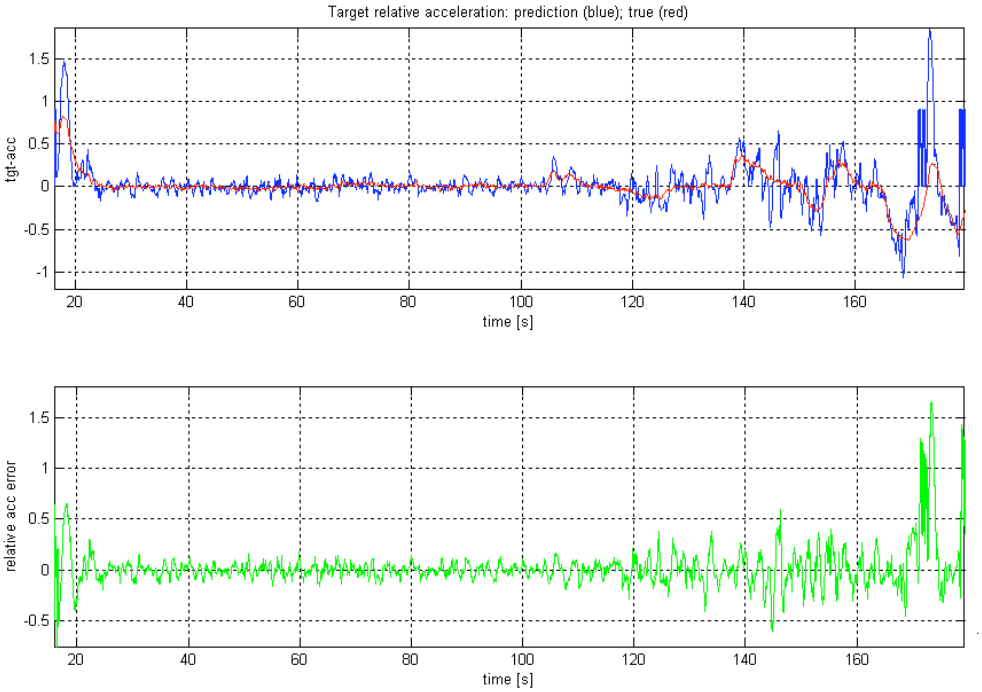

Figure B-4 - Front moving target absolute acceleration error

B.2.2 Static Object Lateral Distance Measurement, Prediction / Estimation Error

Since there is a moving target in the front of the bus from the starting point, the firm tracking should be consistent along the test course. Static targets (boxes or parked cars) can only appear in the LIDAR's field view for a short time period.

Since the front LIDAR catches the most relevant target, only front LIDAR data are analyzed.

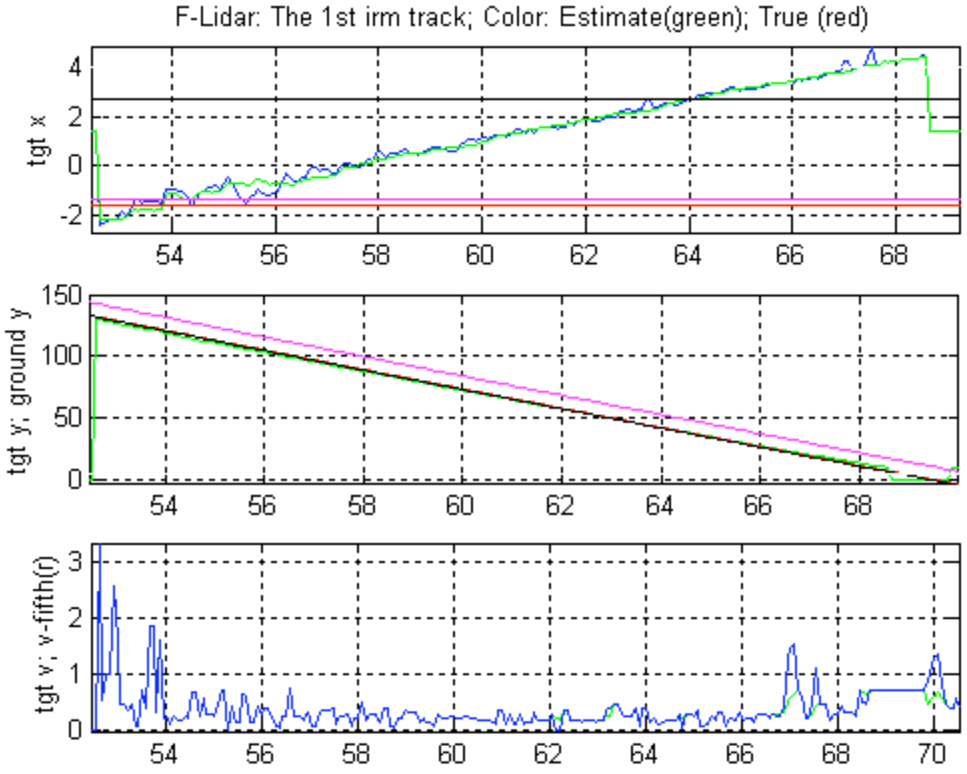

Figure B-5 - Lateral, longitudinal and speed estimation/prediction of first firm track

Discussion of Figure B-5 and Figure B-6:

Upper plot: LIDAR began to detect the static targets from about 130 m away. Initial lateral distance to the target started from -2 and gradually approached the black line representing the true target location as the bus approached it, and then went further to the right. This is mainly due to the long distance to the target and the estimation process, which needs improving in future work.

Middle plot: Longitudinal tracking error is consistently in the range of 0.8~1.0 m, as seen by the difference between the green plot (estimation) and black plot (closest true static target location) in Figure B-6.

Lower plot: This plot shows target speed estimation (green) and prediction (blue). Within this range, a target is considered as static, which means that the speed estimation is within the range of LIDAR measurement error for target speed. Figure B-6 is zoomed from Figure B-5 to show more clearly the longitudinal error.

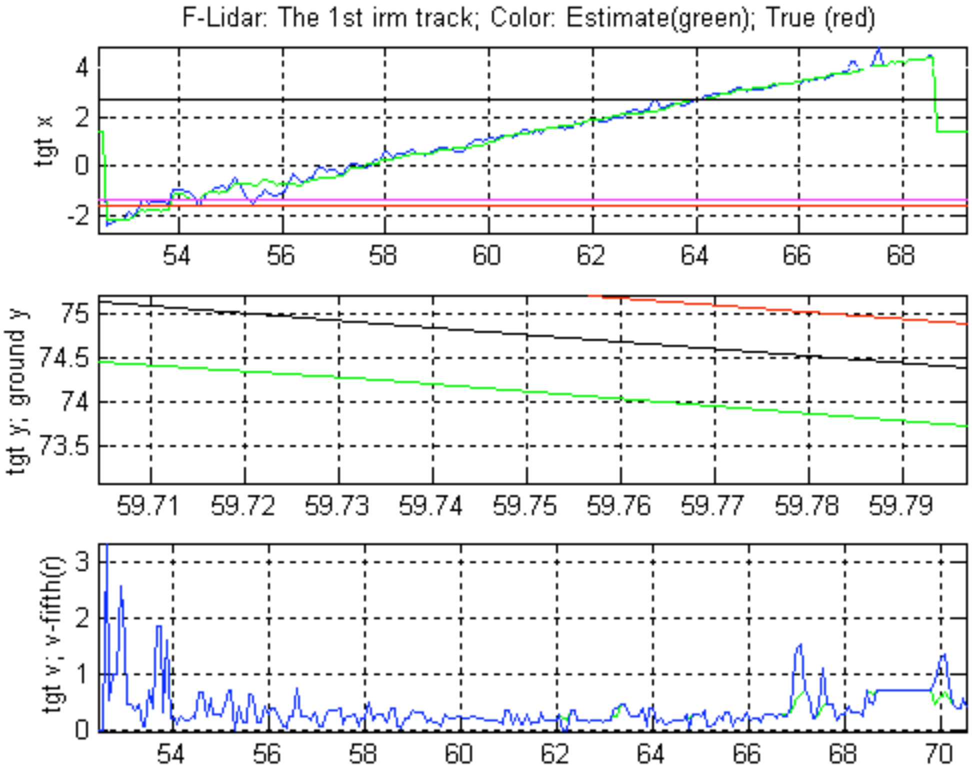

Figure B-6 - The same as Figure B-5 with zoomed middle plot

Discussion of Figure B-7 **and** Figure B-8: We can observe the same phenomenon for the second firm track as the first firm track except that, for the second firm track, the LIDAR caught one of the left hand side targets. According to the middle plot, this target is likely to be the car instead of the box. In this case, the lateral estimation and prediction approaches the target lateral position at the distance of about 25 m.

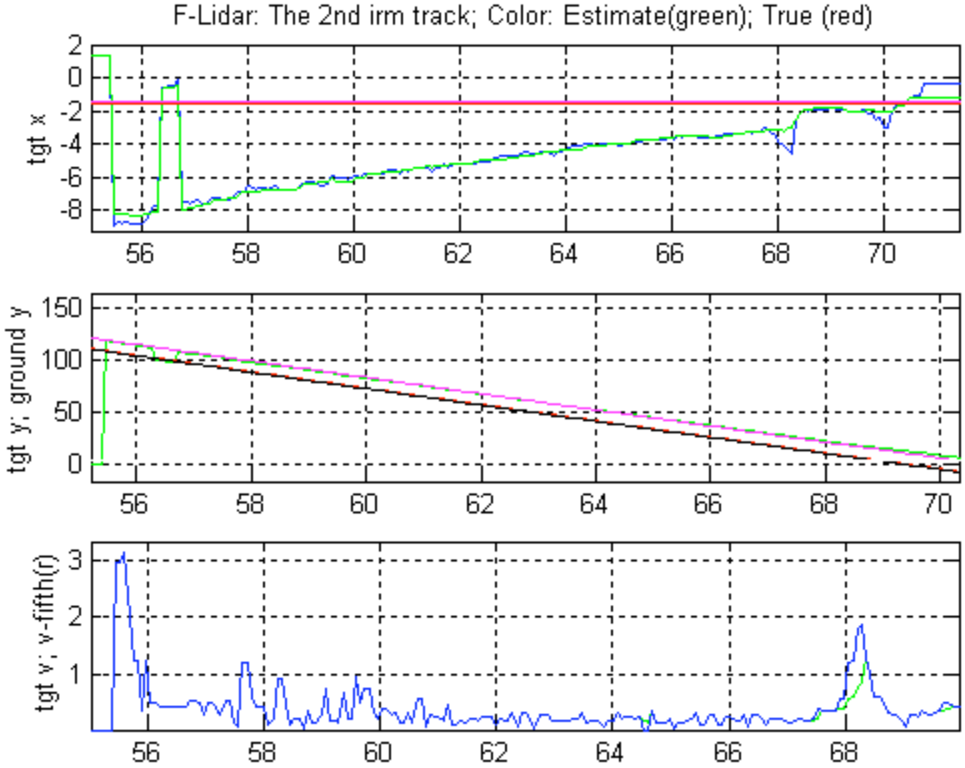

Figure B-7 - Lateral, longitudinal and speed est / prediction of second firm track

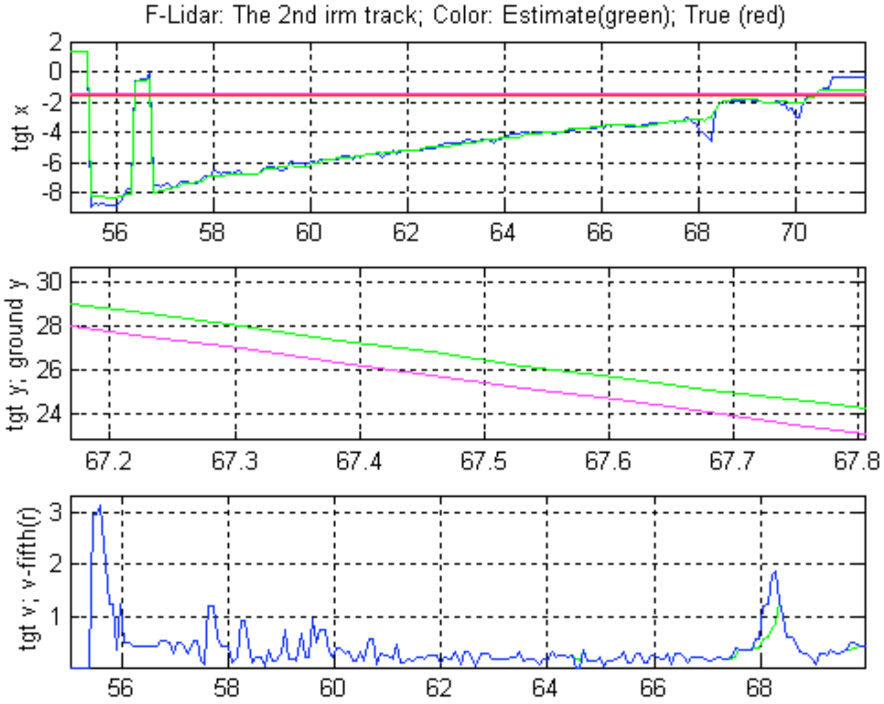

Figure B-8 - The same as Figure B-7 but with zoomed middle plot

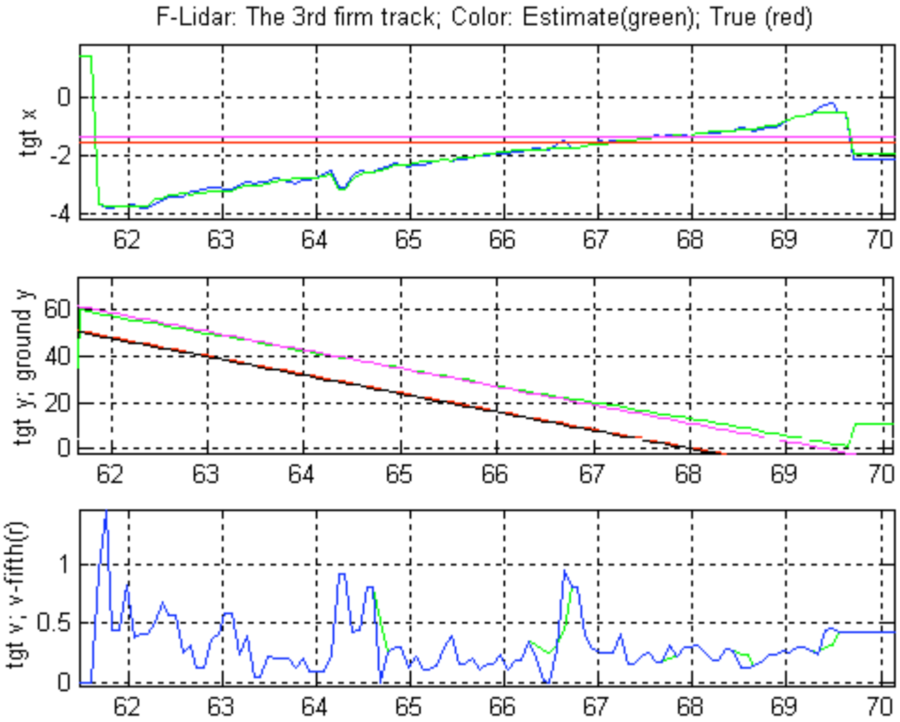

Figure B-9 - Lateral, longitudinal and speed estimation/prediction of third firm track

Discussion of Figure B-9 **and** Figure B-10: The situation is similar to the first and second firm targets except that the lateral estimation and prediction is better for this run.

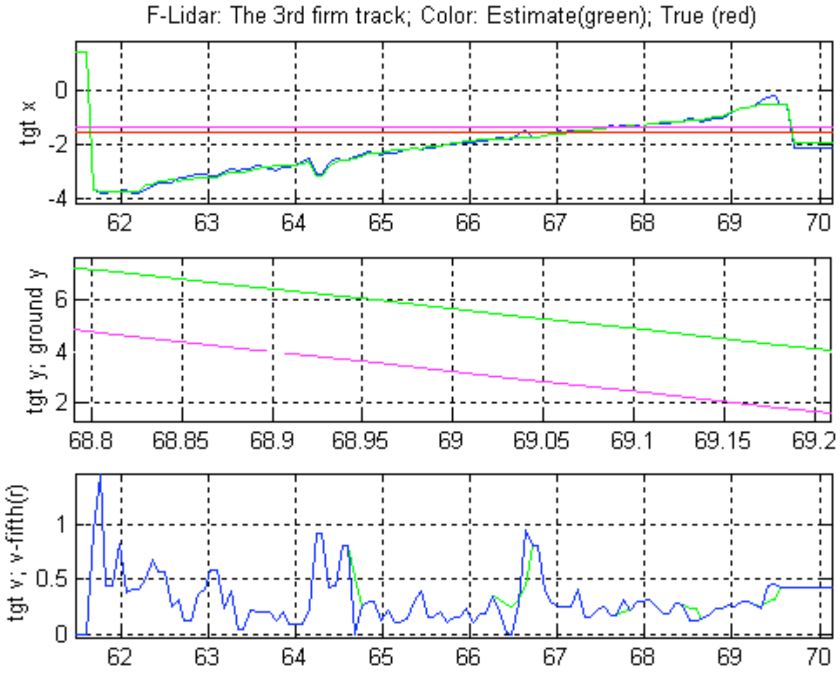

Figure B-10 - The same as Figure B-9 with zoomed middle plot

B.2.3 Time Delay Test Data Analysis

Because estimation/prediction errors are intertwined with time delay, it is difficult to separate those two. Several parameters have been considered as candidates for time delay analysis. Alternative methods also have been considered such as Fourier analysis, but they are not suitable for this purpose since we cannot control the bus or the target vehicle manually such that the relative speed is strictly sinusoidal. Since the target vehicle speed was specified to be nearly sinusoidal for this test, the speed difference between the true target vehicle speed measured by the fifth wheel and that estimated and predicted from the LIDAR detection can be determined. Those parameters are compared at some typical points such as peaks, valleys, and deceleration segments of the speed curve. To reduce the noise in those parameters, a low-pass filter has been applied simultaneously to all the data, including the true speed (from fifth wheel), its estimation and prediction. Through such analysis, some average values for time delay have been obtained.

