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Development of Requirement Specifications for Transit Frontal Collision Warning System

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12. ABSTRACT This report documents the development of a preliminary specification for a transit bus frontal collision warning system, based on a system engineering approach. The research efforts included: 1) a literature review, 2) detailed analyses of the five-year safety records of a group of California transit properties to identify the causes of their safety problems, 3) an in-depth data collection and analysis from instrumented buses serving San Mateo County, CA, and 4) development and testing of three generations of transit bus frontal collision warning systems, incorporating enhancements to meet the needs identified by the bus drivers using the prototype systems. The analyses of the safety records and the combination of video and engineering data from the instrumented buses provide a uniquely rich pool of data for diagnosing transit bus safety challenges. The prototype warning systems incorporated innovations in signal processing to ensure that warnings are issued with high reliability and low rates of false alerts. Finally, the results of this work led to the definition of a preliminary specification for a frontal collision warning system for subsequent field testing.				
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PROJECT No. **COPY No. _____**

DEVELOPMENT OF REQUIREMENT SPECIFICATIONS FOR TRANSIT FRONTAL COLLISION WARNING SYSTEM

FINAL REPORT

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Aaron Steinfeld[1], Matt Hanson, and Wei-Bin Zhang

California PATH Program
University of California, Berkeley

in collaboration with

Federal Transit Administration
San Mateo Transit District
California Department of Transportation
and
Gillig Company

August 2003

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Dave Nelson, Paul Kretz, Dan Empey, Bart Duncil, Thang Lian, Mark Miller, Doug Cooper, Steven Shladover and Yongquan Zhang of PATH, Sonja Sun and Ron Deleon of Caltrans, Frank Burton, Chuck Harvey, Jerie Moeller and James Castagno of SamTrans and Gail Ewing and Brian Macloed of Gillig for their technical assistance and support, and the Advisory Committee members for their active participation of the project.

EXECUTIVE SUMMARY

Bus transit systems need to use all the tools at their disposal to enhance the public perception of the desirability of their service, including its safety. Although bus transit is already a very safe mode of travel, more can be done to help bus drivers avoid crashes and the near-misses that may require them to brake suddenly. This project has explored how ITS technologies can be used to help avoid frontal collisions (collisions with other vehicles or objects located ahead of the bus). The project has followed a system engineering approach, beginning with a definition of the problem, preliminary identification of the requirements, preliminary design, testing and evaluation, and then several iterations of redesign and re-evaluation to refine the system and to lead toward the definition of a system specification.

The safety challenges posed by frontal crashes have been defined first, based on a literature review, analysis of the safety records of a group of California transit properties, and then an extensive program of data collection on buses serving San Mateo County, CA. Based on the knowledge gained from this information, three generations of frontal collision warning systems have been developed and tested in daily use by bus drivers, with refinements to the designs incorporated at each generation based on the reactions of the drivers. Finally, the results of this work led to the definition of a preliminary specification for a frontal collision warning system to be field tested in wider use.

This project was sponsored by the U.S. Department of Transportation, Federal Transit Administration (FTA), under the Intelligent Vehicle Initiative (IVI) Program. The U.S. DOT selected a public/private/academic partnership of industry specialists and researchers to define the most effective means of mitigating frontal collisions. The team includes the San Mateo County Transit District (SamTrans), University of California PATH Program (PATH), California Department of Transportation (Caltrans) and Gillig Corporation. Most of the transit agencies in the San Francisco Bay Area are also participating in the project at an advisory level and have provided significant inputs to the project.

CRASH DATA ANALYSES

The national statistics (from the NHTSA GES database) indicate that the initial point of impact for 28% of bus crashes is frontal, and therefore these should be susceptible to mitigation using a frontal collision warning system. More detailed data are available from the insurance records of the individual transit properties, and for this project the relevant data from 35 California transit properties (including three large ones in the San Francisco Bay Area) were analyzed in greater depth. Over a five-year period, these agencies experienced 5255 crashes, of which 31 were classified "serious" (costing over $100 K), for a total cost of over $22 million (more than half of which was attributable to the small number of serious crashes). Among the 31 serious crashes, eleven were for "bus hitting pedestrian" and nine were for "bus rear-ending another vehicle". Among the 23 "severe passenger injury" incidents, costing a total of about $4.4 million over five years, one quarter of the events and the costs were because "passenger fell due to abrupt stop". Of the bus crashes that involved serious casualties, 55% were frontal collisions, and about half of the collision costs were also for frontal collisions. So, although the frontal crashes involving buses are not dominant in their frequency of occurrence, they are dominant in their severity.

The crash data were augmented with advice provided by the project advisory committee of representatives from most of the major transit properties in and around the Bay Area. They helped confirm the importance of some of the observations derived from the crash data:

- Most of the crashes occurred at speeds below 30 mph;
- The crashes are typically in complex urban and suburban driving environments with heavy traffic, pedestrians, bicyclists and parked vehicles, rather than in the more open highway environment;
- Many of the incidents occur around the front corners of the bus, when it is pulling out from a stop or turning a corner, or when another vehicle is moving aggressively ahead of the bus;
- It is not only important to avoid crashes, but it is also important to help the driver react early to threats in order to avoid hard braking events that cause standing passengers to fall and injure themselves, even if an impact with another vehicle is avoided.

These aspects of the transit bus operations indicate the unsuitability of the commercially available collision warning systems for this application. Those systems are designed for use in the highway environment, where the patterns of movement of the equipped vehicle and the surrounding vehicles are much simpler and do not change as rapidly.

FIELD DATA COLLECTION AND ANALYSIS

In order to design a collision warning system that bus drivers must use every day, not just in the rare emergency condition, it is necessary to have an accurate characterization of their driving environment. Samtrans buses operate under a very diverse set of conditions, ranging from the highest urban densities of downtown San Francisco to suburban commercial and residential arterials, rural roads and high-speed suburban freeways. In order to develop a solid quantitative characterization of these operating conditions, three Samtrans buses were equipped with sensors and data acquisition systems. These included video cameras looking ahead on both sides of the bus, together with forward-looking laser and millimeter-wave radar and sonar sensors to measure the distances and closing rates to objects that could represent hazards to the bus, plus internal sensors to record engineering data about the bus location, speed, accelerations and driver actions (steering, braking, etc.).