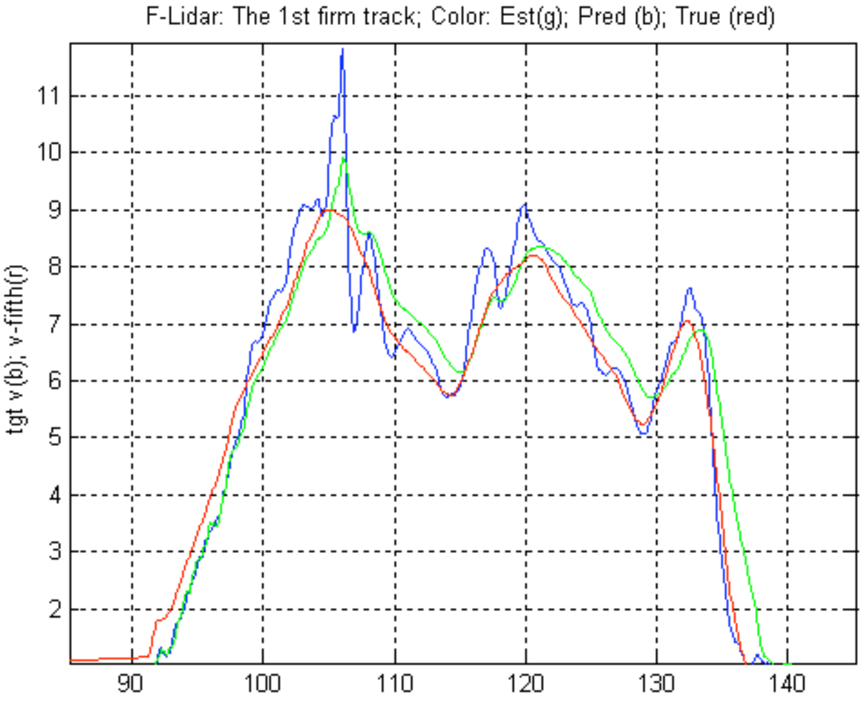

Figure B-11 - Target speed: fifth wheel (red), estimation (green) and prediction (blue)

The rest of the related figures are zoomed from the selected sections of the speed curve in Figure B-11. Delay has been averaged for each selected segment first and then the mean of all the averaged values is used to represent the time delay caused by estimation and prediction. From Figure B-12, horizontal lines show the speed points at which the delay has been estimated. The three points are chosen as v = 5.8, 5.4, and 5.0, to estimate the time delay and average to obtain:

Time delay caused by estimation: (1.0+1.25+1.3)/3 = 1.18 s
Time delay caused by prediction: (0.4+1.0+1.2)/3 = 0.8667 s

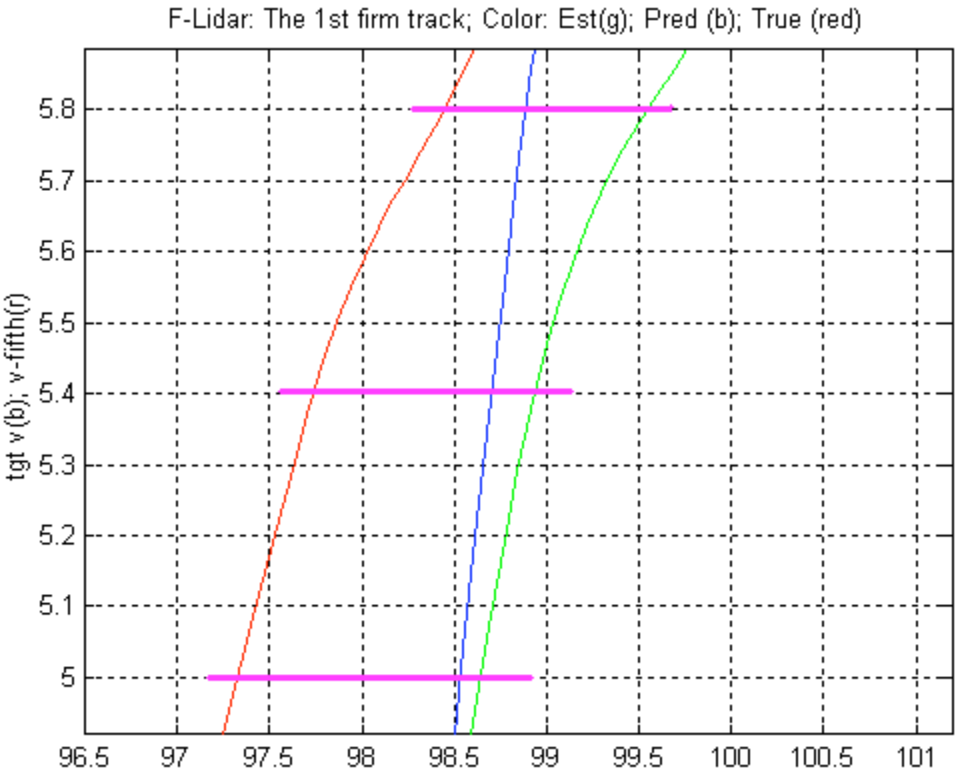

Figure B-12 - Zoomed from Figure B-11

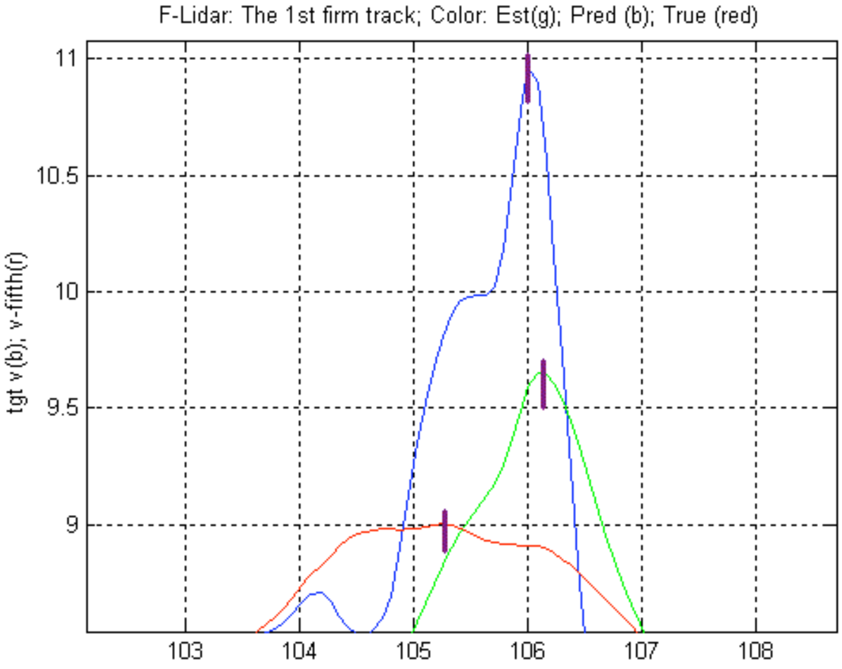

Figure B-13 - Zoomed from Figure B-11

In Figure B-13, the three vertical marks show the peaks of truth, estimation and prediction at which the delay has been estimated. The three peaks are compared to obtain the time delay as follows:

Time delay caused by estimation: 0.9 s
Time delay caused by prediction: 0.7 s

In Figure B-14, the vertical line marks show the minima of true value, estimation and prediction at which the delay has been estimated. The three valleys are compared to obtain the time delay as follows:

Time delay caused by estimation: 0.7 s
Time delay caused by prediction: 0.2 s

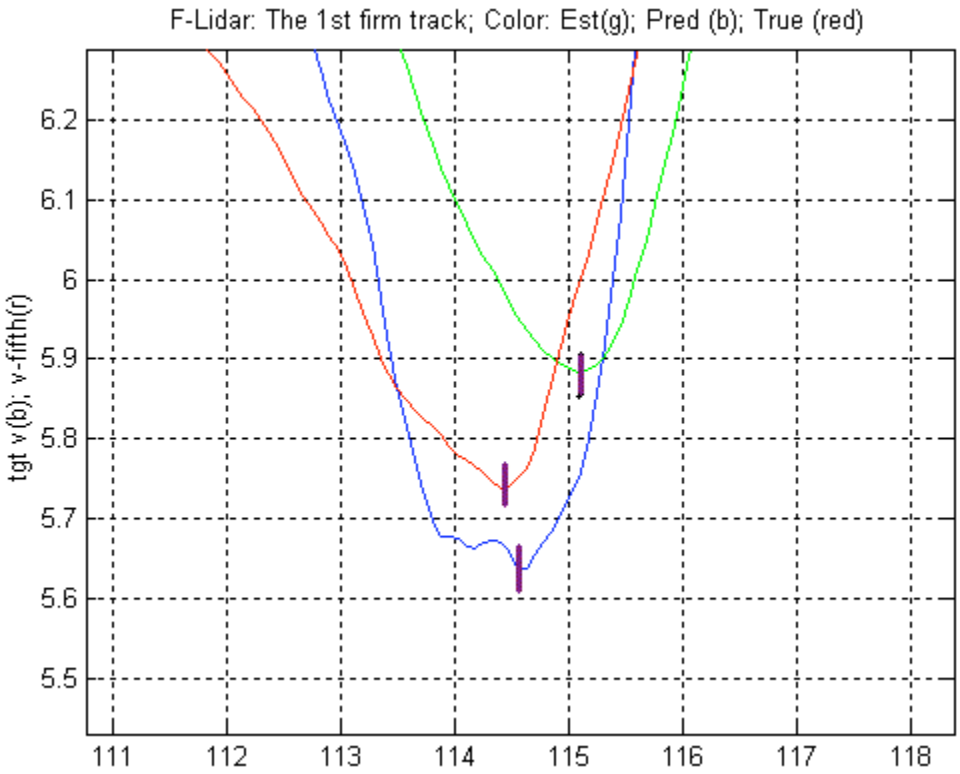

Figure B-14 - Zoomed from Figure B-11

From Figure B-15, the horizontal lines show the speed points at which the delay has been estimated. The five points are chosen as v = 7.8, 7.4, 7.3, 7.1, and 6.8 to estimate the time delay and average to obtain:

Time delay caused by estimation: (1.3+1.45+1.52+1.38+1.0)/5 = 1.33
Time delay caused by prediction: (0.7+0.25+0.15+0.8+0.3)/5 = 0.44

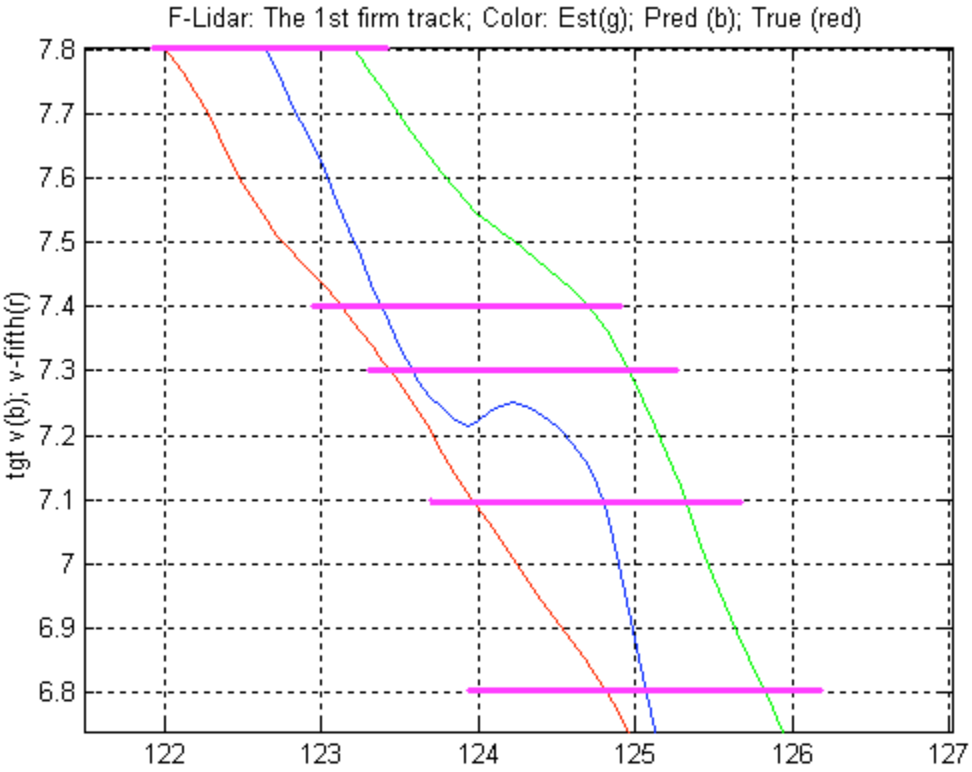

Figure B-15 - Zoomed from Figure B-11

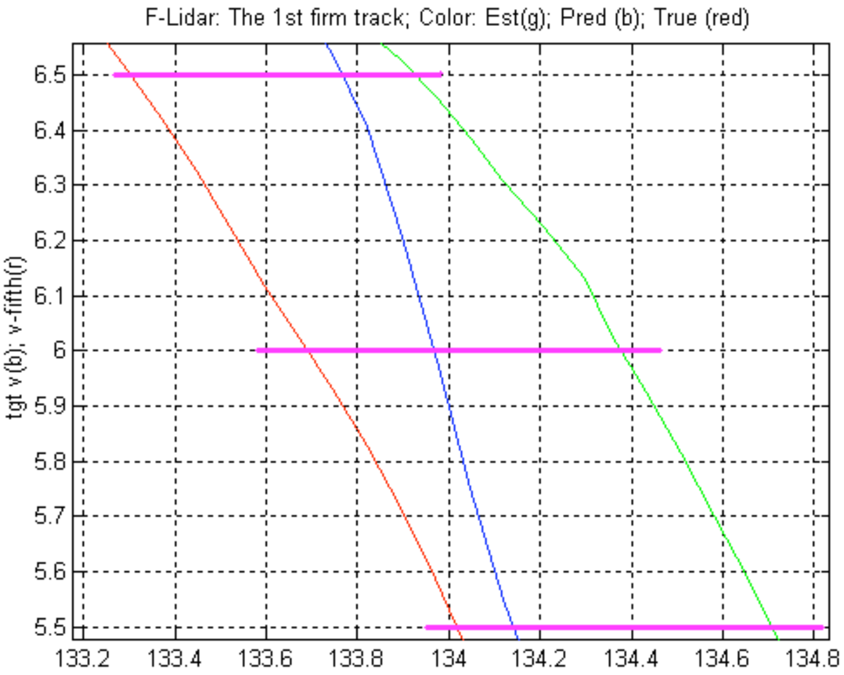

Figure B-16 - Zoomed from Figure B-11

From Figure B-16, the horizontal lines show the speed points at which the delay has been estimated. The three points are chosen as v = 6.5, 6.0, and 5.5 to estimate the time delay and average to obtain:

Time delay caused by estimation: (0.6+0.65+0.7)/3 = 0.65
Time delay caused by prediction: (0.45+0.25+0.15)/3 = 0.28

Now, by averaging all the five estimated time delay values, we obtain the overall estimated average time delays as follows:

Estimated average time delay caused by estimation:

(1.18+1.1+0.7+1.33+0.65)/5 = 1.0 s

Estimated average time delay caused by prediction:

(0.8667+0.7+0.2+0.44+0.28)/5 = 0.4973 s

Other scenario based test data analysis is presented as follows.

B.2.4 Gyro Rate Angle Measurement Tests

These two tests were very consistent and the gyro yaw angle integrated from the measured gyro yaw rate was very precise as shown in Figure B-17 and Figure B-18. The dwell between 40 ~ 60 seconds indicates the bus did not turn.

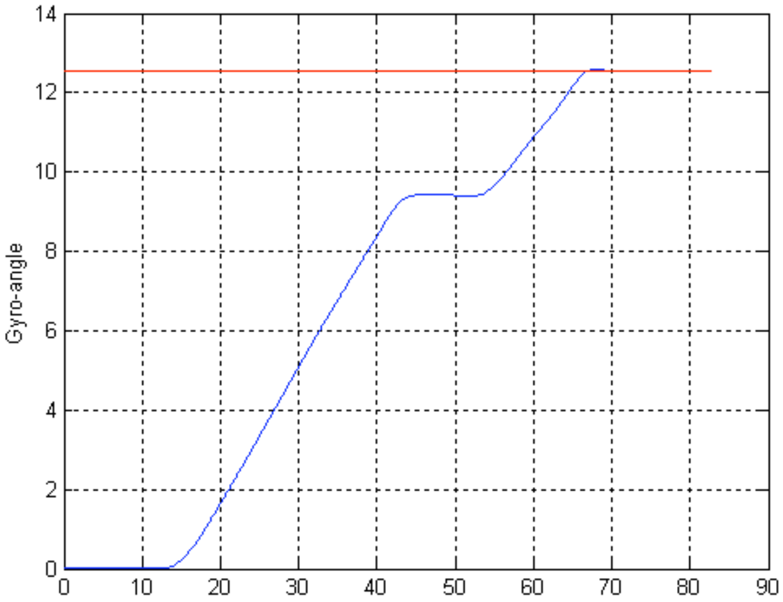

Figure B-17 - Yaw angle estimate from yaw rate measurement: radians vs. seconds

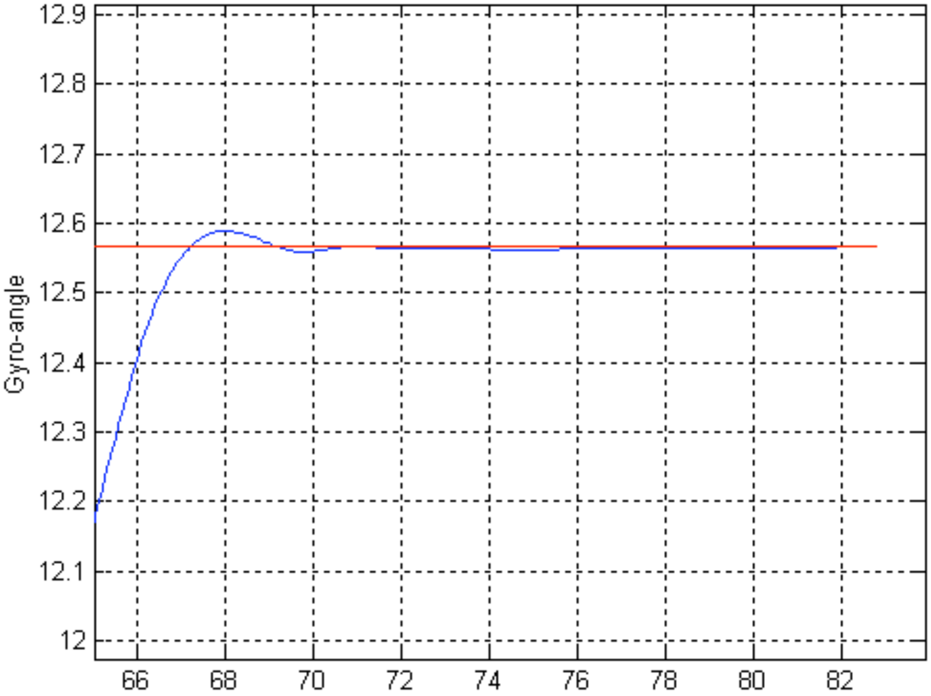

Figure B-18 - Zoomed from Figure B-17 to see the error

This indicates that the yaw rate gyroscope measurement is precise enough.

B.3 Scenario-based System Verification

B.3.1 Vehicle Following

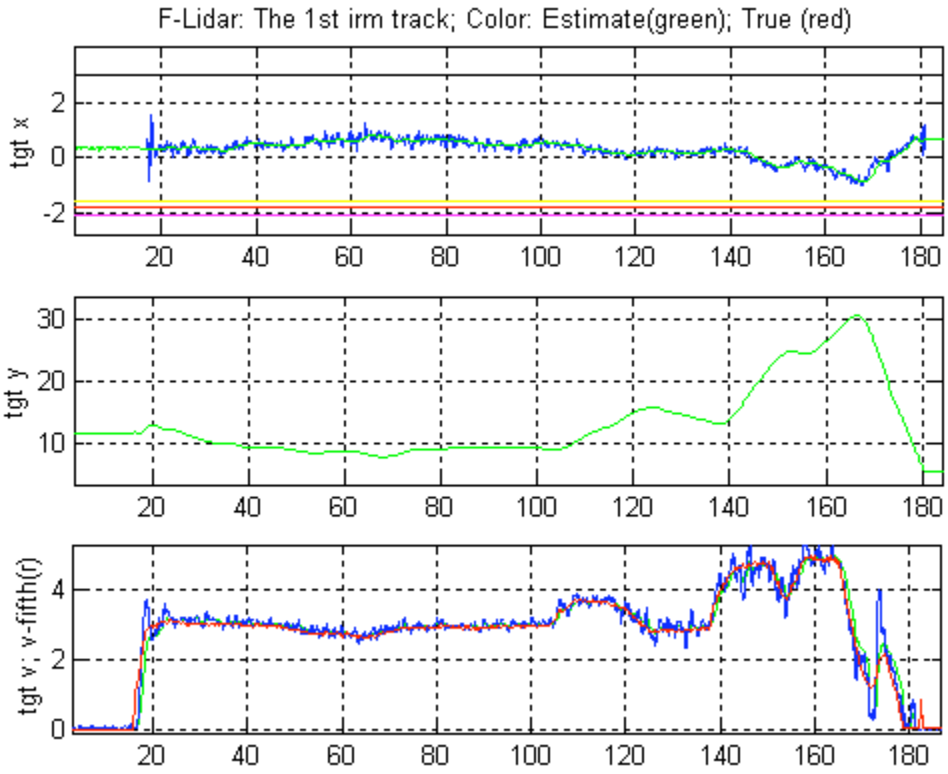

Figure B-19 - Lateral position, longitudinal relative distance and speed for Scen 1

Discussion of Figure B-19 **and** Figure B-20**:**

Upper plot - lateral positions of static targets: yellow, red and magenta represent three static targets (boxes) on the lane to the left of the bus. The black line represents the lateral position of the right side static target. The green curve and blue curve are the lateral position estimation and prediction of the first firm track respectively, representing the forward target vehicle. Considering the width of the target vehicle, which is 2.3 m, the lateral estimation and prediction is good. The first firm track was very consistent and it was not distracted by the static targets on either side.

Middle plot – Longitudinal relative distance [m], estimation and prediction. Because there is no string pot in this scenario, it is impossible to tell if the estimation is accurate enough.

Lower plot – Target speed estimation (green) [m/s], prediction (blue) and ground truth (red). The speed accuracy is better evaluated using Figure B-11, which shows the relative speed error [m/s] for target speed estimation (green) and prediction (blue). It is noted that speed sensor measurement at lower speed has worse performance than at higher speed, which may be caused by the transients at around $t = 20s$ and $t = 170s$, which are removed in data analysis.

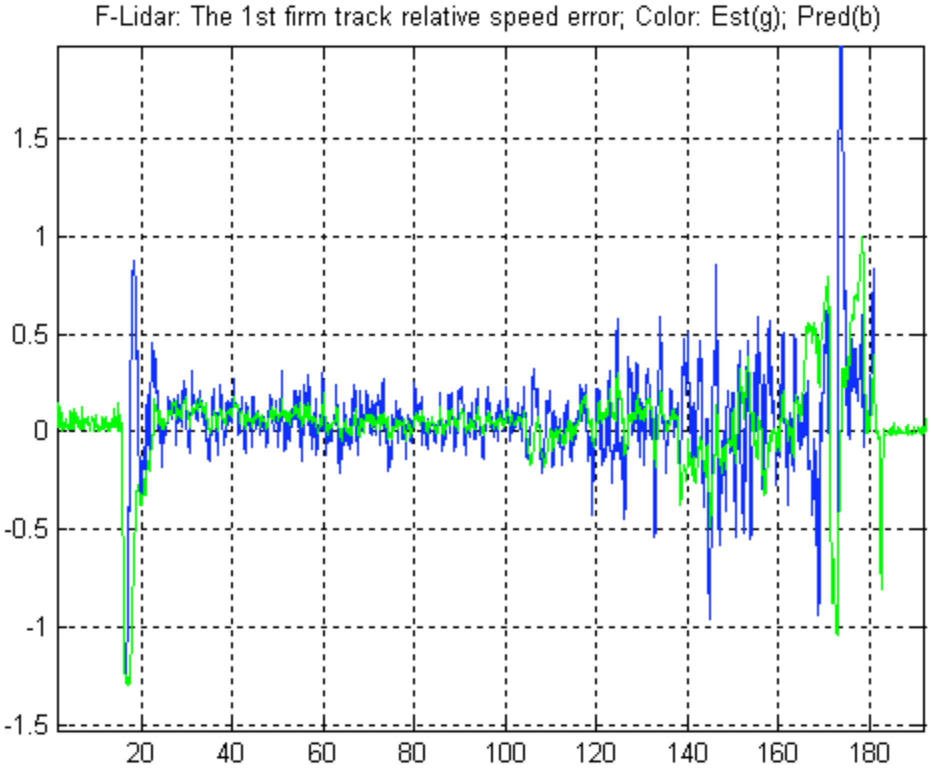

Figure B-20 - Relative speed tracking error wrt the fifth wheel of the target vehicle

Discussion of Figure B-21 **and** Figure B-22**:** Because the static targets (boxes) are far away from the starting point of the bus and there is a moving vehicle in front of the bus blocking the field of view of the LIDAR, the LIDAR did not detect the static targets until the bus was about 30 m away from the targets (Figure B-21).

Upper plot – The target caught by the LIDAR was obviously the right hand side lane single box.

Middle plot - The estimation (green) of longitudinal position [m] is close to that of the ground truth (black straight line), corresponding to the target on the right hand side, which is consistent with the lateral target tracking.

Lower plot – Target speed estimation (green) and prediction (blue). Within this range, a target is considered static, which means that the speed estimation [m/s] is within the range of LIDAR measurement error for target speed.

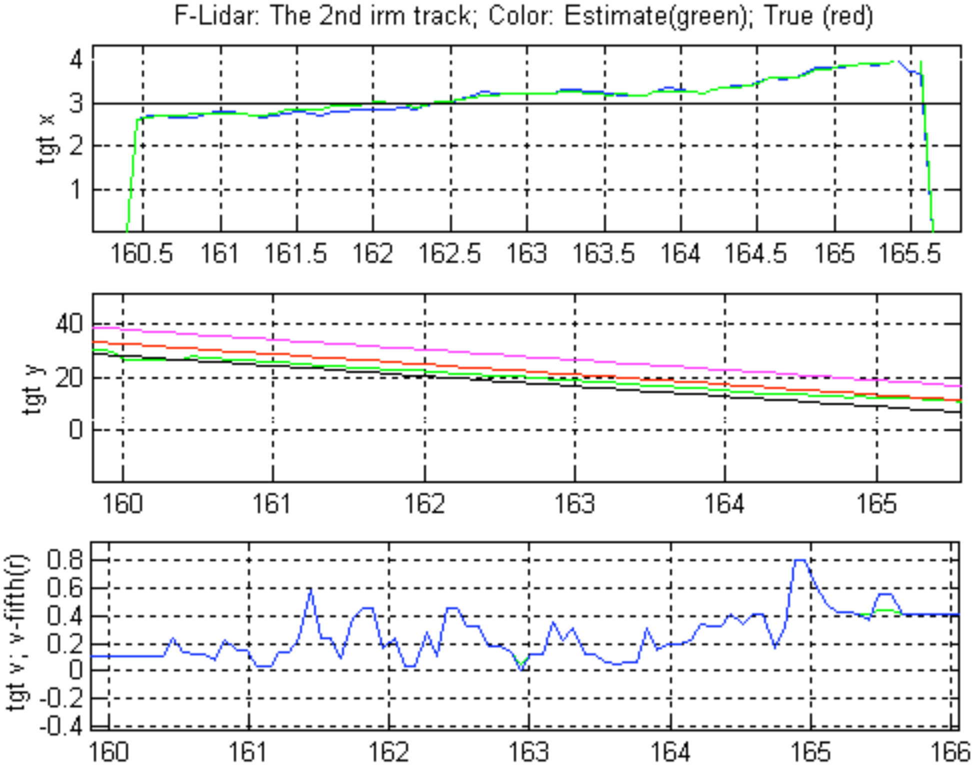

Figure B-21 - Second firm track lat. position, relative long. position and speed

It can be observed that the maximum lateral tracking error is about 1.9 m and the maximum longitudinal distance tracking error is about 2.0 m (Figure B-22). This may be the potential cause of some false positive and negative warnings. Fusion of video camera information into tracking and threat assessment should be helpful to solve this problem.

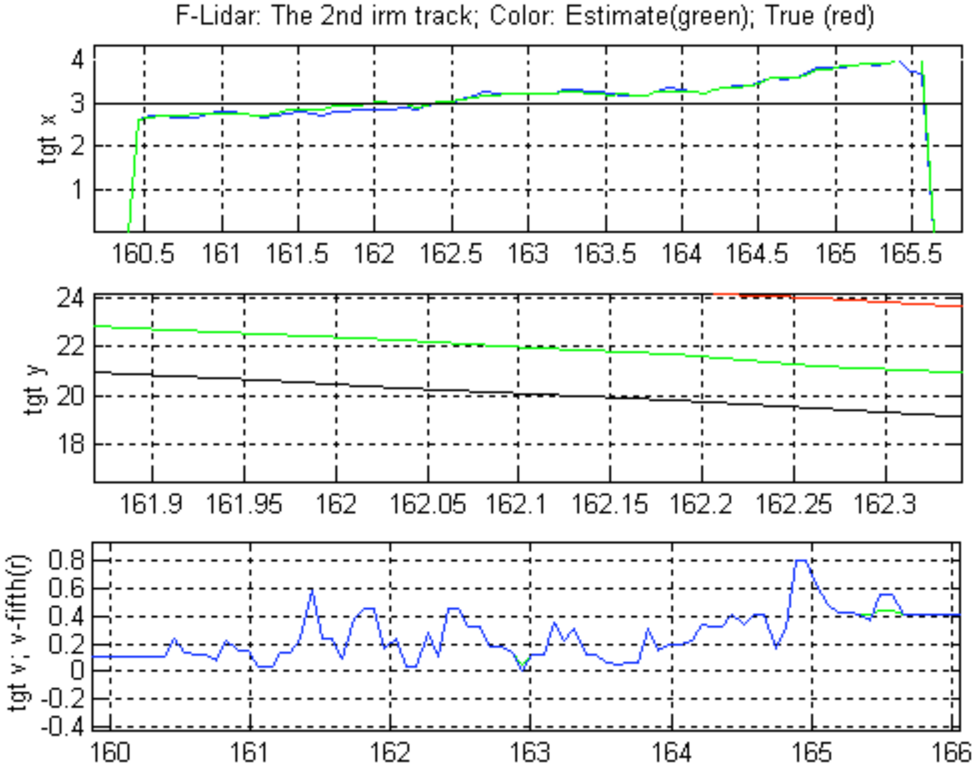

Figure B-22 - Lat. and relative long. position and speed with middle plot zoomed

Discussion of Figure B-23 **and** Figure B-24**:** Similarly, because the static targets (boxes) are far away from the starting point of the bus and there is a moving vehicle in front of the bus blocking the field of view of the LIDAR, the LIDAR did not detect the static targets until the bus was within about 40 m of the targets. The third firm track caught the left hand side targets.

> Upper plot: Lateral position of the third firm track is close to those of the right hand side targets. From the middle, the actual target tracked is the nearest static target (yellow). The tracking error is about 1.0 m.
>
> Middle plot: The estimation (same as prediction) of longitudinal position of the third firm track is close to the nearest static target (yellow) on the left hand side. The tracking error is about 1.0 m.
>
> Lower plot: Target speed estimation (green) and prediction (blue). Within this range, a target is considered static, which means that the speed estimation is within the range of LIDAR measurement error for target speed.

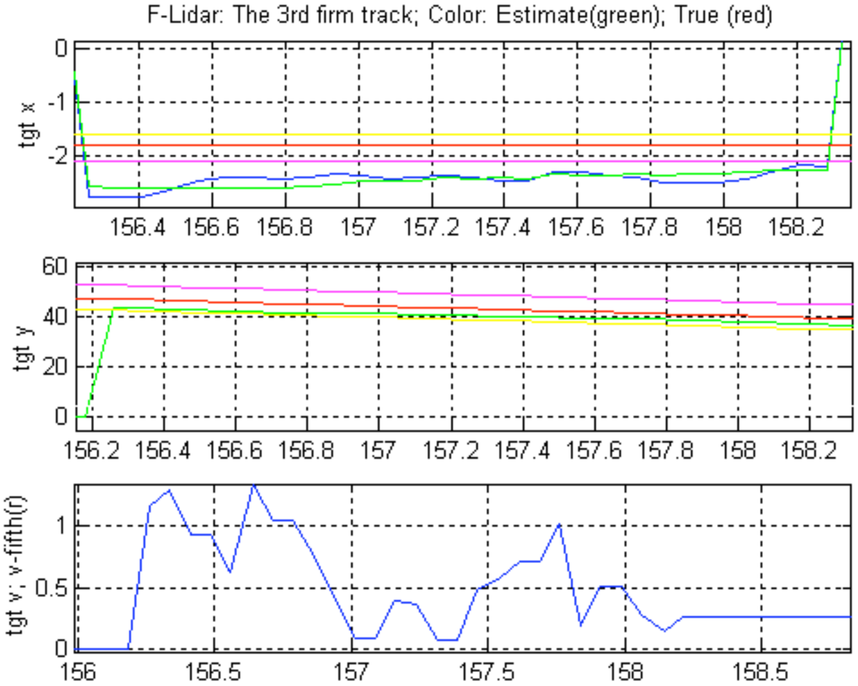

Figure B-23 - Lat. position, long. relative position, and target speed estimate

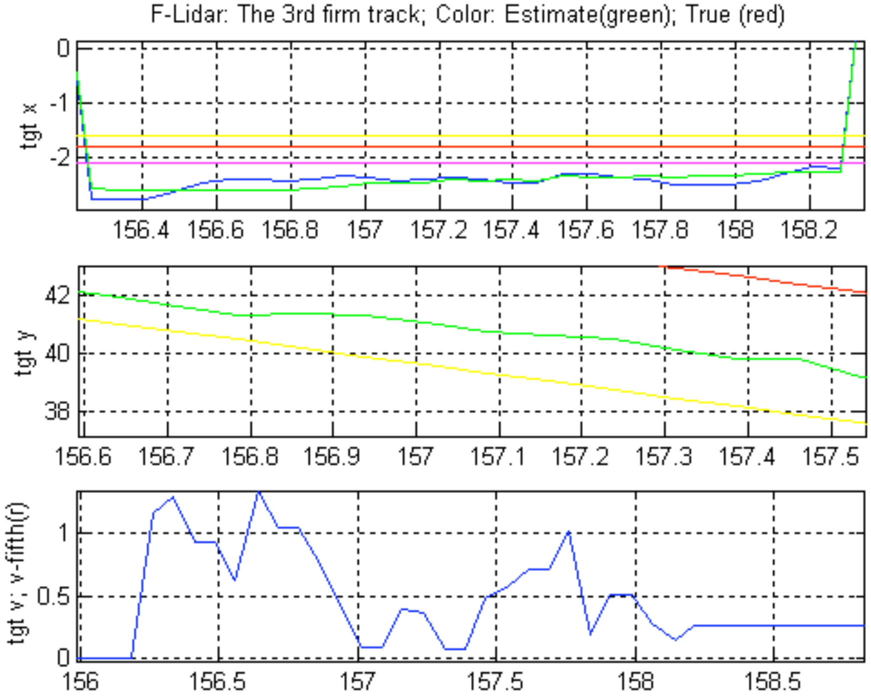

Figure B-24 - The same as in Figure B-23 but with zoomed middle plot

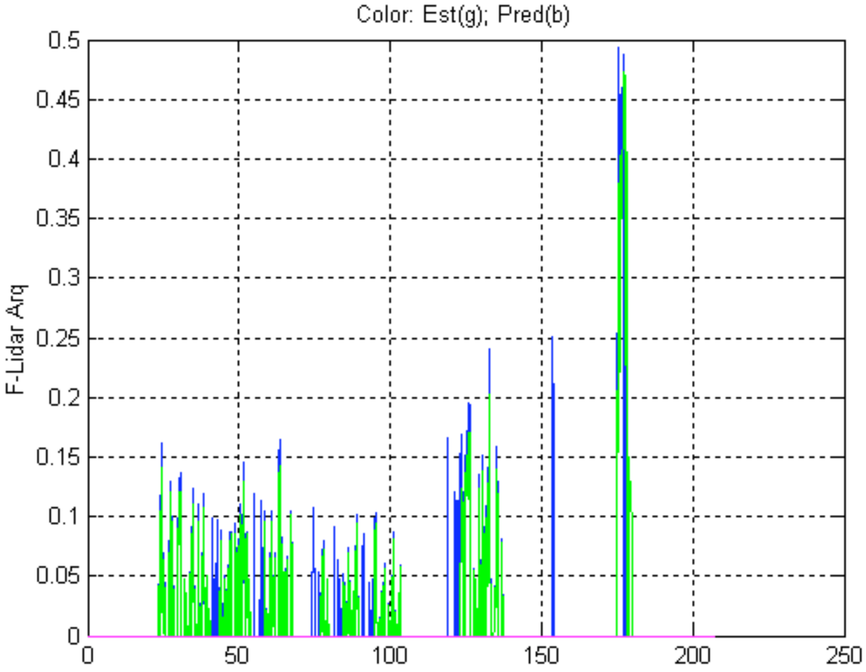

Figure B-25 - The *Arq* parameter for Scenario 1

Figure B-25 shows the *Arq* corresponding to the moving target in front. The *Arq* parameter can be determined from the moving target which can be told from the tracking ID, etc. Due to the small magnitude, no warning was triggered, which was the appropriate response.

The data displayed here correspond to the run with maximum speed of 15 mph.