The recorded video data enabled the analysts to understand the environmental conditions associated with the data acquired from the other sensors. This also made it possible to determine the effectiveness of those sensors in detecting different types of potential hazards, when the sensor outputs were examined in conjunction with the video. The sonar sensors were not found to be useful for frontal collision warning because of their severely limited range. The laser and millimeter wave radars that were tested had complementary characteristics based on their specific designs, but these are not necessarily inherent attributes of other sensors using these respective technologies. The laser radar provided a wider field of view, with good azimuth angle resolution and accurate target range data, but no information about range rate (closing speed). The millimeter wave radar relied on the Doppler effect, which provided it with good range and range rate capabilities when the targets were moving at a significant speed relative to the bus, but led to a loss of target at low relative speed. The millimeter wave radar had a narrower field of view and poorer azimuth angle resolution, but was less vulnerable to degraded performance in wet weather conditions.

The recorded engineering data provided the basis for characterizing the statistical distributions of operating speed and acceleration of the buses, as well as other features such as the distribution of brake use at different levels of brake pressure, and minimum following distances and closing rates to other vehicles. These data taken individually do not necessarily reveal much about safety considerations, but when they are combined they can be more useful. For example, these data made it possible to define the distribution of bus speed at the time the driver first applies the brakes, showing that most brake initiations are at speeds between 9 and 27 mph. The data also show clearly that the level of brake pressure at the onset of braking is very heavily weighted toward small values, indicating that the large majority of braking is smooth rather than abrupt.

The forward ranging sensor data provide useful statistical information about the range and closing speed to forward targets at the initiation of braking. The probability distribution of forward target range at the time of brake application is broad, with a peak at about 30 m and relatively smooth slopes from zero at the short end to maximum sensor range at the long end. The distribution of time-to-collision to the closest target at the onset of braking shows a peak at about 6 seconds, with smooth slopes away from that on both sides, but very few samples below 2 seconds. This needs to be treated cautiously because the targets that were measured here may not have been the direct reasons for the braking to occur (not in the lane of travel, etc.). When the distribution of the ratio of the speed of the target to the speed of the bus at the onset of braking is plotted, there are two peaks, at ratios of 0.04 and 0.9. This indicates that most of the targets the driver is trying to avoid are either very slow (stationary) or moving at a speed similar to that of the bus. Cross-plotting this ratio with the bus speed for all braking events provides a visual indication of the kinds of circumstances in which the driver is more or less likely to find the need to apply the brakes.

PROTOTYPE FORWARD COLLISION-WARNING SYSTEM DESIGN AND EVALUATION

Based on the knowledge of the transit bus driving and crash hazard environment, prototype forward collision warning systems were designed, developed and tested in use by Samtrans drivers. The primary sensor for the prototype warning system was the laser radar (lidar), based on its wider field of view and accurate range measurements, while the measurements from the other sensors were recorded for later analysis and evaluation. The key challenge in the design of the warning system, as with most such systems, was in setting the warning threshold low enough to issue alerts under all serious hazard conditions without making it so low that it would issue too many false or nuisance alerts (when the driver would not consider the alert to be appropriate). If the nuisance alert rate is too high, the driver will dislike the system and will come to disregard its alerts, even when they may indeed be valid.

All of the warning algorithms had to build on a foundation of strong signal processing to identify and track targets from the raw radar data. Once the targets were identified and tracked, several approaches were applied to decide when to issue warnings to the drivers. The first approach used linear prediction to estimate the time to collision (TTC) between the bus and the targets. This was not well accepted by the drivers because it tended to generate too many false positives, primarily associated with objects to the side of the vehicle's travel path (parked cars, guard rails) and with yaw motions of the bus.

The problem with the yaw motions was greatly reduced in the second iteration of the warning algorithm design by using a coordinate transformation, based on compensating for the yaw rotation of the vehicle, to express all target measurements in an inertial reference frame rather than the vehicle's (rotating) reference frame. This greatly simplified the analysis needed to assess the threats posed by each of the targets, so that attention could be focused on the targets that were really in the path of the vehicle. The result was the elimination of most of the false positives that occurred while the bus was turning.

The third iteration of the warning algorithm further reduced the nuisance alert level by changing from a TTC warning criterion to a criterion defined based on the rate of braking the driver would need to apply to avoid hitting the target. The naturalistic driving data collected from the Samtrans bus drivers was used to define the braking onsets in the phase plane of range and range rate measurements. This scatter plot showed dramatic clustering of braking onsets, indicating a well-defined boundary of combinations of range and range rate at which the large majority of drivers would apply the brakes. This boundary, as an empirical representation of the braking preferences of the drivers, provides an excellent way of specifying the warning frontier to minimize nuisance alerts, and the drivers who have tested-driven the warning systems based on it have generally accepted it.

The driver-vehicle interface (DVI) is a critical element in the design of the warning system, and has benefited substantially from continuing involvement of the Samtrans drivers in the design process. The bus driving application is very specialized because they are professional drivers, like truck drivers, but they are also sensitive to the reactions of the passengers they are serving. Therefore, it is important to them that the DVI not be so salient that it attracts the attention of their passengers, when it issues a warning. Also, because of the importance of avoiding hard braking events that could injure standing passengers, they need to receive the warnings early enough to be able to brake at a moderate deceleration rate. The night-time drivers prefer an audible alert to a visual alert because they are concerned about the visual distraction of a lighted display in the bus when they are trying to watch a dark driving scene, but the day-time drivers tend to prefer the visual alert because it is less likely to draw the attention of their passengers. Because of the diversity of driving styles, there was also a significant preference among the drivers for adjustability of the warning sensitivity and the salience of the DVI alert.

The prototype warning system uses two vertical rows of colored LEDs installed on the center and left A-pillars of the bus. These are illuminated in a sequence from yellow to red and from top to bottom as the urgency of the threat increases. If the threat is primarily to one side or the other of the bus, the LEDs on the more seriously threatened side are illuminated, but if it is straight ahead, both LED rows are illuminated.