B.3.2 Detection of Moving Target in Adjacent Lane

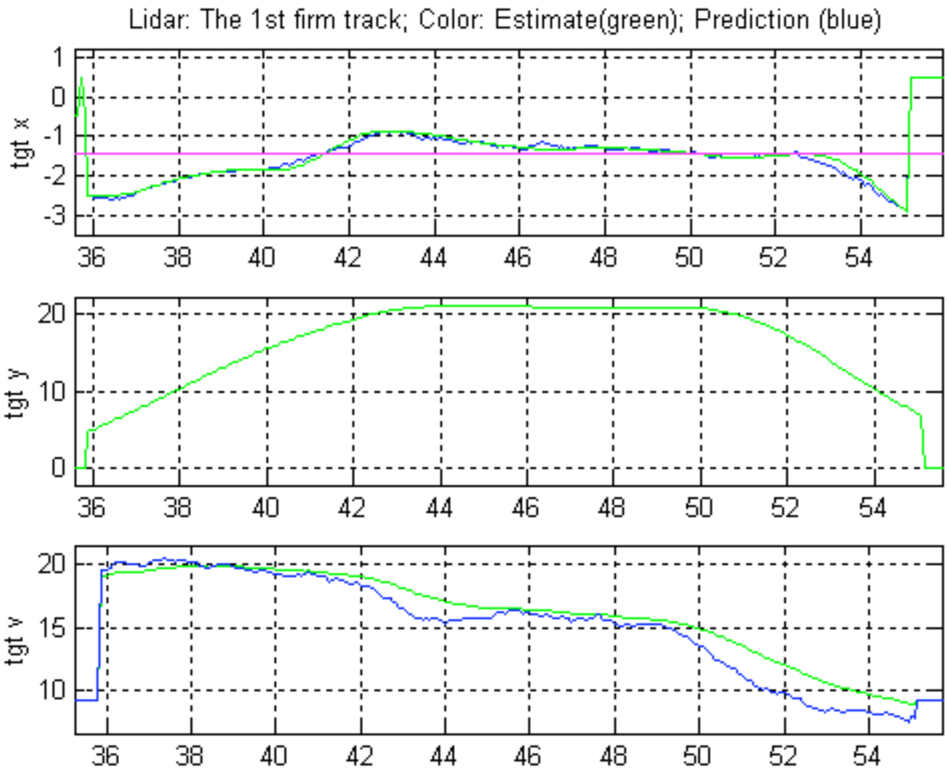

Figure B-26 - Left adjacent lane moving target (vehicle) detection

Discussion of Figure B-26**:**

Upper plot: Magenta – moving vehicle (target) true course (side line near the bus) in left lane. Green and blue are lateral distance estimation and prediction from the sensor and tracking algorithm. Lateral position estimation has larger error when the moving vehicle is close to the bus and less error while the moving target is far away from the bus. This may be due to the azimuth characteristics of the LIDAR and estimation error.

Middle plot: Longitudinal distance of the target vehicle with respect to the bus.

Lower plot: Speed estimation and prediction of the moving target in left lane.

B.3.3 Cut-in and Cut-out Test

Two runs were made for this test. Only one firm track was built during each run, which is reasonable.

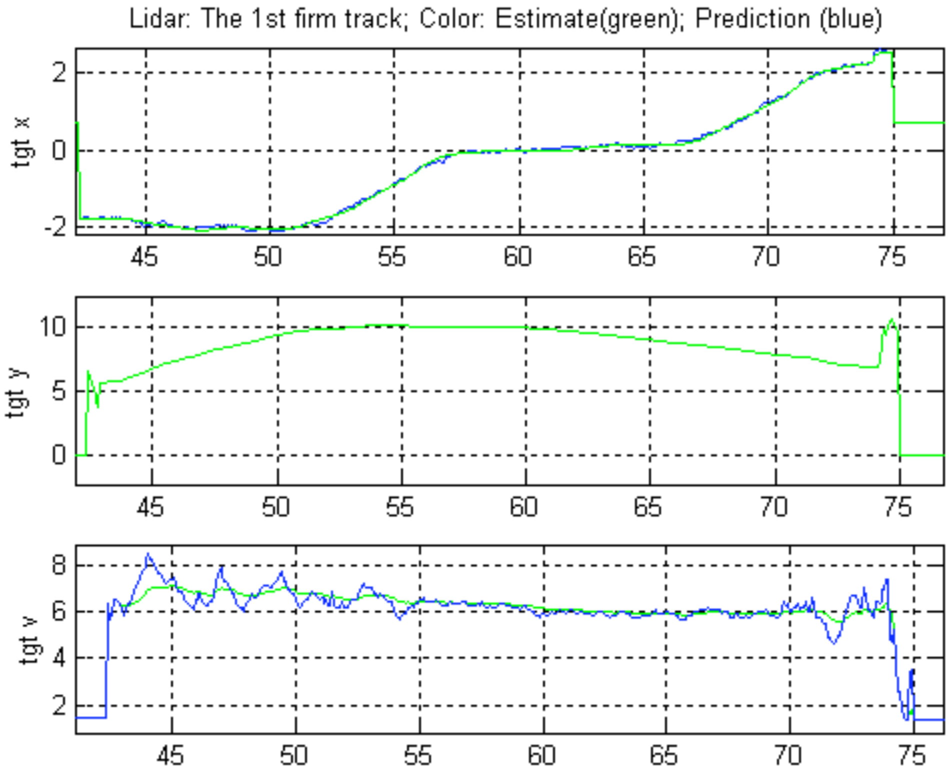

Figure B-27 – First firm track lat. and long. position, speed estimate and prediction

Discussion of Figure B-27**:**

> Upper plot: This plot shows the lateral distance estimation and prediction of the moving vehicle (target). The first firm track begins to build as soon as the target vehicle moves into the field of view of the front LIDAR from the left lane at about 43 s. The cut-in vehicle completely moved into the bus lane at about 57 s. It remained in front of the bus until 66 s and then began to move to the right lane. It completely moved to the right lane at about 70 s.
>
> Middle plot: Cut-in and cut-out (target) vehicle distance with respect to the bus.
>
> Lower plot: Cut-in (target) vehicle speed [m/s].

B.3.4 Low Speed Approaching / Crashing into a Static Object

Two runs were made for this test and the results were consistent.

From Figure B-28 the subject vehicle begins to generate threat assessment at the distance of 10.5 m (at 67 s, Figure B-28) towards the target (a box); and begins to issue a warning (Figure B-29) at the distance 10.0 m (at about 68 s).

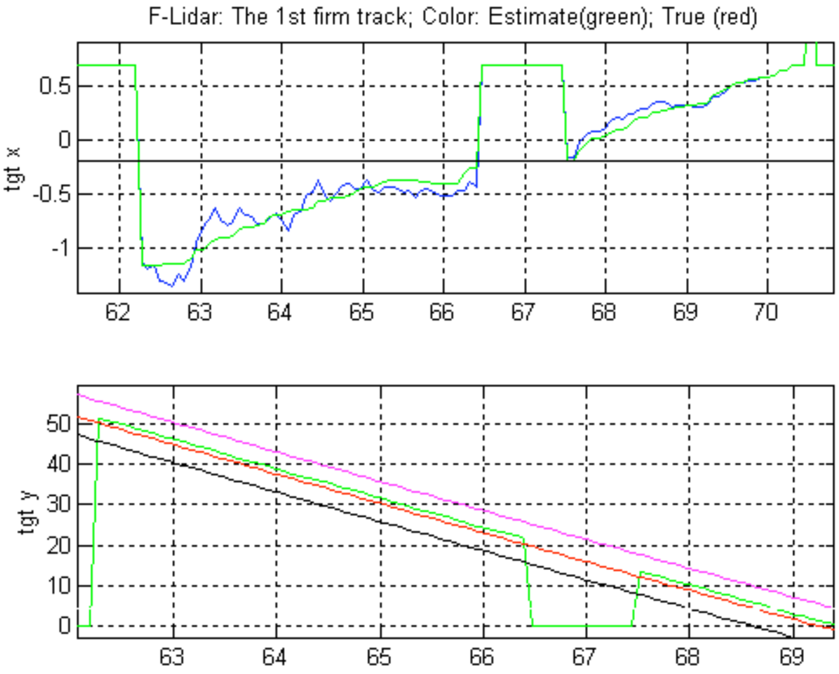

Figure B-28 - Front target lateral and longitudinal distance estimation

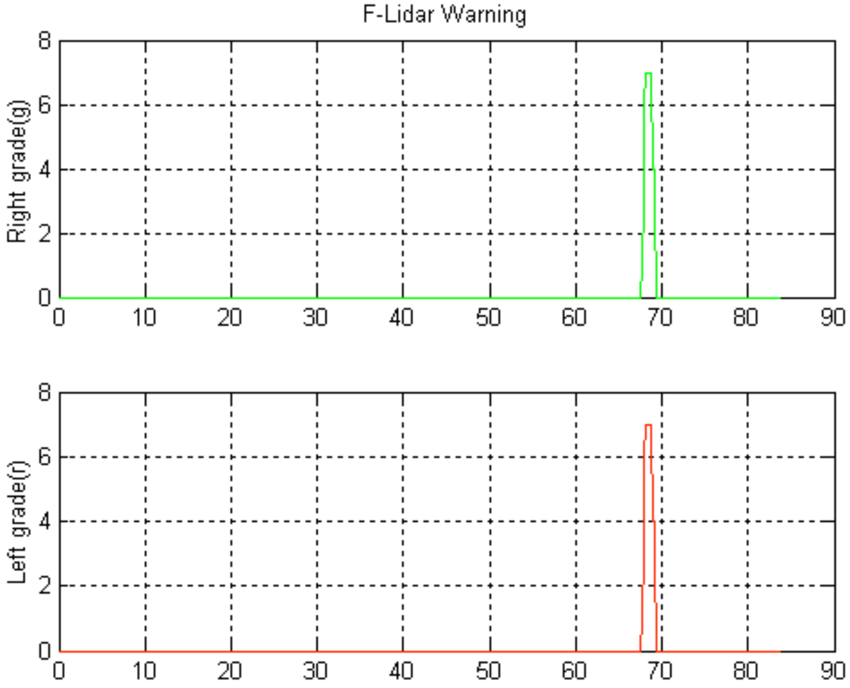

Figure B-29 - Low-Speed Crash Test, Left and Right Warning Levels

Discussion of Figure B-29**:**

Upper plot: The warning grades issued by the algorithm to the right LED display.

Lower plot: The warning grades issued by the algorithm to the left LED display. It can be observed that both warnings were issued at the same time, with the same level and lasted for the same time period.

[xviii] X. Q. Wang, *Transit Bus Forward Collision Warning System, Algorithm Summary*, California PATH Program, (August 2003).

Appendix C Detailed Data Plots for Chapter Three

C.1 Database Records of Driving Statistics for Seven Bus Operators

Figure C-1 though Figure C-3 below shows the total driving minutes of three SamTrans bus operators (from 06/11/04 to 05/06/05) and Figure C-4 through Figure C-7 shows the comparable data for four PAT bus operators.

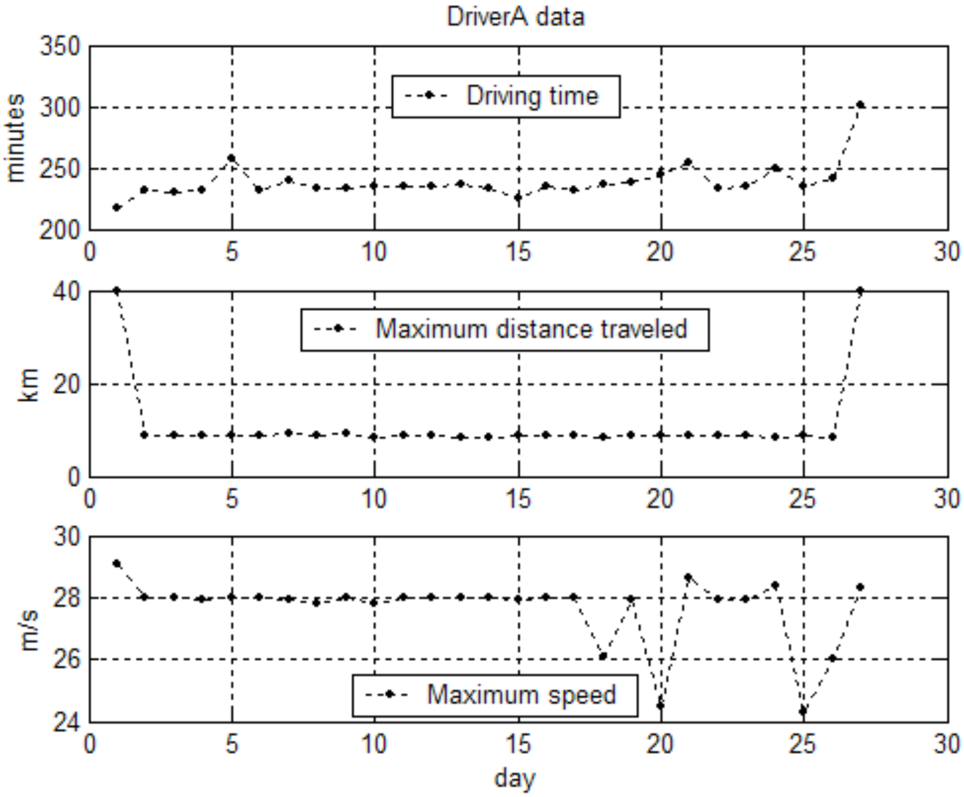

Figure C-1 - Driving statistics by day for bus operator A

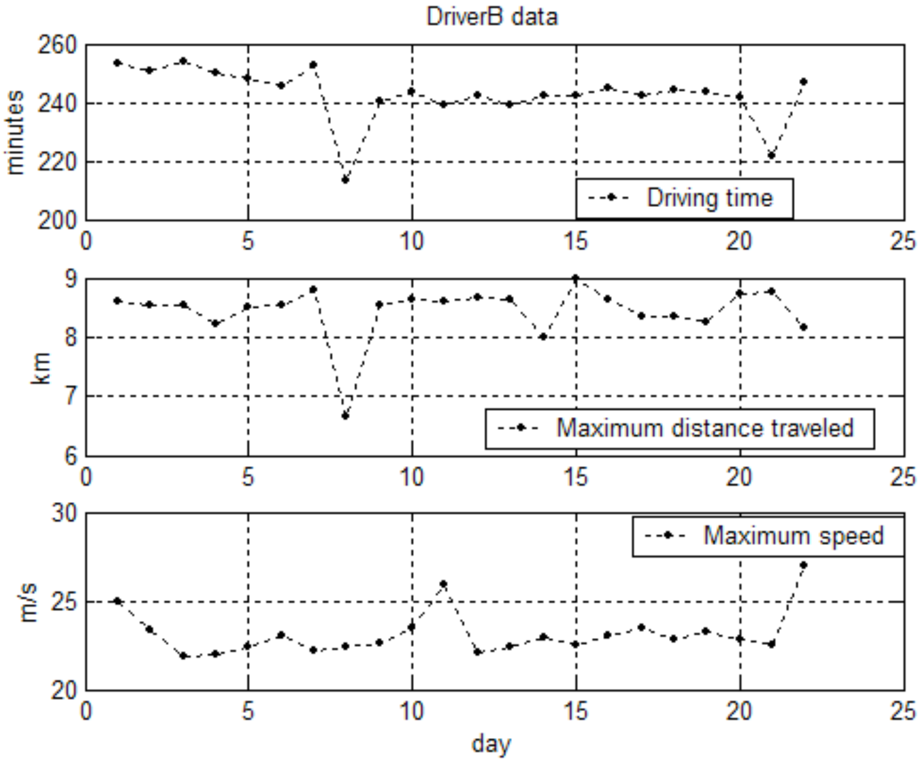

Figure C-2 - Driving statistics by day for Bus operator B

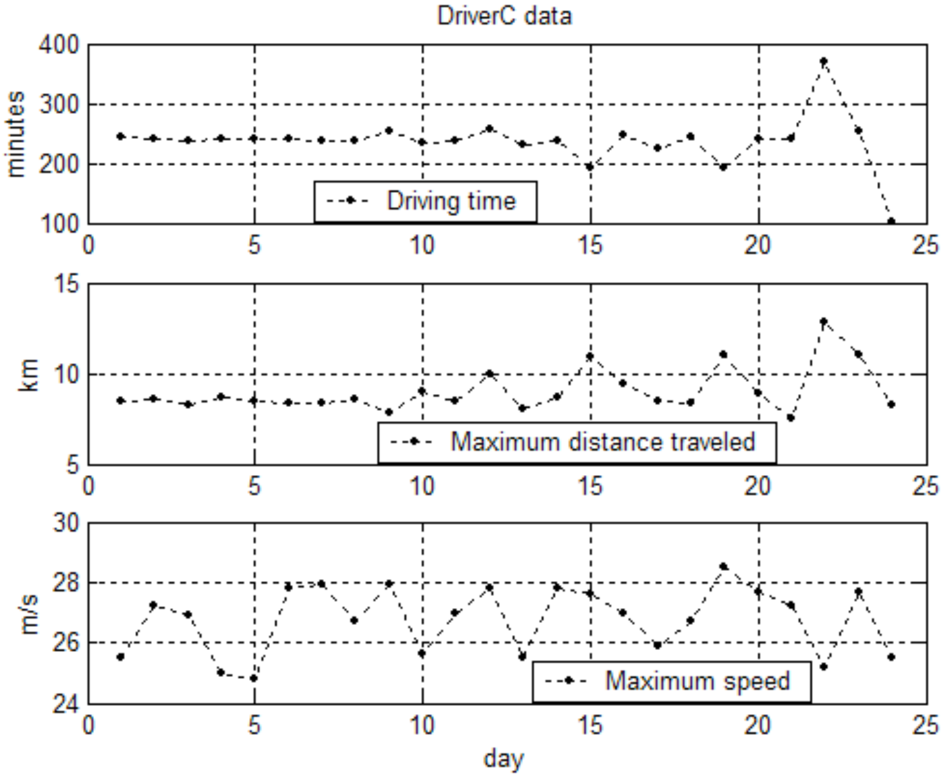

Figure C-3 - Driving statistics by day for Bus operator C

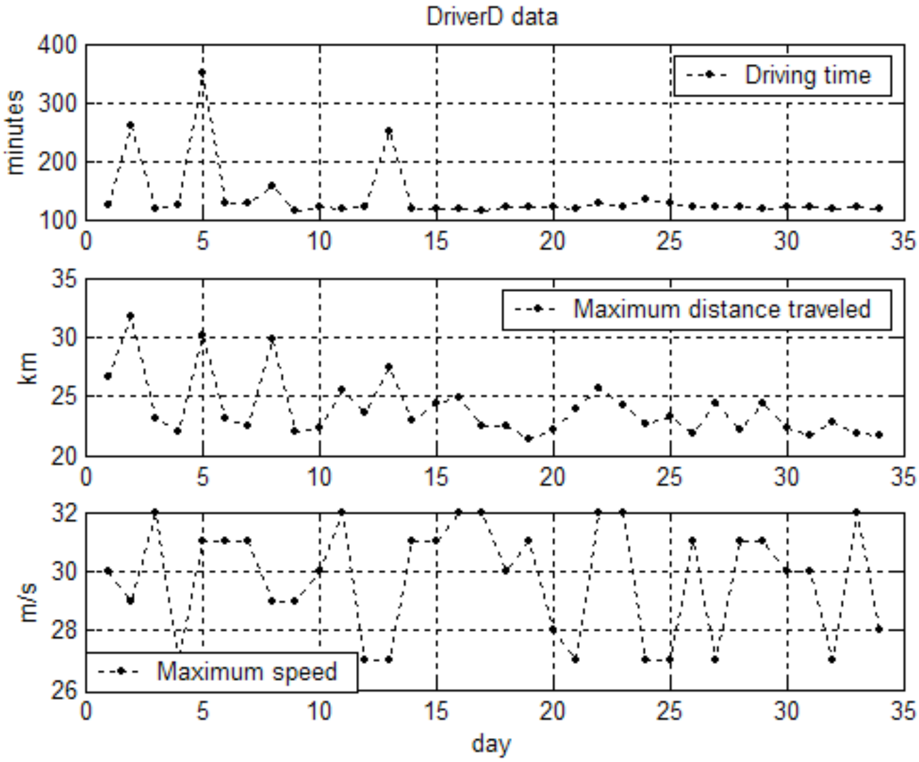

Figure C-4 - Driving statistics by day for Bus operator D

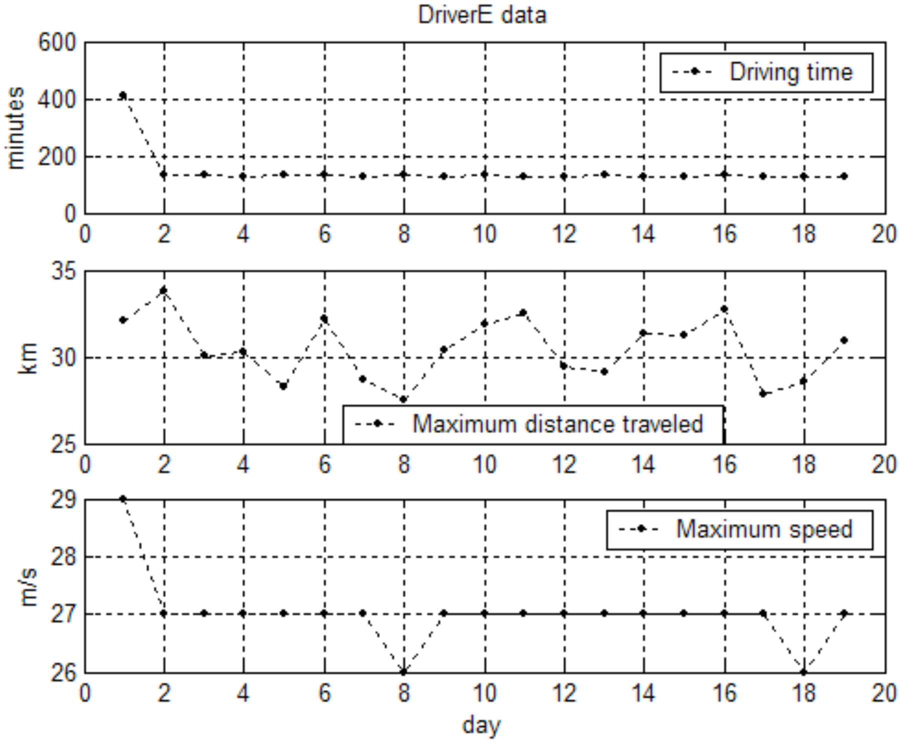

Figure C-5 - Driving statistics by day for Bus operator E

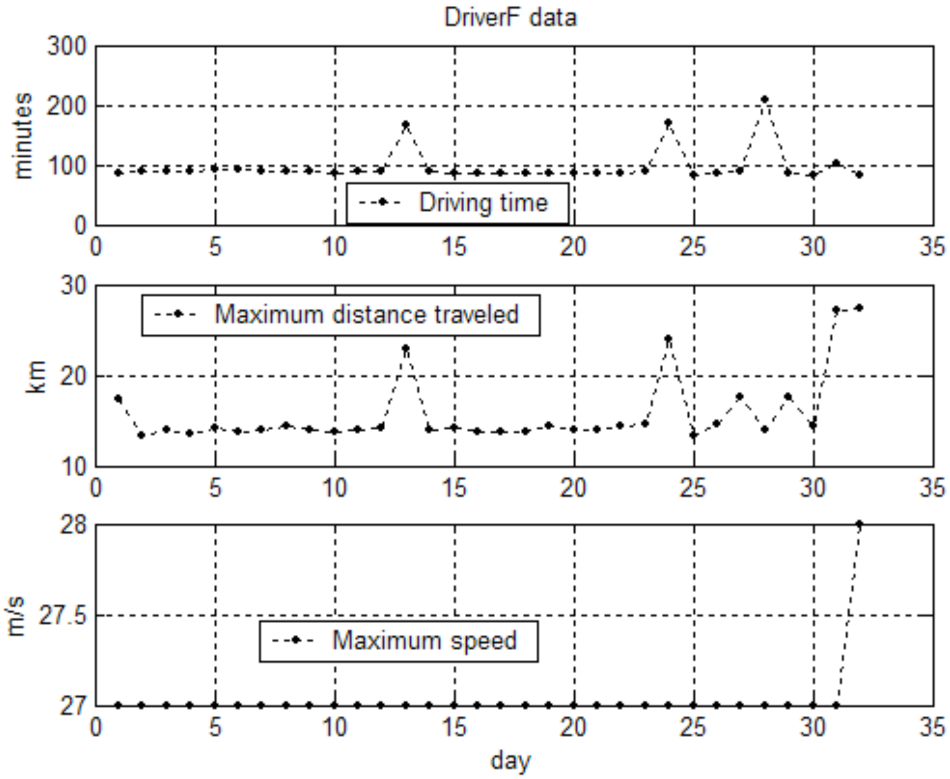

Figure C-6 - Driving statistics by day for Bus operator F

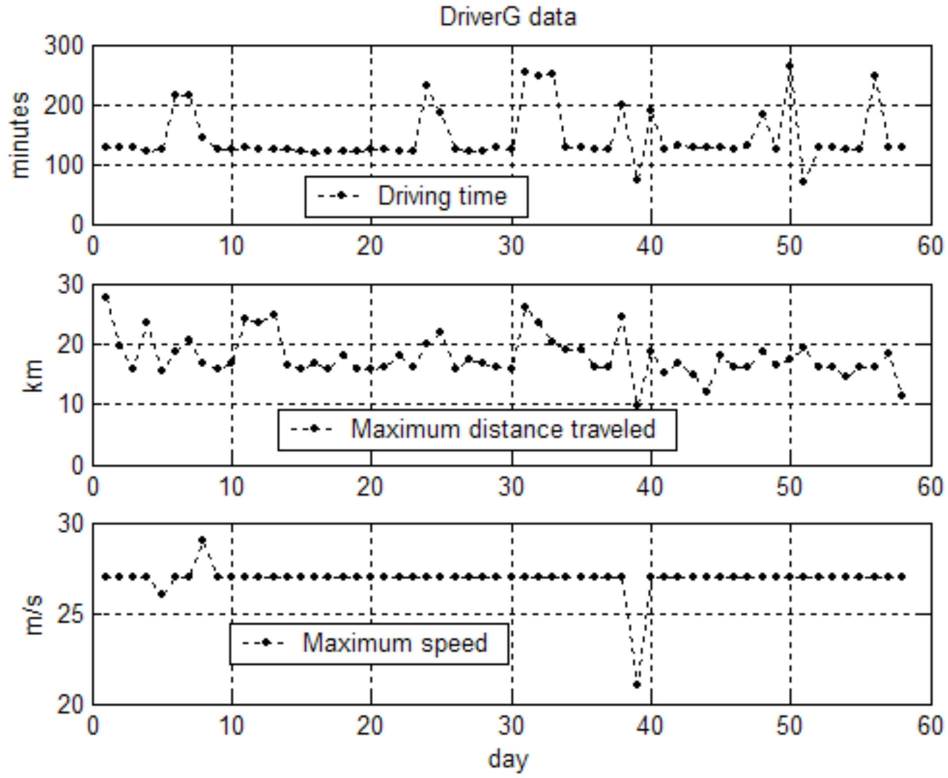

Figure C-7 - Driving statistics by day for Bus operator G

C.2 Table of Vehicle Following Time Gap Percentile Values

Table C-1 - Lower percentiles of car-following time gaps in seconds with std dev.

Operator	5% before	5% after	10% before	10% after	20% before	20% after
A	0.55 s (0.09)*	0.87 s (0.37)	0.68 s (0.11)	1.1 s (0.44)	0.92 s (0.12)	1.44 s (0.45)
B	1.37 s (0.13)	1.25 s (0.16)	1.63 s (0.09)	1.50 s (0.16)	1.99 s (0.13)	1.88 s (0.15)
C	1.61 s (0.11)	1.53 s (0.13)	1.79 s (0.11)	1.8 s (0.13)	2.16 s (0.13)	2.16 s (0.15)
D	0.57 s (0.27)	0.61 s (0.14)	0.75 s (0.30)	0.78 s (0.15)	1.05 s (0.31)	1.03 s (0.17)
E	0.97 s (0.28)	1.40 s (0.23)	1.26 s (0.25)	1.72 s (0.20)	1.58 s (0.25)	2.10 s (0.17)
F	0.45 s (0.13)	0.38 s (0.08)	0.56 s (0.14)	0.49 s (0.09)	0.72 s (0.16)	0.66 s (0.12)
G	1.00 s (0.37)	1.10 s (0.30)	1.23 s (0.36)	1.3 s (0.29)	1.55 s (0.34)	1.56 s (0.29)

* Standard deviations across days are shown in parentheses

C.3 Cumulative Distributions of Brake Pressure Applied by Operators

Bus operator A showed an appreciable reduction in higher-pressure braking for some of his days of driving, as evident in Figure C-8. It was difficult to discern differences in the braking responses of the cautious Operator B (Figure C-9), and it appeared that the very cautious Operator C (Figure C-10) had a slightly increased frequency of harder braking events after the activation of the warning system, perhaps associated with over-reactions to alerts from the new system.

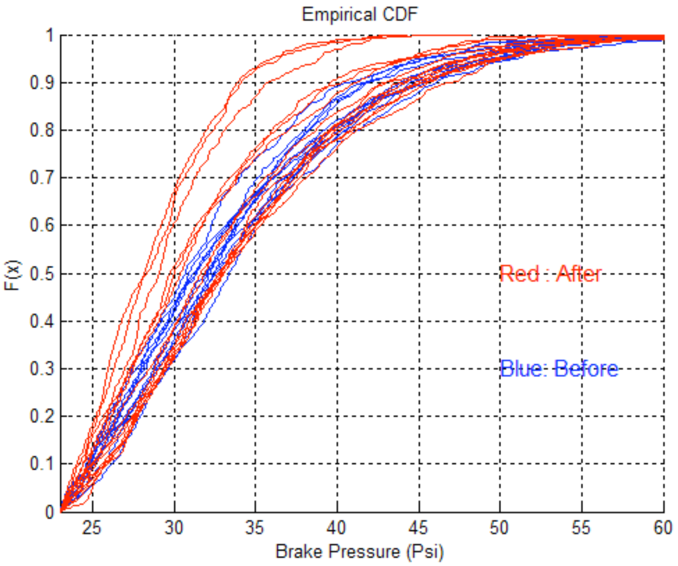

Figure C-8 - Brake Pressure Cumulative Distribution (Operator A)

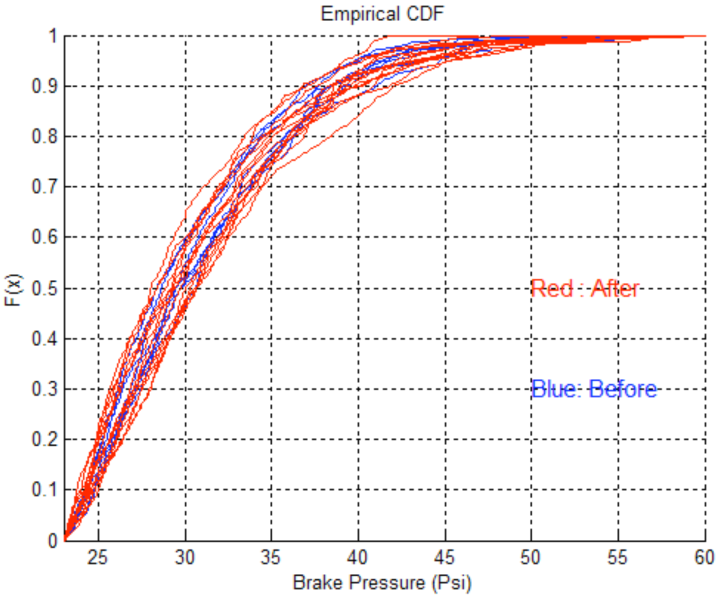

Figure C-9 - Brake Pressure Cumulative Distribution (Operator B)

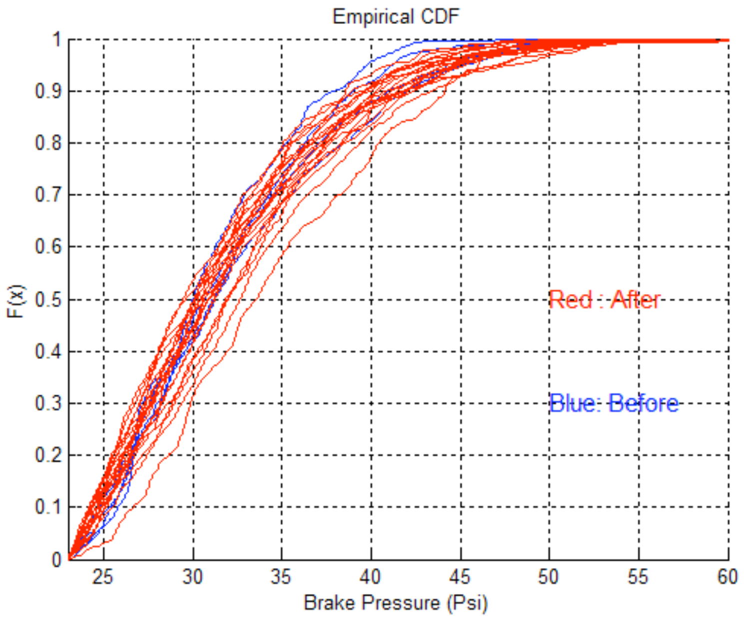

Figure C-10 - Brake Pressure Cumulative Distribution (Operator C)

The upper tail percentile values for these cumulative distribution functions are shown below.

Table C-2 - Upper Tails of Brake Pressure Distributions, psi with standard deviations

Operator	95% before	95% after	90% before	90% after	80% before	80% after
A	48.1 (2.0)*	45.6 (5.0)	43.8 (1.7)	41.8 (4.3)	39.4 (1.2)	37.9 (3.2)
B	41.8 (1.6)	42.5 (1.8)	38.6 (1.2)	39.3 (1.5)	35.2 (0.9)	35.6 (1.2)
C	42.4 (2.4)	44.4 (1.7)	39.9 (1.7)	41.1 (1.3)	36.7 (1.3)	37.2 (1.2)

* Standard deviations across days are shown in parentheses

C.4 Cumulative Distribution of Accelerations

These distributions are very similar to the shapes of the brake pressure distributions since there is a direct relationship between the brake pressure and the deceleration of the bus. Bus operator A (Figure C-11) shows the greatest reduction of harder decelerations after the activation of the DVI, but he was also the most aggressive operator in the “before” cases. Bus operator B (Figure C-12) had the most consistent deceleration behavior, while Operator C (Figure C-13) was in the middle. It is worth noting that some of the “after DVI” days for Operator A showed noticeably less frequent occurrences of harder decelerations than was typical for the other two operators, whose car following behavior was generally more conservative.

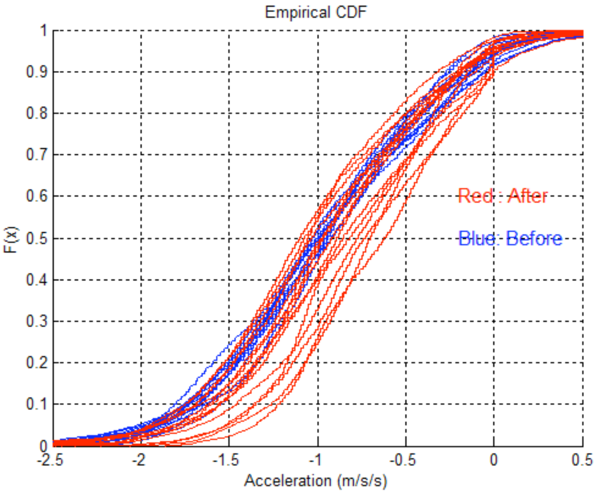

Figure C-11 - Acceleration Cumulative Distribution (Operator A)

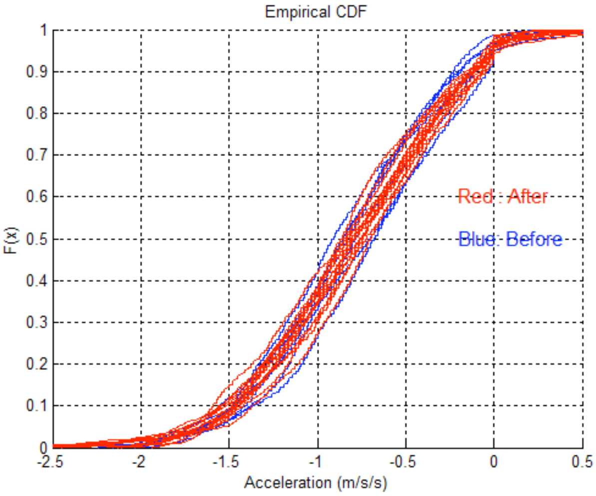

Figure C-12 - Acceleration Cumulative Distribution (Operator B)

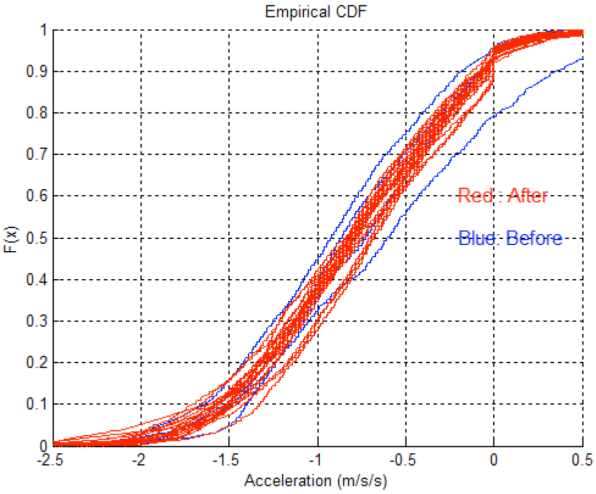

Figure C-13 - Acceleration Cumulative Distribution (Operator C)

Estimates of the lower tails of these distributions are shown below.

Table C-3 - Lower percentiles of driving acc. distribution (m/s/s) with std dev.

Operator	5% before	5% after	10% before	10% after	20% before	20% after
A	-1.88 (0.08)*	-1.74 (0.19)	-1.68 (0.07)	-1.54 (0.17)	-1.44 (0.07)	-1.33 (0.16)
B	-1.64 (0.06)	-1.67 (0.07)	-1.44 (0.06)	-1.49 (0.06)	-1.22 (0.07)	-1.26 (0.06)
C	-1.71 (0.12)	-1.72 (0.11)	-1.51 (0.08)	-1.51 (0.08)	-1.28 (0.07)	-1.28 (0.07)

* Standard deviations across days are shown in parentheses

C.5 Cumulative Distributions of Time To Collision (TTC)

The differences across bus operators in the TTC distributions were much less than the differences in the other measures that were evaluated previously, and in most cases it was difficult to discern the changes between the before and after cases. Somewhat surprisingly, the most cautious operator, Operator C, showed somewhat smaller TTC values after the system was activated than before, indicating that perhaps the system gave him more confidence about following more closely than he would have done otherwise under comparably dynamic conditions (recalling that his steady car-following time gaps did not change). While his “before” values were larger than those for most of the other operators, his “after” values were very similar to those of the other operators.