Field tests were conducted using three instrumented Samtrans buses. The drivers who have used it have generally accepted the warning system and its DVI, but the sample of drivers and extent of their usage remains limited. Longer-term test-driving results will be needed to determine the extent to which their driving behavior is modified based on their experience with the warning system.

PRELIMINARY PERFORMANCE REQUIREMENT SPECIFICATION

Based on the knowledge gained from the successive cycles of system design and evaluation, a preliminary performance requirement specification has been defined for the frontal collision warning system. This can serve as the basis for the design of the next generation system for larger-scale field-testing and evaluation, to lead toward the development of a system that can eventually be widely deployed on buses throughout the U.S.

FUTURE WORK

Future development is planned in the following areas: to further determine optimal warning rates, ways to reduce false and nuisance warnings, ways to provide alternative display modalities, ways for the system to recognize certain scenarios and ways. Future analysis is planed to compare drivers' performance prior to implementation of the system with driver performance after implementation.

INTRODUCTION

The U.S. Department of Transportation (US DOT) initiated the Intelligent Vehicle Initiative (IVI) Program with the goal of improving safety through the application of advanced technologies. The frontal collision warning function has been identified as one of the key safety improvement measures for the transit vehicle platform of the IVI Program. Frontal collision, defined as a bus colliding with a vehicle in front of the bus, is a frequent incident in transit bus operations and the cause of property damage, personal injuries, and interruption to bus operations. A team that includes San Mateo County Transit District (SamTrans), the University of California PATH Program (PATH), California Department of Transportation (Caltrans), and the Gillig Corporation has been selected by the US DOT to develop and validate performance and technical requirement specifications for Frontal Collision Warning Systems (FCWS) for transit buses. Additionally, a group of local transit agencies are participating in the project in an advisory level. The project began in January 2000 with a planned duration of two years.

SamTrans operates a fleet of 316 buses in the counties of San Mateo, Santa Clara, and San Francisco that covers one of the most congested areas in the United States. Accident statistics tracked by SamTrans in recent years indicate frontal collisions can result in significant property damage and liability. In addition to frontal collisions, passenger falls resulting from emergency braking also contribute to an increased potential for passenger injuries and liability. This finding is further supported by the accident data collected by a number of transit agencies in the Bay Area (members of FCWS Bay Area Transit Advisory Committee). The accident data analysis suggests that a FCWS using advanced sensing and computer technologies can potentially reduce frontal collision accident rates, which will minimize losses and reduce operational interruptions. The collision warning system may also help the driver to adequately respond to the hazard with smoother maneuvers. Furthermore, information collected through sensors can be recorded for the purpose of accident analysis and for avoiding false claims.

The ***purpose*** of the transit Frontal Collision Warning System (FCWS) under the context of this project is to (a) address imminent crashes, (b) provide warnings for smoother maneuvering, and (c) provide warnings when a bus is too close to a forward vehicle.

Previous studies on collision warning and collision avoidance have focused on highway applications, freight trucks, and light-duty passenger cars. The project team has conducted a literature review and found no existing work on FCWS for transit buses, the subject of the current project. The transit bus application environment differs from existing CWS development efforts mainly in the following two ways. First of all, most of the transit frontal accidents occurred in urban areas. The urban and suburban operating environment is dramatically different from those targeted in previous CWS studies, thus present considerable challenges with respect to the diversity of obstacles to be detected and the different traffic patterns. The transit FCWS must be able to deal with the environment that current CWS deals with as well as in complicated urban settings. The second major difference is the driver/passenger population. Transit bus drivers are professional drivers who may have different needs from and sensitivities to a FCWS. In addition, operators have expressed concern regarding the presentation of warnings that can be detected by passengers. Bus passengers may find warnings for advance cues of potential threats to be annoying and potentially alarming. There is a lack of past human factors research in FCWS within the transit environment. Topics that need further examination include visual display placement, warning thresholds for both advanced cues and critical warnings, and the impact of transit specific driving tasks.

Despite the differences between the collision warning applications, the FCWS for transit buses requires the same functional elements that are used by other CWS. A principal functional element of a CWS is sensing and detection of presence of an hazardous object. This function must be able to match the environment in which it is intended. A second functional element is the warning generation function that: (1) processes the sensory information to “detect” the targets that may potentially collide with the bus, (2) determines the threat level, and (3) generates warnings at an appropriate time. The third functional element is the Driver Vehicle Interface (DVI), which communicates the warning message to the driver. Fig. 1 depicts the functional description of the collision warning system.

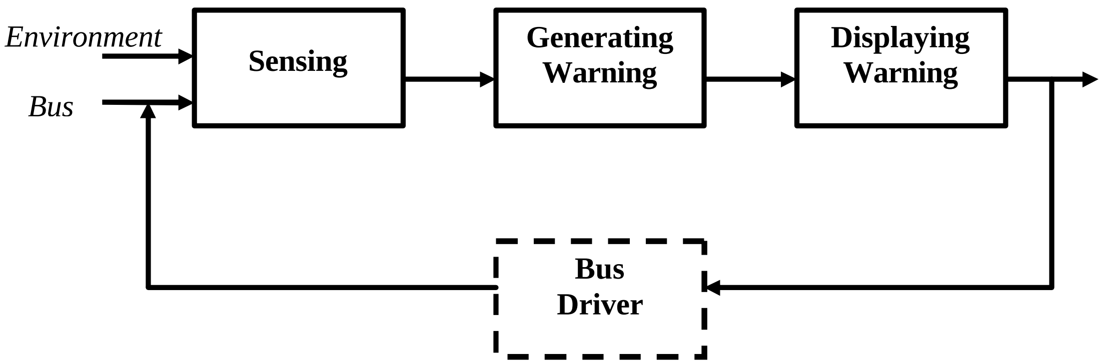

Fig. 1 Frontal collision warning system functions

The project team, under the direction of the Federal Transit Administration (FTA) and with the support of the FCWS Advisory Committee, conducted research on the requirement specifications for FCWS for transit buses. The scope of the project includes:

- Perform literature and national data review
- Analyze frontal collision accidents
- Develop a definition of FCWS functions and preliminary functional requirements
- Develop a data acquisition system for data collection
- Collect data
- Study approaches for the FCWS
- Design collision warning scheme and algorithm
- Build and test the FCWS
- Perform field verification and validation tests
- Develop requirement specifications

In addition, following the requirement analysis process defined under the System Engineering Process (SEP), the team emphasized the following aspects of the analysis:

(1) Data collection and analysis: In order to define the operational environment and the bus operation scenarios, a thorough data collection and analysis effort was conducted, which established a foundation for the determination of sensor performance and system specifications and for the definition of the performance requirements.