Just as surprisingly, the most aggressive operator, Operator F, showed the largest increase in TTC values after the system was activated and indeed his TTC values after activation were the largest among all the operators even though his car-following time gaps were the smallest. This seems to imply that he is a sporty driver who is following other vehicles closely but also responding quickly to the slowing of forward vehicles that can lead to lower (potentially more hazardous) values of TTC. Operator G, the one with the largest day-to-day variations in driving style, also showed a noticeable increase in TTC values after the system was activated.

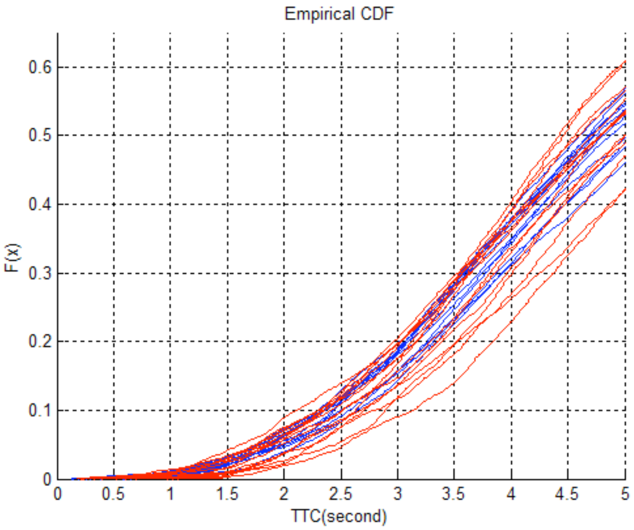

Figure C-14 - Time to Collision Cumulative Distribution (Operator A)

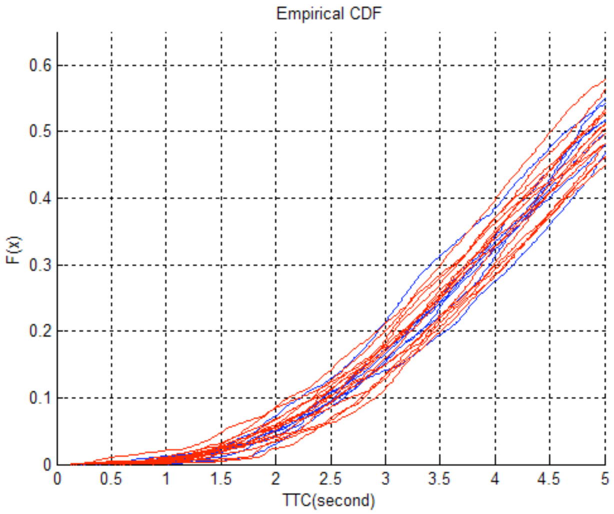

Figure C-15 - Time to Collision Cumulative Distribution (Operator B)

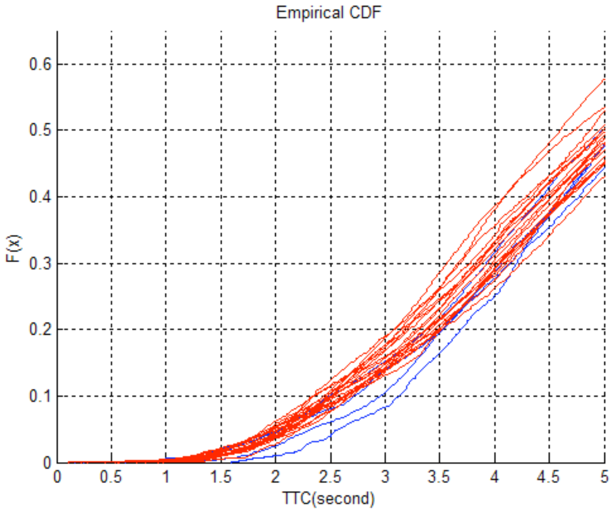

Figure C-16 - Time to Collision Cumulative Distribution (Operator C)

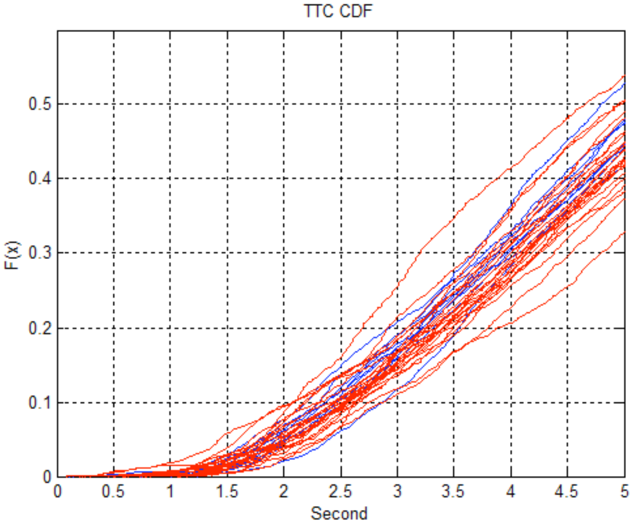

Figure C-17 - Time to Collision Cumulative Distribution (Operator D)

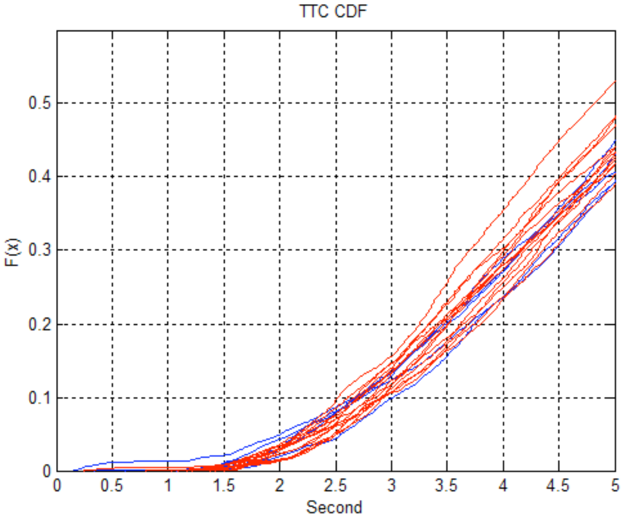

Figure C-18 - Time to Collision Cumulative Distribution (Operator E)

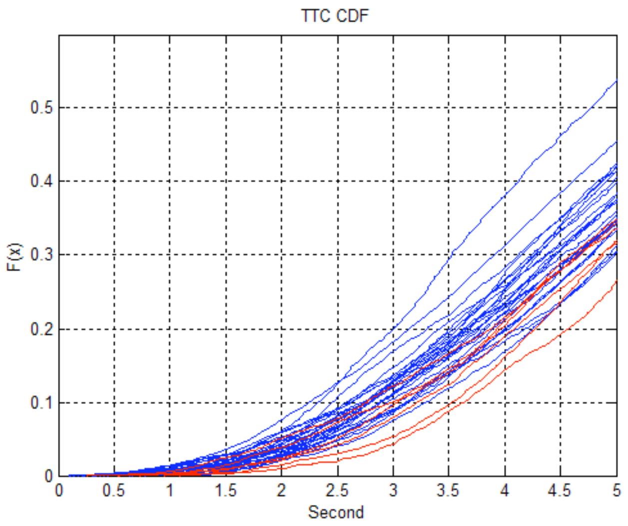

Figure C-19 - Time to Collision Cumulative Distribution (Operator F)

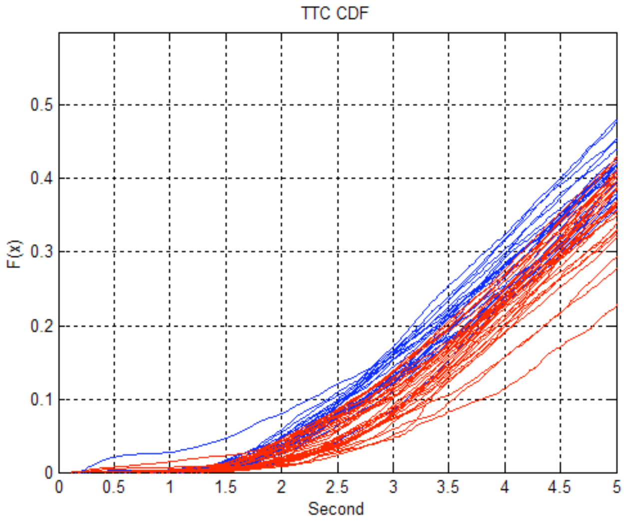

Figure C-20 - Time to Collision Cumulative Distribution (Operator G)

The characteristics of the lower tails of these distributions are summarized below.

Table C-4 - Lower Percentiles of Time-to-Collision Distribution (sec) and std dev.

Operator	5% before	5% after	10% before	10% after	20% before	20% after
A	1.94 (0.14)*	1.99 (0.25)	2.47 (0.12)	2.52 (0.24)	3.17 (0.12)	3.27 (0.25)
B	2.04 (0.10)	1.95 (0.22)	2.49 (0.12)	2.49 (0.12)	3.25 (0.17)	3.23 (0.17)
C	2.25 (0.23)	2.06 (0.09)	2.82 (0.25)	2.55 (0.10)	3.53 (0.17)	3.34 (0.14)
D	1.97 (0.20)	1.98 (0.20)	2.46 (0.20)	2.47 (0.20)	3.22 (0.18)	3.36 (0.23)
E	2.17 (0.14)	2.34 (0.12)	2.79 (0.27)	2.79 (0.13)	3.64 (0.10)	3.52 (0.16)
F	2.18 (0.25)	2.53 (0.37)	2.79 (0.27)	3.18 (0.27)	3.70 (0.29)	4.10 (0.23)
G	2.14 (0.18)	2.44 (0.27)	2.67 (0.17)	3.01 (0.26)	3.50 (0.16)	3.82 (0.25)

* Standard deviations across days are shown in parentheses

C.6 Cumulative Distributions of Required Deceleration Parameter

These results indicate that the activation of the forward collision warning system had no discernible effect on Operators C and G, and only modest effects on the other operators. Operator D appeared to show slightly higher values of the required deceleration parameter after system activation than before, implying somewhat riskier driving, but he was initially one of the most cautious operators based on this performance measure. All the other operators showed reductions in the value of required deceleration, and the reduction was largest for Operator A, who started out with the highest value of this performance measure. The overall effect of the warning system activation was to reduce the diversity of driving performance across the seven operators and to produce a modest decrease in the occurrence of larger values of the warning criterion, the required deceleration parameter.

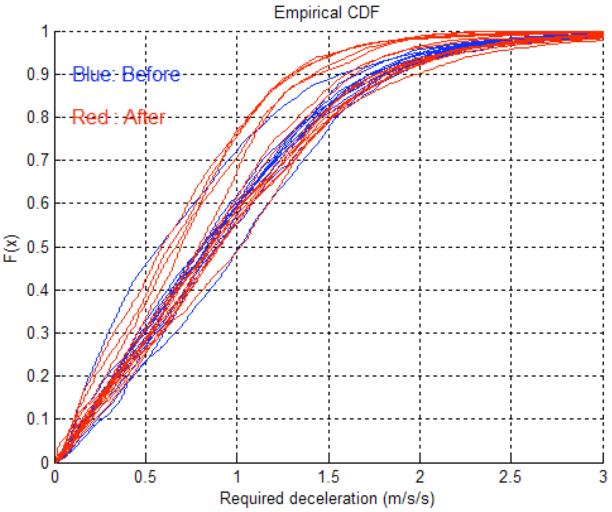

Figure C-21 - Required Deceleration Parameter Cumulative Distribution (Op. A)

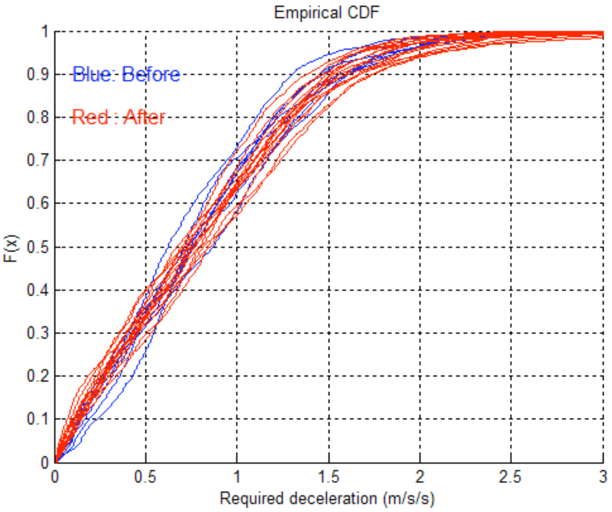

Figure C-22 - Required Deceleration Parameter Cumulative Distribution (Op. B)

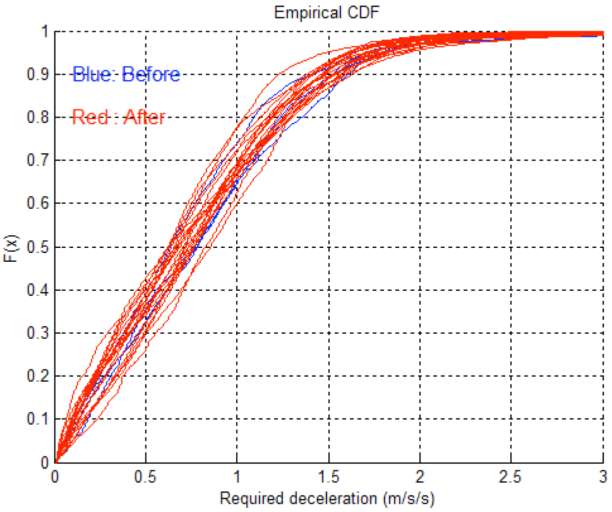

Figure C-23 - Required Deceleration Parameter Cumulative Distribution (Op. C)

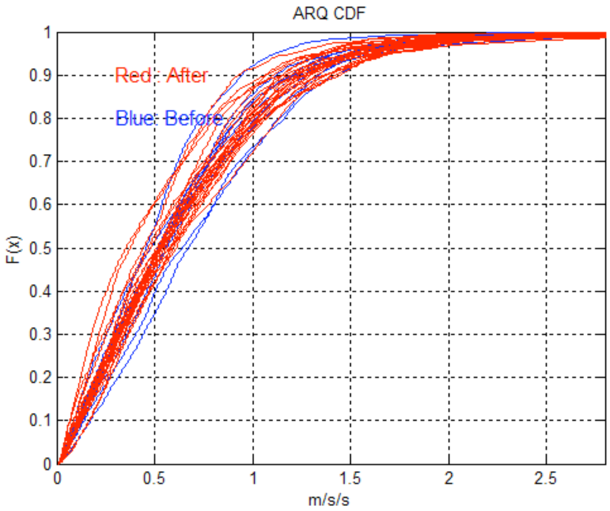

Figure C-24 - Required Deceleration Parameter Cumulative Distribution (Op. D)

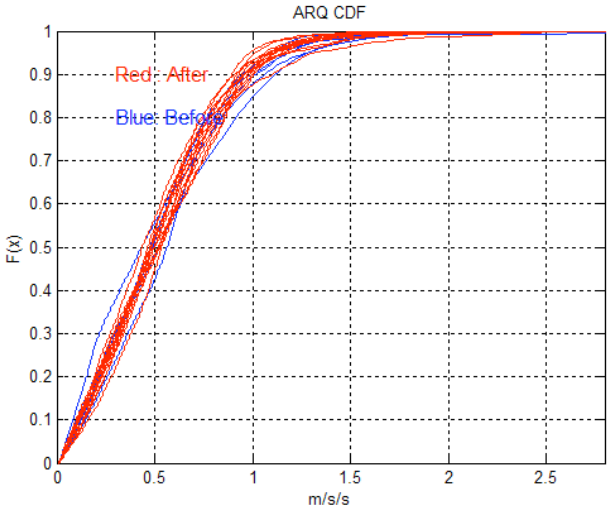

Figure C-25 - Required Deceleration Parameter Cumulative Distribution (Op. E)

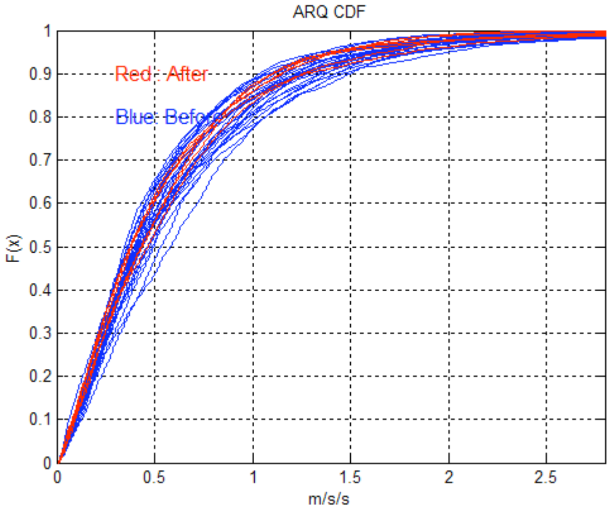

Figure C-26 - Required Deceleration Parameter Cumulative Distribution (Op. F)

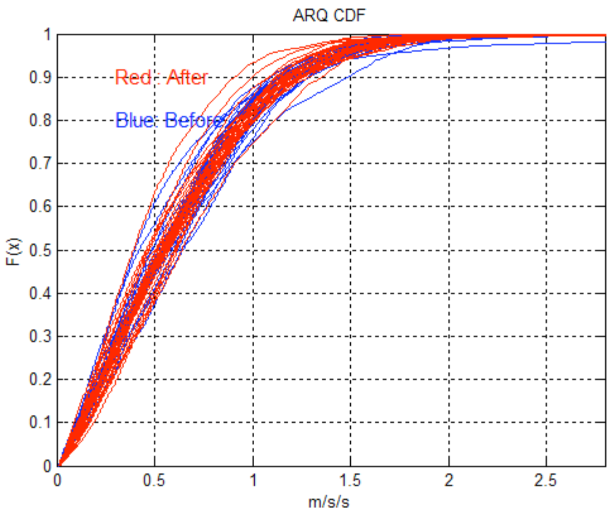

Figure C-27 - Required Deceleration Parameter Cumulative Distribution (Op. G)

The upper percentile of required deceleration parameter are shown below.

Table C-5 - Upper Percentiles of Req'd Deceleration Parameter, m/s/s, with std dev.

Operator	95% before	95% after	90% before	90% after	80% before	80% after
A	2.09 (0.08)*	1.95 (0.29)	1.74 (0.10)	1.64 (0.23)	1.39 (0.12)	1.34 (0.19)
B	1.76 (0.14)	1.86 (0.16)	1.49 (0.12)	1.58 (0.10)	1.23 (0.09)	1.29 (0.08)
C	1.74 (0.07)	1.72 (0.11)	1.53 (0.07)	1.48 (0.09)	1.24 (0.09)	1.21 (0.08)
D	1.47 (0.15)	1.53 (0.13)	1.23 (0.13)	1.25 (0.20)	0.97 (0.05)	0.97 (0.09)
E	1.24 (0.06)	1.12 (0.08)	1.08 (0.06)	0.97 (0.05)	0.87 (0.06)	0.80 (0.04)
F	1.61 (0.16)	1.54 (0.15)	1.24 (0.13)	1.17 (0.07)	0.89 (0.10)	0.85 (0.03)
G	1.42 (0.10)	1.39 (0.10)	1.19 (0.08)	1.18 (0.08)	0.94 (0.07)	0.95 (0.06)

* Standard deviations across days are shown in parentheses

Appendix D Questionnaires and Direct Operator Feedback

The primary goal of gathering operator feedback was to determine both whether the developed ICWS was acceptable to operators and what changes they thought would be useful to implement. With these goals in mind we conducted a literature search to determine other issues about which we could obtain useful operator feedback. The collected feedback also built on previous operator data collections from SamTrans operators during the development of the FCWS system. Operator and agency feedback was then obtained through a variety of different interactions, including:

- Questionnaires
- Ride-alongs
- Emails
- Phone calls
- In-person meetings
- American Public Transportation Association (APTA) conference demonstration

Each method of data collection was used to obtain different types of information. The questionnaires were used to gauge operator opinions of the ICWS whereas the other methods were designed to collect data in real time and to obtain preliminary operator feedback to help "fine-tune" the system. The demonstration was used to collect transit agency feedback. The results for all methods of data collection are presented in a combined format under headings that represent the variables of interest.

D.1 Questionnaire Methodology

As mentioned in the previous field testing methodology section, the operators were trained in use of the system by a project team member. The operators were then left to use the system with a "cheat-sheet" card that had the team member's contact details. The operators were asked to report any problems encountered, either to the transit agency dispatcher or a project team member. During the period that the DVI was "on", efforts were made to check in at least once with the operators to see if any problems were occurring and to answer any questions. Toward the end of each bid (operator assignment to the instrumented bus) a project team member would get the operators to fill out a questionnaire (Appendix E). The ride-alongs occurred after the operators had filled out the questionnaire, in an effort to not bias the operators' responses.

D.1.1 Respondents - SamTrans

Nine questionnaires were completed by the SamTrans operators. This included one operator who completed two questionnaires and one who completed three questionnaires. This occurred because the two operators had driven the instrumented bus for more than one bid and had filled out a questionnaire at the end of each bid. As the results of the questionnaires were to be kept anonymous, it is unclear what effect getting more than one response per individual had on the overall results. Although it would have been better to have responses from more operators, the decision was made to try to keep the operators on the buses for as long as possible to maximize the amount of driving data for each operator.

All of the respondents listed operator as their current employment position. The respondents ranged in bus driving experience from 3 to 21 years. The operators reported having driven with the DVI on for a range of 2 days to 9 months. The respondent who had only driven the system for two days had not been trained with the system prior to the questionnaire and was interviewed, as a team member happened to encounter him. The rest of the operators had driven with the system on for a minimum of one bid period (3 months).

D.1.2 Respondents - Port Authority

Questionnaires were provided to the operators with self-addressed stamped envelopes but none were returned to the project team.

D.2 Ride-Along Methodology

The objective of the ride-along was to collect dynamic information regarding operators' opinions of warning timings and to view scenarios that operators were concerned with or were interested in. Also included in the results of this section is information received from operators via email, phone calls and in-person meetings.

One ride-along was conducted with a Port Authority operator and three were conducted with SamTrans operators. The ride-alongs involved one researcher sitting with the operator on a normal in-service route. Feedback from operators who were driving with the FCWS only (on another bus) has also been included here, as they add to the completeness of the review. Attempts were made to gain information in a variety of operating conditions; those encountered included: daylight, clear skies, dusk, night time, fog and rain.

During the ride-alongs a team member answered any questions the operators had and the operators were asked to comment on:

(1) warnings that occurred (whether they thought they were appropriate or not and if the timing was appropriate or not).
(2) situations when they thought a warning would have been helpful
(3) any other areas they liked or disliked about the system
(4) what they thought individual warnings were for

D.3 Operator Acceptance of the ICWS

D.3.1 Questionnaire Results

The operators were asked to rank their answers to system acceptance questions shown in Table D-1. The results suggest that while the forward system was slightly easier to use than the side system the operators liked the side system slightly more than the forward system. The results also suggest that the ICWS showed potential in the following areas: conveyed a sense of urgency, to increase safety, help to avoid potential collisions, and ability to identify what warnings were for. In addition, a majority of the respondents felt the system was not distracting or annoying; it gave warnings when needed and that operators would become comfortable in a relatively short period of time. The operators reported having some passengers ask about the system and that they made mostly favorable responses. The range of responses did show that at least on operator did have an unfavorable view of the system. The area of most concern is the responses to the question “how often does the system cause you to look for the hazard in the wrong location”. One operator responded – every time and the mean rating of 2.3 is midway on the scale verbal feedback from the operators indicates that this relatively poor rating may be related to the false alarm rate being higher than operators would have liked. However, it is interesting to note that the operators generally feel that the system did not cause them to make an inappropriate maneuver or error in judgment.

The operators were then asked to describe any other applications that the system could be used for. For example, could the system be a useful training aid? Seven of the operators responded that it could be used for training. In addition, one operator thought that the system would be helpful for rookie operators right after training and for when an operator is put on a new run to help identify where the difficult spots are (e.g., particular intersections or corners). It should be noted, though, that the wording of this question was leading, in that we mentioned training. The results are consistent with previous operators and instructor opinions of other uses during the development of the forward collision system.

Lastly, operators were asked to list any other comments/suggestions regarding the system. Under this question the following responses were received: “It’s good – keep it up!”, “It’s a good system”, “Thanks!”, “system still activated for no reason”.

Table D-1 - Summary of Operator Responses to Questionnaire

Question	Ranking Scale	Min	Max	Mean
How easy is the system to use overall?	1=not easy, 5= very easy	3	5	4.5
How easy are the forward warnings to use?	1=not easy, 5=very easy	2	5	4.4
How easy are the side warnings to use?	1=not easy, 5=very easy	2	5	4.1
How much do you like the system overall?	1=not at all, 5=very	2	5	4.1
How much do you like the forward warnings?	1=not at all, 5=very	2	5	3.8
How much do you like the side warnings?	1=not at all, 5=very	2	5	4.1
How well do you think the warnings conveyed a sense of urgency?	1=not at all, 5=very	2	5	3.9
How much did the system increase your safety?	1=not at all, 5=very	1	5	3.5
Did the system make your overall driving less or more safe?	1=less safe, 5=more safe	2	5	4.1
How often has the system helped you avoid potential collisions?	1=never, 5=every time	1	5	3.4
How annoying was the system?	1=not at all, 5=very	1	4	2.1
How distracting was the system?	1=not at all, 5=very	1	4	1.8
Was it easy to identify the hazard that led to a warning?	1=not easy, 5=very easy	3	5	4.3
How often does the system cause you to look for the hazard in the wrong location?	1=never, 5=every time	1	5	2.3
How often does the system cause you to make an inappropriate maneuver or error in judgment?	1=never, 5=every time	1	2	1.1
How often does the system give a warning when it is not needed?	1=never, 5=every time	2	4	2.4
How often does the system not give a warning when it is needed?	1=never, 5=every time	2	3	2.1
How long do you think it will take someone to become comfortable with the system?	1=hours, 5=months	1	4	2.3
If you had more time with the system, do you think you would you like it more?	1=no, 5=yes	1	5	3.5
Did passengers ask about the system?	1=not at all, 5=very	1	5	2.4
If yes, what was their response?	1=unfavorable, 5=favorable	3	5	3.8

D.3.2 Ride-Along Results

When asked to show or explain any areas where they had difficulties with the system or that they felt were most useful, the operators gave the following examples.

- In times where viewing conditions are compromised. Such conditions occur when driving directly towards the sun, at night in fog and at dusk. The system may detect and warn about hazardous objects that may have been missed by the operator. One operator noted that in situations when driving the bus directly towards the sun, the glare meant that the operator could see neither the road ahead nor the display.
- The system was helpful when maneuvering the bus around parked cars. This was seen to be particularly helpful in situations where there were multiple cars in confined areas.
- The system was also seen as helpful when the operators received what they termed “Appropriate warnings” in construction areas. When asked to further define “Appropriate warnings” operators thought that it was objects that they were likely to make contact with or that were hard to see.
- In situations where there is a narrow bus express lane going in the opposite direction to the main traffic flow.
- To help alert operators to vehicles cutting-in (or about to cut-in) front of the bus. The operators felt that car cut-ins represented a real threat to transit operators.
- For pedestrian detection, particularly in areas such as bus stops where pedestrians can move erratically.
- At night on freeway on-ramp/off-ramps that curve – lack of ability to see the guard-rail at the Jersey barrier. (Note: this comment came from a previous iteration of the forward collision warning system. The system was subsequently changed to prevent warnings in this situation. But, because no system is perfect and this relates to a fairly serious safety hazard we have included it here.)
- Three of the four operators felt that the system lacked consistency. This was particularly an issue for operators who drove the bus for more than one bid. During the ride-alongs this was apparent when operators would ask what the experimenter thought individual warnings were for - stating that they were not sure. There appeared to be some areas on their route where they always received warnings (particular guard-rails, and in steep hill sections) and other areas where, although they thought they were driving in the same way, they sometimes received warnings and sometimes did not. One operator noted: “The system however fails to function all the time. It simply quits relating information sometimes for brief or short moments, and at times it turns off completely”. This operator felt that the system was precise when it was operating.
- One operator thought that the position of the display was good. The operator commented “not obstructing, ideal place for these”. Another operator wanted the display made shorter, as they felt that it obscured their view of the mirrors.

D.4 Did the System Prevent a Crash?

No crashes occurred during the testing. However, given that crashes are a rare occurrence and we only had two buses in the study no conclusions can be drawn from this. When asked if the system ever prevented an accident, the operators suggested that in the following situations the system had helped them out:

- In situations when the bus is going above 25 mph and cars are passing on both the left and the right it is good to see the arrow coming on.
- At a bus stop a car came around just as the bus was getting ready to move. Sometimes you get so busy with the fare box that all need is a wee light (alarm).
- When driving straight road sections for two hours straight with cars constantly cutting in you start to get fatigued and may miss something hazardous.
- When exiting bus stops the system alerts the operator to passing vehicles, forward vehicles and pedestrians.
- One example occurred during a ride-along, in a situation when the operator was attending to some trees on his right, but the bus inadvertently went over the white lane divider line. There was a car passing in the adjacent lane, which caused a warning, leading the operator to move the bus back into the correct lane. The operator was very pleased with this warning and felt that it had come at just the right time.

D.5 Operator Reliance

Two operators were concerned about the risk of other operators relying on the system and having a crash due to a missed hazard. These operators felt that it was important to emphasize that the system is an aid only.

D.6 Alarm Rates

Input for this section come from the ride-alongs.

D.6.1 Nuisance Alarms and False Alarms

One of the main challenges in developing a collision warning system is to get the right balance between system effectiveness and annoyance. Both false and nuisance alarms have the potential to create hazardous situations as they may draw the operators attention from where it is needed (Maltz, et al)[xix]. Nuisance and false alarm rates occur both as a result of where the alarm threshold is set as well as other algorithm parameters that determine what warnings are given for. Previous researchers suggest that high rates of false warnings will reduce operators’ confidence in the system (Wheeler, et al)[xx] (Sherican)[xxi]. Three of the four operators felt the level of nuisance alarms was acceptable. The operator who did not thought that there were not enough true alarms for things they were interested in. The operator wanted more alarms for street furniture and other vehicles when making tight turns. When asked if they would prefer to drive with or without the system they said that “you could leave it on”.

Operators did not feel that warnings for cars passing in adjacent lanes were nuisance alarms.

Operators noted that they received false warnings when making tight hill turns and sometimes when going over speed bumps. One operator noted that the frequency of occurrence of false warning was acceptable. The other two were more focused on understanding in what situations they occurred.

When asked to report what various warnings were for, operators were not always sure. Some of these warning instances were taken back to the design team to determine the location of the hazard.

D.6.2 Missing Alarms

When asked to indicate any times on the ride-along when an operator would have either liked or expected an alarm but did not receive one, the operators pointed out several scenario types. The first scenario which was mentioned by all the operators was that they wanted more coverage and assistance when making tight turns in close proximity to other vehicles and street furniture, especially at slow speeds. The operators pointed to turns that were 90 degrees or less where they made right turns onto a cross street and there were parked cars on the side of the street and/or cars waiting to go straight through. In some of these instances the operator (when possible) would need to gesture to the other vehicle driver and get them to back up so the bus could make the turn.

The second scenario was that they wanted to have creep detection to aid in situations when the bus is stopped for traffic at a traffic signal. One operator indicated that in such situations, when they saw the traffic signal turn green they would assume that the other cars were moving and start to creep forward, yet sometimes the car in front may not be moving due to stopped traffic in front of them or because the other driver had not seen the signal change.

When approaching forward vehicles, operators would occasionally try to “force” an alarm. The operators did not find that the boundary between where they would or would not get an alarm was intuitive. Later analysis of the data from these events suggests that the operator did not reach the warning threshold. Because this was not the way that the system was intended to be used, it seems that it was extremely difficult to force an alarm this way.

On the ride-alongs it became apparent that operators did not see all of the warnings. While some of these may have been too short to be detected, others that occurred when the operator was busy and subsequently pointed out by the researcher did not register with the operator. It was unclear if these were pre-attentively screened out or if they were missed.

D.6.3 Multiple Alarms

Sheridan[xxii] discusses inter-correlation and inhibition of alarms due to a usually high correlation for warnings from one automated operating system. He notes that experienced operators report that they observe patterns in alarms – though they cannot describe these or formally understand how they occur. We were interested to know if a similar thing would occur for an integrated collision warning system. It seemed reasonable that an object may from one moment to the next move from being a side hazard to being a forward one. However, none of the operators talked to by the researcher reported noticing any pattern of objects moving from one system to the other.

The operators did not report any situations when two alarms occurred at once (or in close time proximity to each other) that caused them confusion. The operators thought that while it might have happened they would be scanning the environment for hazards regardless.

D.6.4 Fog Alarms

Operators noted that they were getting false alarms in fog conditions. Changes were made to the forward system to limit the number of fog warnings and the operators reported that they were receiving fewer fog alarms.

D.7 Operator Sensitivity Ratings / Reports

The bus operators were able to select from three different sensitivity settings while the bus was stationary. Previous researchers (Wheeler, et al)[xxiii] have noted that whether operators should be given the ability to adjust the sensitivity of a system remains an un-answered question. Wheeler, et al suggest that the benefit is a potential increase in operator acceptance of the system but that it might cause alerts to be issued with too little time for the operator to respond. We were interested to understand whether the operators could tell the difference between the sensitivity levels and if they had a preference. Two operators reported that they either did not or “didn’t much” change the sensitivity. One operator reported making the system least sensitive (to get fewer warnings) and one said they left it in the middle setting, citing that they felt that this gave them about the right time to react.

The operator’s selection of the sensitivity setting provides us with information about the operator’s preferences. However, it should be noted that there is a chance that operators will not change the settings, therefore for this analysis we considered both the number of times it was changed per day as well as the average setting per day and the mode setting per operator over the days of data collection. At all times the system had to be set to one of the settings, as the operators were not given the ability to turn the system off.

One operator wanted more variability in the settings. The operators noted that they had very few forward warnings.

D.8 Operator Suggested Changes

When asked about features that the operators would want added or removed the operators wrote down the following answers:

- One operator requested a warning tone, while one operator wrote that they did not want a tone as it would be “annoying”. One operator requested to get a “signal” every time a vehicle passed on the left or the right.

- Two operators mentioned the display in this section, one operator requested removal of the bottom “flashing lights” (side system), one requested smaller lights with a faster flashing (amber color).
- One operator wanted the side scanner size to be reduced. The issue was further discussed with the operator on a ride-along and although the individual understood that the scanner would retract if it was about to hit something they felt that seeing it in the mirrors altered the way that they maneuvered the bus because of the added width to the bus.
- Proximity warnings when making tight turns. There seemed to be some variance on the question of whether operators wanted warnings for all street furniture in tight turns or not. All of the operators thought it acceptable if such a function was possible if it were linked to the sensitivity settings – so that operators who wanted it could have one setting and those who did not could have it removed.
- Addition of an audible warning was a very contentious issue among operators. Some operators requested a warning sound, while others, without any experimenter prompting, commented that they did not want an audible warning.

D.9 Training Type and Amount for Users of an ICWS

D.9.1 Questionnaire Results

The first question that the operators were asked was to describe the system the way they would to another operator who had not seen or used the system. The purpose of this question was to determine how well the operators understood the system. The results indicate that the operators understood the system quite well when trained with it, that they felt the system was useful to them, but that it sometimes lacked consistency in the warnings. Table D-2 below represents the operators’ answers to this question:

One operator who answered the questionnaire had not been trained with the system. We thought it would be an interesting opportunity to see what experience an untrained operator had had with the system. Other than answering background information questions, the operator declined to fill out the questionnaire so no conclusions could be arrived at.

The operators who had received the training all indicated that the level of training given was appropriate and did not suggest any improvements. However, anecdotally it seemed that the system did require some re-explaining after the operators had driven with the system on. This may have occurred as the operators experienced system faults and were trying to determine what was normal and what was not.

Table D-2 - Summary of Operator Responses to Questionnaire

Questionnaire number	Answer
1	A flash of awareness, constantly detecting hazards on either side of the bus. Aside from being very precise, the system, however fails to function all the time. It simply quits relating information sometimes for brief or short moments and at times it turns off completely. It is, nevertheless an excellent system, capable to assist operators in those little moments- and we all have those moments frequently –when the attention vanishes and a person seems to drift his or her thoughts without being aware of dangerous blind spots around the bus. There is the warning flash from the system saving us again.
2	Wasn’t trained of it (ICWS) so I would not know what to tell another driver
3	(Good for) sunlight and darkness, get warnings at dusk, hill in front, at stop sign – across intersection, lights, around parked cars on the side, always grateful for any help – but so far nothing I didn’t see. Sticks out a little on the side may cause to hit something.
4	It would be useful when first put on a new route, as it would alert the operator to the difficult spots (e.g., narrow roadway sections and difficult turns). (Comment paraphrased by researcher).
5	No answer
6	The system provides a warning to the driver of potential collision conditions by using radar and LIDAR and computers to sense traffic conditions and warn the driver with lights and sound of possible accident conditions. The lights have a graduated system that changes color and brightness depending on possible severity of collision.
7	The ICWS is a warning tool to alert the driver of the potential for rear end collisions and side collisions. The system uses lights in increasing number and tint and brightness depending on possibility of collision. Radar is used with computers to calculate traffic speed and bus speed then show driver there may be a likelihood of an accident if following too close.
8	Left blank
9	Accurate give warning every time vehicle in front get closer 1st orange then red. Wakes you up when driving in mind is flying. Is very sensitive on the freeway – get side warning for cars coming on side. Really stay alert because of the light. I wish all the buses had them. It’s really dependable, close both sides and front.