(2) Study of driver needs: As bus drivers are the intended users of the transit FCWS, it is important to form the requirements and to develop the FCWS to meet the driver's needs. To do so, the FCWS team has closely interacted with SamTrans drivers to understand their needs, expectations, operational environment and to define system boundaries.

(3) Verification of requirements through field testing: In order to verify that the performance requirements developed under this project are indeed within a reasonable and reachable range, a prototype FCWS was developed and instrumented on three SamTrans buses. Field testing of the system under regular service provides valuable inputs to the development of the requirements.

This report summarizes the development efforts conducted in conjunction with the development of performance specifications for FCWS for transit buses.

BACKGROUND

In order to understand the goal of the IVI program and the status of the development of a Frontal Collision Warning System (FCWS), the project team has been conducting a continuous literature review.

TRANSIT IVI

The Transit IVI Committee, composed of the FTA, representative transit agencies, manufacturers, and academia, have identified four user services as high priority transit IVI services, using systems that enable drivers to process information, make better decisions, and operate vehicles more safely:

(1) Lane Change and Merge Collision Avoidance
(2) Forward Collision Avoidance
(2) Rear Impact Collision Mitigation
(2) Tight Maneuvering/Precision Docking

These services focus particularly on the safety of the driver (and indirectly both passengers and pedestrians) and the vehicle in preventing accidents.

Following a recommendation by the Transit IVI Steering Committee, a study was conducted by Volpe Center to identify and prioritize transit industry requirements and problems involving IVI technologies [1]. This study concluded that although the total number of accidents involving transit buses is relatively small within the national accident data statistics, accidents involving transit buses do result in significant social and economic consequences. The study further indicated that the largest single cost component among the economic cost of motor vehicle accidents of all vehicles, is property damage, which accounted for over one third of total costs. Of equal or greater importance is the safety of the bus passenger and pedestrian public. Among the transit-related IVI applications that have potential to boost safety and efficiency, in-vehicle collision avoidance/warning systems, and in-vehicle obstacle and pedestrian warning systems are listed as highest priority.

The Volpe study further pointed out that the transit industry, with increasingly restricted funding, finds itself bearing the cost of expensive technologies and infrastructure necessary to support their systems. Transit managers cannot afford to be adventurous. There tends to be a reluctance to "be the first" or to be the testing ground in public arenas. There is also a perception in the transit industry that the deployment of new technologies is high-risk. Additionally, there is the need to obtain acceptance from unions where implementing technology changes will affect individuals' jobs. The importance and uniqueness of the existing transit infrastructure must be recognized. Any deployment of new technologies should be synergistic with existing infrastructure, thus eliminating the need to create new infrastructure accoutrements. Recognizing these unique transit characteristics, it is important for the IVI program to develop collision warning technologies that meet specific transit needs and to conduct field testing to demonstrate system feasibility and cost effectiveness.

STATUS OF DEVELOPMENT OF FCWS

From recent literature, it was found that significant studies have been conducted in various aspects of CWS designs for transportation applications. Research and development efforts were evenly distributed in industrial, academic, and governmental sectors. In the last five years, the publications have been quite intensive, indicating that research and development results have gradually materialized and that systems have been commercially deployed. Among the topics of research and developments within this review, there are studies across a diverse range of subject areas. Research and development are documented in the following areas:

Accident Statistics in Publications

Wilson [2] stated that data from the General Estimate System (GES) and the National Highway Traffic Safety Administration (NHTSA) Fatal Accident Reporting Systems (FARS) showed that rear collisions are 23% of all police reported crashes per year. Among them, 77%-84% are caused by driver inattention, and 7%-18% are caused by following too closely.

In another publication [3], statistics showed that 85% of rear-end collisions involved two vehicles; equal occurrence at intersection and non-intersection; 91% on straight road, 60% on dry roads; 75% in well-lit conditions; 67% without injuries. GES from 1992 data showed that 59% are caused by the leading vehicle having stopped; 37% by the leading vehicle decelerating; 80% in clear weather and 70% under well-lit conditions; 73% on dry roads; 95% on straight roads.

Asher [4] reiterated that about 20-25% of accidents are rear-end collisions and reported that about 60% rear-end collisions could be avoided if the driver had an additional 0.5 sec of warning before the incident.

It was estimated in another publication [5] that rear-end crashes accounted for 24% of all crashes from NHTSA research. These crashes occurred mostly during the daytime (77%), on straight roads (90%), and under dry weather conditions (79%).

The National Automotive Sampling System (NASS) GES provided the most usable data about all types of crashes and related vehicle types. By restricting attention to police-reported crashes, the GES concentrates on those crashes of greatest concern to the safety community and the general public. The GES data was supplemented by direct transit industry input. The five most frequent crash types involving motor coaches are: lane change, rear end, intersection, with a parked vehicle, and backing up scenarios. The total for the top five crash categories comprises approximately 87% of crashes involving motor coaches within the United States.

The study by Volpe that focuses on nationwide collision statistics has concluded that the highest-accident-rate-and-severity-rating accident is intersection type of crashes where a bus is struck by another vehicle. The second major scenario is rear-end type of collisions where a bus is struck by another vehicle. These two types of crashes account for almost one third of the top five scenarios. The mid-level types of accidents, which carry a medium range of risk and severity, include the other half of the intersection type of accidents where the bus strikes another vehicle; rear-end type where the bus does the striking, and both backing up type of crashes. There remains a critical need for gathering real life data that is transit specific. In order to specifically evaluate the effectiveness of IVI technologies, the accident data needs to be more specific with respect to the accident characteristics, including causal factors. All transit IVI projects should require a detailed accident analysis phase.

Benefits Evaluation from Selected Applications

Farber [6] compared two collision-warning algorithms: Closing Rate Algorithm (CRA) and Stopping Distance Algorithms (SDA). It was estimated that SDA provides advanced warning and eliminates 95-100% crashes, but it also produces a substantial volume of incorrect warnings. CRA provides last moment warnings and only eliminates 65-70% of crashes, but it produces fewer incorrect warnings. This illustrates that a compromise may be necessary between frequent warnings and false alarms.

In a study [7] of CWS for commercial trucks, it was found that a 37% reduction of hard braking of 0.25g ($1g = 9.8m/s^2$) or greater could be achieved. This led to a 2-10% reduction in fuel consumption. In one test, fuel savings as high as 20% was obtained. In a separate field review [8] of CWS for heavy-duty trucks, it was revealed from a survey of 171 drivers that 80% changed their way of driving, which had a positive effect.

An evaluation of Adaptive Cruise Control (ACC) [9] showed that if the automated braking function was incorporated into ACC, the total number of accidents and fatalities can be reduced by up to 85-90% and 30-80% respectively.

Even though these evaluation studies have been conducted for different settings and applications, they show that the deployment of CWS potentially can reduce accident numbers and fatalities. It is also significant that by alerting the driver to obstacles ahead there might be a reduction in hard braking which will result in smooth maneuvers, thus leading to fewer passenger falls in the case of transit bus operations.

Sensors

Most collision warning systems demand the use of radar or optical sensing devices. The descriptions of the sensor performances or their design issues have been examined in numerous reports, such as those in [8,10,11,12,13,14]. Wilson [2] gave a comprehensive review of performance guidelines for radar or other forward-looking sensors in the requirements for range, and lateral and vertical field of view. However, those guidelines are given for passenger cars for use in mainly highway applications.

Human Factors Research

Past human factors explorations of forward collision warnings have emphasized scaled time-based headway [15 & 16] and binary warnings [17 & 18]. Time-based warnings, often formulated using Time-To-Collision (TTC), have been championed as they are less affected by speed when compared to distance-based warnings. Furthermore, they relate well to models of how drivers maintain longitudinal separation [19].

Binary warnings are more often used for critical scenarios where early warnings would not be possible. For example, a simulator study on how people responded to vehicles cutting in from parked positions compared icons, text commands ("Swerve Left"), and the baseline case of no warning [18]. In some scenarios it will be impossible for sensors to provide advanced cues to alert the driver to potential threats. In these events, the system will need to proceed directly into a full warning state, thus emulating a binary warning interface. The aforementioned study did find that drivers were able to gain some benefit from the binary warning.

Recent work on snowplows has used distance-based displays [20] as they were deemed easier to transition to should a sudden period of low visibility (e.g., a white-out) obscure an actively watched forward obstacle. As low visibility is a rare event for a bus, a time-based approach is probably more suitable. The research on snowplows also deemed binary warnings unsafe given the likelihood of low traction, a scenario that is also conceivable for transit during adverse weather. Furthermore, sharp braking or swerving actions are not desirable within the transit community due to passenger falls. This suggests that binary warnings requiring fast intervention are not preferable for transit applications.

In fact, most literature on visual warnings for CWS applications suggests a graded approach to warnings [16,21,22,23,20]. This commonly involves a scale of some sort implying increased danger. Also commonly suggested is the use of auditory warnings when TTC has reached a critical point and braking action is sorely needed. In fact, auditory tones are incorporated into the Eaton-Vorad CWS, which is offered by several truck Original Equipment Manufacturers (OEM) as an option. Research on strictly auditory warnings has also shown beneficial results [17]. Extending this notion was a government-funded study on the value of localized auditory warnings to assist drivers in identifying the location of hazards [24]. While the results suggested that such a feature is promising, the authors also found that such a system requires special care with respect to speaker location and sound choice.

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Section One

Understanding Transit Frontal Collisions

1 Accident Data Analysis

Frontal collision accounts for a significant portion of all collisions. Data from both the Automotive Sampling System (NASS), General Estimate System (GES), and the NHTSA Fatal Accident Reporting Systems (FARS), showed that rear collisions are 20-25% of all police reported crashes per year [1,4,5]. Further studies [2,5] showed that frontal collisions occurred mostly during the daytime (~75%), on straight roads (~90%), and under dry weather conditions (60-79%). These studies revealed that 85% of rear-end collisions involved two vehicles with equal occurrence at intersection and non-intersection, 77%-84% are caused by driver inattention, and 7%-18% are of caused by following too closely, 67% without injuries. Asher [3] reported that about 60% frontal collisions could be avoided if the driver had an additional 0.5 sec of warning before the incident, this suggests that a collision warning system may offer great potential for reducing frontal collisions.

Both NHTSA and GES accident statistics also include accident data involving buses. The statistics in NHTSA *Traffic Safety Facts 2000* [5] offers some insights into the types of crashes. Roughly, frontal collisions and rear collisions each account for one-fourth and side collisions half of all crashes. The following table outlines the distribution of crashes by the initial point of impact:

Table 1 Buses involved in all crashes by the initial point of impact

Initial Point of Impact	Number	Percentage
Front	16,000	28.2
Left Side	14,000	24.3
Right Side	13,000	23.3
Rear	13,000	22.9
Non-collision	*	0.3
Other/Unknown	1,000	1.0
Total	56,000	100

*Less than 500 or 0.5 percent.

The GES data has concluded that the five most frequent crash types involving motor coaches are: lane change, rear end, intersection, hitting parked vehicles, and backing up scenarios. The total for the top five crash categories accounted for approximately 87% of crashes involving motor coaches within the United States. GES from 1992 data showed that 59% of crashes are caused by leading vehicle stopped; 37% are leading vehicle decelerating; 80% in clear weather and 70% under well-lit conditions; 73% on dry roads; 95% on straight roads.