D.9.2 Ride-Along Results – Operator Questions

The type of operator questions provides an interesting insight into the operators’ understanding of the system after they have been trained with and used the system. They also give an indication of what situations the operators encountered and give an understanding of the areas of concern, where the system needs to be more user-friendly or where training needs to be improved. The questions that could not be answered on the spot by the researcher were taken back to the design team and then the answers were relayed back to the operators.

Table D-3 - Summary of Operator Questions About the System

Question	Design Team Answer
Is the system more sensitive (gives more warnings) at night than during daylight hours?	No, we think that the alarms were easier to see at night due to the increased contrast than during the day, which gave this illusion. One interesting finding of the ride-alongs was that the operators do not see all of the alarms, and indeed neither did the researcher, who was obviously not engaged in bus driving duties. It seemed that some warnings may have been too short in duration and that perhaps some of the warnings were attended to on a sub-conscious level (though this would need to be verified by an eye-tracker).
Why don't the side sensors always come out – does it mean that the system is not working?	Yes, it did means that system was not working
What are the rules for the sensors retracting (side)? Operators had tried to figure these out. The operators thought that there were different retraction rules	No but the retraction speeds may be different.
Should there be or is there a warning issued when they retract (assuming that they go in because they may hit something)?	No, but this issue is being given further consideration.
Could the sound of the retraction of the side scanner be made less? Operators reported incidents of thinking that they had hit something when they heard the sound of it retracting.	This comment came from the SamTrans operators. The installation on the SamTrans bus was louder than that on the Port Authority bus and the Pittsburgh operator did not raise this issue.

D.10 Long-term Effects of Using a Collision Warning System

While there is a growing number of commercially available collision warning systems (Parasurman et al)[xxiv], objective and subjective study of driver behavior on them has previously only been conducted for relatively short durations, for example, data published in 2005 from the ACAS field operational tests collected at most one week of reference data and three weeks of experimental data using a forward collision warning system and an adaptive cruise control system in Buick LeSabre cars. Many researchers (Wheeler, et al)[xxv] (General Motors Corp)[xxvi] report the need to better understand the long-term effects of driving with such systems. In this area there appear to be three main questions:

a. Do such systems permanently improve operator behavior if used for long periods of time?
b. Do operators' opinions of the systems vary over time and with use?
c. Are there any unintended applications of the systems that develop over time?

While the quantitative analysis results show some positive operator behavior changes more data analysis is necessary to determine changes over time. With regard to the second question, the only change in the operators' opinions over time (6 + months of driving) appeared to be that they noticed a lack of consistency of alarms from the system more. As there were some times when the system was not working well, it could be that the longer that each operator drove, the more likely they were to encounter periods when part of the system failed. It may also be that the longer operators drove with the system or the more they experimented with it, they found that it was difficult to "force" alarms. Based on discussions with operators, they felt that this showed inconsistency because for some instances they could force an alarm and then in what seemed to them to be an identical situation they could not. Explanations that this could be a result of differences in where the warning threshold was set (in that while the situations may appear identical, the smallest difference in bus heading angle or speed could mean that the alert criteria were not met) were listened to by the operator, but they expressed concern about not knowing when the system was fully working.

We did not hear or see any unintended applications of the system in the course of this study. Two operators were, however, concerned that other operators may overly rely on the system and not monitor their surroundings as carefully as they should.

D.11 Relaying of Passenger Queries and Comments

When asked if passengers had asked questions about the system or made any comments we received the following responses:

- A passenger saw a camera and then asked about the system. The operator explained the system, and passengers thought it was "fabulous, amazing, wonderful".
- An operator had good feedback from passengers who could see "that he braked when the warning came on"

D.12 Final Notes

Because algorithm development continued throughout the period of the project, it is important to note that different operators encountered different versions of the system. The operator who was least satisfied with the system was operating with the first version of the FCWS system.

One operator made the comment that on local runs the side alarms are more important, whereas on freeway sections the forward alarms are more important.

D.13 Discussion

The ultimate goal of any collision warning system is to bring about a reduction in the type of collisions that the system is designed to address. As transit bus accidents are an infrequent event the fact that no accidents occurred during the testing of this system cannot be used to conclude that the system affected driving behavior. Instead of accident rates we investigate operator behavior before and after the system was introduced. There are reasons that we may expect a collision warning system to not have a big effect on transit operators. The first reason is that bus operators are professionally trained drivers who are less likely to get into hazardous situations, partly because they are trained not to but also because a high degree of importance is placed on customer service within the transit agencies whereby giving passengers a smooth ride (with minimal hard accelerations or decelerations) is emphasized. In addition for behaviors such as vehicle following we found that this was an infrequent event.

Analysis of the operator behavior suggests that there is some variation in the driving behavior of different operators, with some operators exhibiting more aggressive car following behavior than others. The results show some evidence that the introduction of the warning system lead to more consistent and mostly safer behavior for some of the operators in terms of less; hard brake applications, small time gaps, small time-to-collisions, and high values of required deceleration.

Preliminary analysis of the FCWS alarm rate for individual operators suggests that the operators driving behavior did change over time with them receiving a gradual but steady decrease in alarms after the DVI was turned on. Global analysis of the side Alarm rates indicate a decrease in warnings that last more than 1.5 seconds suggesting that the system induces operators to make faster changes by issuing an imminent warning than they did in the DVI off condition.

Feedback from the operators suggests that a majority of the operators found the collision warning system very acceptable. It is also notable that even the least satisfied operator opted to keep the system on when given the option of turning it off. Situations when operators felt the system was most useful included in poor viewing conditions, when fatigued, for vehicles cutting-in and when exiting and entering bus stops where it aids in the detection of street furniture, pedestrians and other vehicles.

The operators provided a great deal of feedback that was used to refine and troubleshoot the system and that could be used for future iterations of the system. Two areas that need to be addressed in future systems are ensuring that the system is reliable and giving proximity alarms for objects encountered in tight turns. It would also be useful to further investigate ways to minimize the effect of glare from the sun on the operator’s ability to detect the display. Future research should also be undertaken to determine the trade-off of placing the display lower down in the operator’s field of view because although this would increase the time that it would take for an operator to see an alarm (and may potentially lead to missed alarms) it would alleviate the concern that in negotiating tight curves at night a warning may obscure the operator’s ability to detect street furniture and other objects such as Jersey barriers. Lastly, while there did not seem to be any detrimental effect of operators receiving multiple overlapping alarms and/or alarms in close time proximity due to a hazardous situation, it may be best to study this further in a simulator where an eye-tracker can be used. An eye tracker would allow us to better determine if the warning system was changing operators' visual behavior in a detrimental way.

We recommend that the operators' suggestions that the system would make a good training tool be investigated further. Previous iterations of the frontal collision warning system indicated that inexperienced operators felt that they gained a significant safety benefit from having what they saw as an interactive system teaching them when they were following another vehicle at an unsafe time gap. This recommendation is supported by private motor car studies by Shinar & Schechtman[xxvii], Ben-Yaacov et al[xxviii] and Taieb & Shinar[xxix] , which suggest that there is a benefit to learning what constitutes unsafe time gaps and that they can be easily learned with a collision warning system and that behavior change can be lasting.

D.14 Transit Agency Feedback

In December 2004, a demonstration of the ICWS system was given at the APTA System Safety Meeting in San Carlos, California. The demonstration took meeting participants on a short (approximately 10-15 minute) drive in San Carlos. The drive did not involve any hazardous events and participants had the system explained to them and watched a short video on the system. Those who observed the demonstration were asked by a Caltrans representative to complete a survey, the results of which are reported below.

Twelve questionnaires were completed. The respondents were from nine transit agencies, one consulting firm and two APTA representatives. The respondents were asked to rank their answers to the questions below:

Respondents were next asked what they liked about the system. The answers were:
- Exciting, the concept is good,
- The possibility of reducing collisions
- Great for training
- The fact that there are no false detections.

Respondents were then asked what they disliked about the system. The responses were:
- Incomplete, needs to be refined and simulated on test of real environment; the unknown of not really seeing this perform in a real world test; Doesn't appear to provide adequate warning for driver to take action
- Over-tasking on operators
- Evidence of operator fault in litigation

Respondents were asked for any suggestions for improvements or added functionalities.

Respondents' answers were:
- Eliminate the black box features and only generate warnings; Recording warnings for training;

- Able to monitor operator physical health; need ground and under-carriage sensors; integrate with current safety features as add-ons, this would also alleviate cost.
- Try it on rail street cars;
- Would like to see a better demo; Set up tests in a controlled environment so we can see better results;

Table D-4 - Summary of Transit Agency Feedback to the Questionnaire

Question	Rating (number of respondents within table)					
	5 (most)	4	3	2	1	N/A or can't evaluate
Is there a need in your agency to have a collision warning system such as this to assist bus drivers to avoid collision?	2	1	4			2
How well do you think the system performed during the demo?	1	4	3	2		2
How likely would your agency like to have your fleet equipped with the CWS system in the future?	1	5	1		1	2
How likely do you think your agency would like to have 5 – 10 buses equipped with the system for field test in the next two year if funding is provided?	3	2	1			1
How important is the cost benefits from reduced collision claims for your agency?	3	3				1
What do you think is reasonable cost for your agency to procure the CWS system?	$10K	$5 K	$3 K	$500	N/A	
Number of respondents		3	3	1	2	
Would you like to be a member of our focus group to review the project progress toward the deployment?	Yes	No	Maybe			
Number of respondents	2	1	6			
Which of the following function is most important	Frontal	Side	Frontal & Side	Other (rear)		
Number of respondents			11	1		

The respondents were asked if there are any concerns in deploying the system in their agency. The respondents were able to select from the following options and were asked explain if they indicated others: budget, safety, institutional, other & not applicable.

Three respondents selected budget, one indicated safety, two indicated institutional, one other and one indicated not applicable. The reasons that they gave were:

- Not yet ready; Actual functionality
- Maintenance;

- Operation in some weather condition;

Respondents were then asked what they saw as the main constraints and risks in deployment of the collision warning systems. Their answers were:

- Functionality and validated testing
- Cost to agencies
- Proper training

D.15 Conclusion

The questionnaire results suggest that in general the respondents see a need for a transit bus collision warning system and that it is important that such a system address both frontal and side regions. Five respondents indicated in the two highest ranking categories (most likely) that their agency would participate in a field test within the next two years if funding was provided and that they would likely equip their fleet with a collision warning system in the future. Cost of a collision warning system was considered important to the agencies and an acceptable range between \$500 and \$5,000 evolved – with six of the agency representatives indicating in the range of \$3000 to \$6000. The participants had several suggestions of ways to better demonstrate the system. The main problem with demonstrating the system is that it is difficult and potentially dangerous to deliberately get into situations that will trigger alarms yet if no alarms are triggered observers do not get to see the system working. Following the demonstration a video has been made to better demonstrate the system. In general it appeared that the representatives supported the concept of a collision warning system and were enthusiastic about participating in future deployments.

[xix] Maltz, M and D. Shinar, “Imperfect In-vehicle Collision Avoidance Warning Systems Can Aid Drivers,” *Human Factors Vol. 46*, no. 2, (Summer 2004): 357 - 366.

[xx] Wheeler, W., J. Campbell and R. Kinghorn, in W. Barfield, and T. Dingus (Eds.), *Human Factors in Intelligent Transportation Systems*, Lawrence Erlbaum Associates, Inc (1998).

[xxi] Sheridan, T., *Humans and Automation: System Design and Research Issues*, John Wiley & Sons, Inc., (2002).

[xxii] Sheridan, T., *Humans and Automation: System Design and Research Issues*, John Wiley & Sons, Inc., (2002).

[xxiii] Wheeler, W., J. Campbell and R. Kinghorn, in W. Barfield, and T. Dingus (Eds.), *Human Factors in Intelligent Transportation Systems*, Lawrence Erlbaum Associates, Inc (1998).

[xxiv] Parasuraman, R., P. Hancock and O. Olofinboba. “Alarm Effectiveness in Driver-Centered Collision-Warning Systems,” *Ergonomics*. (1997).

[xxv] Wheeler, W., J. Campbell and R. Kinghorn, in W. Barfield, and T. Dingus (Eds.), *Human Factors in Intelligent Transportation Systems*, Lawrence Erlbaum Associates, Inc (1998).

[xxvi] General Motors Corporation, *Automotive Collision Avoidance System field Operational Test ACAS FOT: Automotive Collision Avoidance System Field Operational Test, Final Program Report, DOT HS 809 886* (March 2005).

[xxvii] Shinar, D. and E. Schechtman, “Headway Feedback Improves Intervehicular Distance: A Field Study,” *Human Factors, Vol. 44*, no. 3, (2002): 474 – 481.

[xxviii] Ben-Yaacov, A., M. Maltz, and D. Shinar, “Effects of an in-vehicle collision avoidance warning system on short and long-term driving performance”. *Human Factors, Vol 44*, (2002): 335 - 342.

[xxix] Taieb-Maimon, M. and D. Shinar, “Minimum and Comfortable Driving Headways: Reality versus Perception,” *Human Factors, Vol. 43*, no. 1, (Spring 2001): 159 - 172.

Appendix E Collision Warning System (CWS) Evaluation Questionnaire

Collision Warning System (CWS) Evaluation Questionnaire

We would like to ask you some questions regarding your opinion of the CWS. We will not be recording your identity and this information will not be associated with you or be used as a means of evaluating your performance. We are only interested in evaluating the system.

Your participation is voluntary. You are free to refuse to take part. You may refuse to answer any question and may stop taking part in the study at any time. Whether or not you participate in this research will have no bearing on you standing in your job.

Background information:

How long have you been driving buses? ___________

Approximately how many hours have you driven the bus with the CWS on?_________

Did you receive any training prior to using the CWS?___________

What is your current employment position?__________

General Assessment:

1. Please describe the system and how it works the way that you would to another driver that has not yet seen or used the system.

____

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For the following questions, please rate how well the system performs:

How easy is the system to use overall?	(not easy) 1 2 3 4 5 (very easy)
How much do you like the system overall?	(not at all) 1 2 3 4 5 (a lot)
How well do you think the warnings conveyed a sense of urgency?	(not at all) 1 2 3 4 5 (a lot)
If you had more time with the system, would you like it more?	(no) 1 2 3 4 5 (yes)
Do you think that they system is beneficial in terms of increasing your safety?	(not at all) 1 2 3 4 5 (extremely)
How annoying was the system?	(not at all) 1 2 3 4 5 (extremely)
How distracting was the system?	(not at all) 1 2 3 4 5 (extremely)
How easy was it to determine what the hazard a warning was for	(not easy) 1 2 3 4 5 (very easy)

2. How long do you think you would need to become comfortable with this system? ______________________

3. Under what conditions was the system most helpful? Have you encountered any events where the system has assisted you in avoiding a potential collision? (If so please describe)

   ____

   ____

4. When a warning came on did the display ever cause you to think it was a forward warning when it was a side or a side when it was a forward? (If so please describe)

   ____

   ____

5. Did the system ever distract you or lead you to make an inappropriate maneuver or error in judgment? (If so please describe)

   ____

   ____

6. Please describe any situations where you observed a warning but felt that the situation did not warrant a warning.

   ____

   ____

7. Please describe any situations where you thought you should have (or would have liked) a warning but was not

   ____

   ____

8. Please describe any other uses that the CWS could be used for? For example, could the system be a useful training aid?

____

____

Suggested Changes:

9. If you could add one feature what would it be & why

____

____

10. If you could remove one feature/display method what would it be & why?

____

____

11. Please list any other comments/suggestions regarding the FCWS

____

____

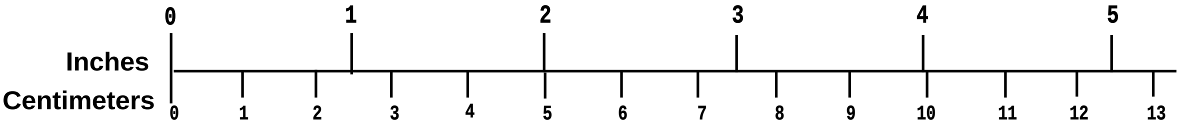
____

____

Appendix F Conversion Tables

ENGLISH TO METRIC		METRIC TO ENGLISH	
LENGTH (APPROXIMATE)		**LENGTH** (APPROXIMATE)	
1 inch (in)	= 2.5 centimeters (cm)	1 millimeter (mm)	= 0.04 inch (in)
1 foot (ft)	= 30 centimeters (cm)	1 centimeter (cm)	= 0.4 inch (in)
1 yard (yd)	= 0.9 meter (m)	1 meter (m)	= 3.3 feet (ft)
1 mile (mi)	= 1.6 kilometers (km)	1 meter (m)	= 1.1 yards (yd)
		1 kilometer (km)	= 0.6 mile (mi)
AREA (APPROXIMATE)		**AREA** (APPROXIMATE)	
1 square inch (sq in, in^2)	= 6.5 square centimeters (cm^2)	1 square centimeter (cm^2)	= 0.16 square inch (sq in, in^2)
1 square foot (sq ft, ft^2)	= 0.09 square meter (m^2)	1 square meter (m^2)	= 1.2 square yards (sq yd, yd^2)
1 square yard (sq yd, yd^2)	= 0.8 square meter (m^2)	1 square kilometer (km^2)	= 0.4 square mile (sq mi, mi^2)
1 square mile (sq mi, mi^2)	= 2.6 square kilometers (km^2)	10,000 square meters (m^2)	= 1 hectare (ha) = 2.5 acres
1 acre = 0.4 hectare (he)	= 4,000 square meters (m^2)		
MASS - WEIGHT (APPROXIMATE)		**MASS - WEIGHT** (APPROXIMATE)	
1 ounce (oz)	= 28 grams (gm)	1 gram (gm)	= 0.036 ounce (oz)
1 pound (lb)	= 0.45 kilogram (kg)	1 kilogram (kg)	= 2.2 pounds (lb)
1 short ton = 2,000 pounds (lb)	= 0.9 tonne (t)	1 tonne (t)	= 1,000 kilograms (kg) = 1.1 short tons
VOLUME (APPROXIMATE)		**VOLUME** (APPROXIMATE)	
1 teaspoon (tsp)	= 5 milliliters (ml)	1 milliliter (ml)	= 0.03 fluid ounce (fl oz)
1 tablespoon (tbsp)	= 15 milliliters (ml)	1 liter (l)	= 2.1 pints (pt)
1 fluid ounce (fl oz)	= 30 milliliters (ml)	1 liter (l)	= 1.06 quarts (qt)
1 cup (c)	= 0.24 liter (l)	1 liter (l)	= 0.26 gallon (gal)
1 pint (pt)	= 0.47 liter (l)		
1 quart (qt)	= 0.96 liter (l)		
1 gallon (gal)	= 3.8 liters (l)		
1 cubic foot (cu ft, ft^3)	= 0.03 cubic meter (m^3)	1 cubic meter (m^3)	= 36 cubic feet (cu ft, ft^3)
1 cubic yard (cu yd, yd^3)	= 0.76 cubic meter (m^3)	1 cubic meter (m^3)	= 1.3 cubic yards (cu yd, yd^3)
TEMPERATURE (EXACT)		**TEMPERATURE** (EXACT)	
[(x-32)(5/9)] °F	= y °C	[(9/5) y + 32] °C	= x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286 Updated 6/17/98