Following a recommendation by the Transit IVI Steering Committee, a study was conducted by the Volpe Center to identify and prioritize transit industry requirements and problems involving IVI technologies [4]. This study revealed that the highest-accident-rate-and-severity-rating accident is intersection type of crashes where a bus is struck by another vehicle. The second major scenario is rear-end type of collisions where a bus is struck by another vehicle. These two types of crashes account for almost one third of the top five scenarios. The mid-level types of accidents, which carry a medium range of risk and severity, include the other half of the intersection type of accidents where the bus strikes another vehicle; rear-end type where the bus does the striking, and both backing up type of crashes. The study concluded that although the total number of accidents involving transit buses is relatively small, they result in significant social and economic consequences.

Although the national accident data provides statistics of transit accidents, detail accident analysis is still needed as in addition to urban transit buses, the national data includes additional sources of bus accidents, specifically school buses and intercity buses. It is not clear the percentage of each vehicle type and the impact of a particular type of vehicles on category of accidents. Additionally, our research suggests that the accidents involving transit buses often occur in very different environments such as urban areas with different speeds than that of automobiles. Furthermore, there is a critical need for gathering real life data that is transit specific so that accident type and associated cost can be investigated in detail to support the benefits of transit IVI systems and provide inputs for developing and implementing FCWS on transit buses. In order to fully understand the environment that transit buses are operated in, the causal factors of frontal collisions involving buses, the characteristics and consequences of these accidents and potential IVI approaches through which frontal collision warning systems can help to prevent or mitigate, the project team has conducted a series of accident data analysis.

In the first phase of the study of frontal collision warning systems, PATH has been working with the AC Transit, Central Contra Costa Transit Authority (CCCTA), Golden Gate Transit (GGT) and San Mateo County Transit District (SMT) in the San Francisco Bay Area to obtain transit accident data. The focus of this initial study is to determine the accident scenarios relevant to the design and implementation of frontal collision warning systems on transit buses. In the course of working with these agencies, it soon became clear that obtaining detailed collision cost data would not be a straightforward process. In many cases, costs such as damage repair, injury, legal, and compensation payout are not processed or tracked by a single agency department or division and the retrieval of this information often requires hand processing as the relevant information cannot be accessed by computer. In other cases, the handling of legal claims is out-sourced to private organizations (e.g., John Glenn Adjusters & Administrators (JGAA) in the Bay Area), so the data are not available directly from the transit agencies.

Following the initial accident analysis, PATH has worked with JGAA to conduct a detailed investigation of accident costs to support a cost-benefit analysis of transit IVI systems. The objectives of this effort are (1) to further determine accident scenarios in order to assist the improvement of the design and implementation of transit collision warning systems, and (2) to assess the overall costs of incidents or collisions.

In addition to the accident cost data for the SMT, Santa Clara Valley Transportation Authority (VTA), and GGT, JGAA has maintained cost data for the members of the California Transit Insurance Pool (CalTIP), which is an insurance authority currently serving 32 California transit operators (see Appendix I for a list of all the 32 members). Given the value of the broader database, it was decided to expand the project to include detailed accident analysis for CCCTA and Riverside Transit Authority (RTA) and generalized accident analysis for an additional 30 CalTIP agencies.

JGAA provided PATH with electronic copies of the accident data. PATH has developed software to automatically process the cost reports and put the information into data forms so that in-depth accident and cost benefit analysis can be carried out.

1.1 ANALYSIS DETAILED ACCIDENT DATA FROM 35 CALIFORNIA TRANSIT AGENCIES

The detailed transit accident data analysis is based on the latest five fiscal years (May 1, 1997 to April 30, 2002) of cost data for 35 transit agencies including three in San Francisco Bay Area and the 32 CalTIP agencies. Those 35 transit agencies operate buses in different regions and operating environments in California, as it is shown in Figure 2 (not shown are the 3 San Francisco Bay Area agencies, VTA, SMT, and GGT).

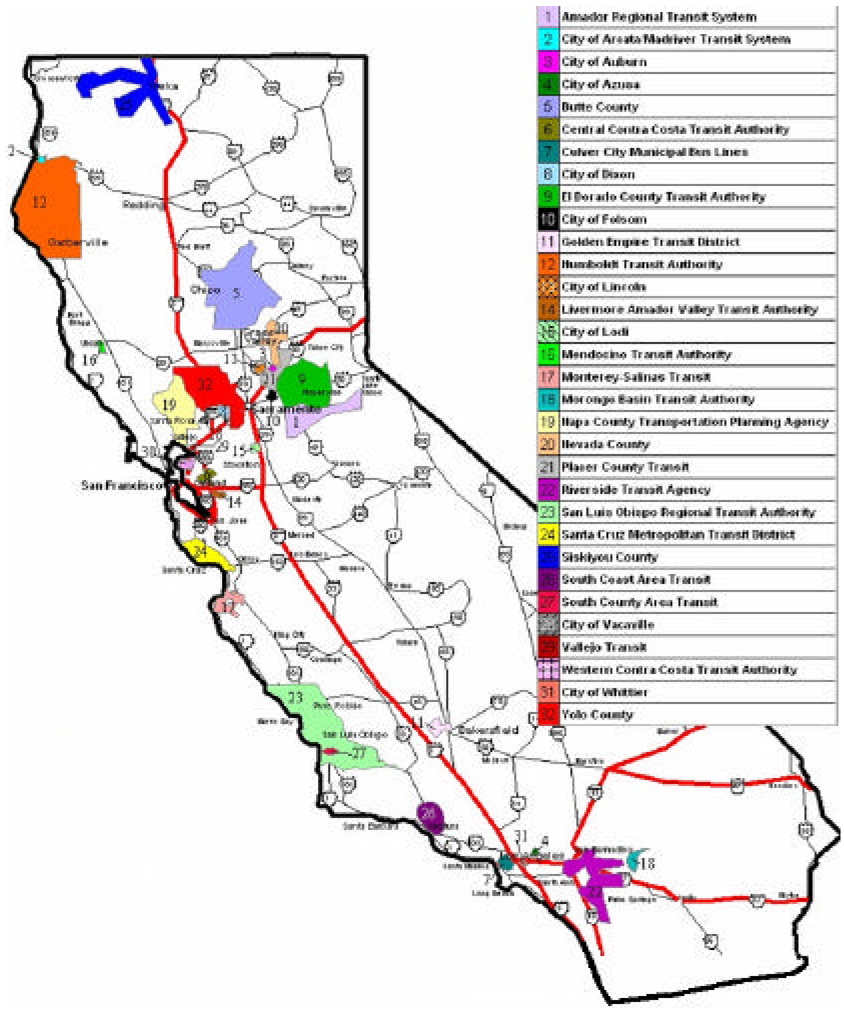

Fig. 2 Service coverage of 35 transit agencies

Each incident or accident is indicated as a claim in JGAA's database. Each claim involves a transit bus and another party, which could be another vehicle, a pedestrian, a stationary object, and/or a passenger on the bus. JGAA tracks the accident costs in three categories: "Body Injury", "Property Damage", and "Legal and Other Fees." The cost for a claim is the sum of these three types of costs. For each claim, JGAA includes a simple accident narrative describing what occurred. Different agencies have different cost report formats (see Appendix II for a sample JGAA cost report).

JGAA uses 103 loss codes to refer to various types of accidents (see Appendix III for the loss code descriptions.). The code system is designed from a legal perspective, and provides little information about the cause of the accident. It was found to be impossible to retrieve the initial point of impact from the loss code. Loss code 1, for example, indicates a bus going straight ahead colliding with a vehicle from its left at an intersection. This could be a frontal collision if the bus hit the other vehicle or it could be a side collision if the other vehicle ran into the bus. In order to understand the association between accident cost and the initial point of impact, PATH and JGAA have obtained the initial point of impact information for four transit agencies (two are CalTIP agencies) by reviewing the original driver reports and police reports. Four possibilities are considered for the initial point of impact: front (F), side (S), rear (R), and not-known (N). The statistics from these four agencies are then extended to other agencies.

The 103 loss codes are categorized into three groups:

1. Collision accident: A collision happened between a transit bus and another party.
2. Non-collision accident: Passenger injured on boarding, alighting, or on board (not caused by a collision).
3. Civil right and ADA violation.

Table 2 summarizes the accident and cost data for the 35 transit agencies. Agency III and IV are CalTIP members, and CalTIP(30) refers to the other 30 CalTIP agencies. For CalTIP agencies, one collision accident happened per 22,000 revenue miles, and one non-collision accident per 22,000 revenue miles.

Table 2 Accident cost data for 35-transit agencies (for 5 years)

Transit Agency	Collision		Non-collision		Violations	
	Claim	Cost	Claim	Cost	Claim	Cost
Agency I	353	$2,904,763	182	$1,188,326	11	$13,500
Agency II	1,146	$6,319,107	669	$1,857,460	13	$35,953
Agency III	358	$997,982	474	$858,162	8	$2,039,006
Agency IV	261	$1,032,796	363	$1,174,749	1	$285
Agency V	261	$1,032,796	363	$1,174,749	1	$285
CalTIP(30)	1,398	$4,783,760	1,198	$5,075,349	7	$442,993
Total	**5,255**	**$22,354,203**	**4,285**	**$13,583,368**	**40**	**$2,531,737**

On average, each collision accident cost $4,254, and each passenger injury accident cost $3,170. Since cost from Civil Right and ADA violations is not directly related to accidents, it is not being included in this analysis.

1.1.1 Accident Costs of Agency I

Most bus routes of Agency I are operated on relatively congested roads. The accident costs for Agency I by accident type and the initial point of impact are summarized in Figures 3 and 4.

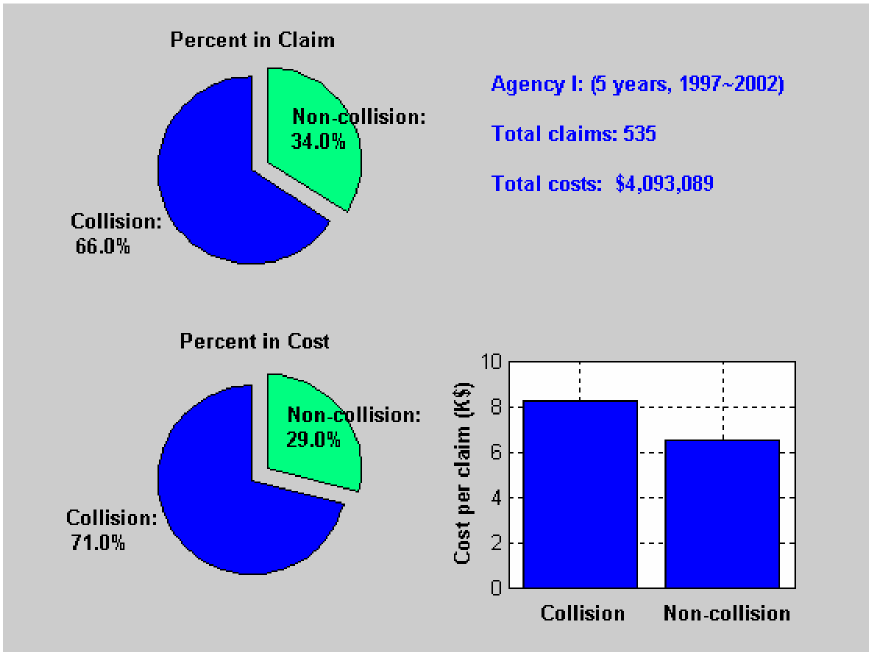

Fig. 3 Agency I: Accident costs by accident type

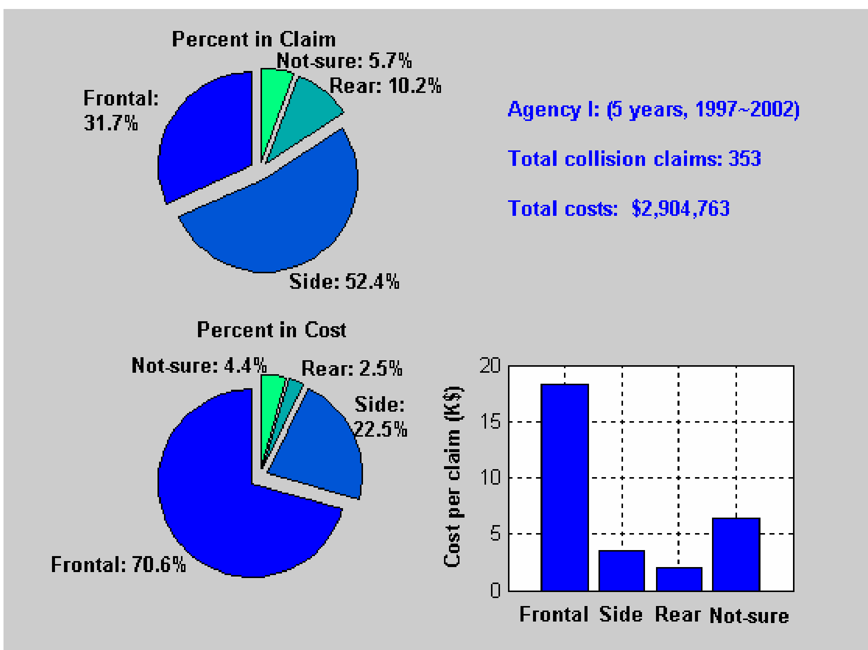

Fig. 4 Agency I: Collision accident costs by initial point of impact

1.1.2 Accident Costs of Agency II

The accident costs for Agency II are summarized in Figures 5 and 6.

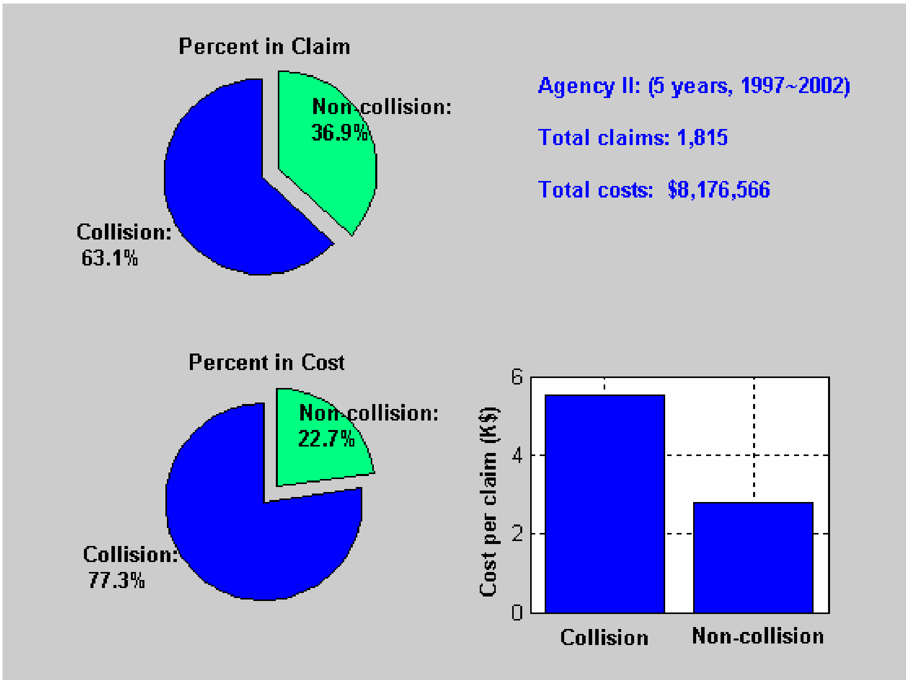

Fig. 5 Agency II: Accident costs by accident type

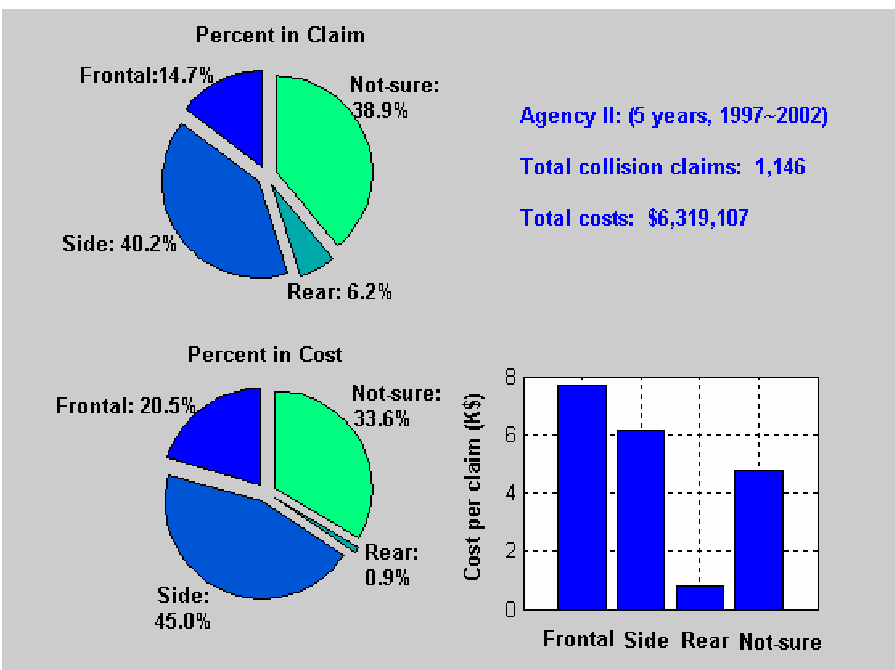

Fig. 6 Agency II: Collision accident costs by initial point of impact

1.1.3 Accident Costs of Agency III

The accident costs for Agency III are summarized in Figures 7 and 8.

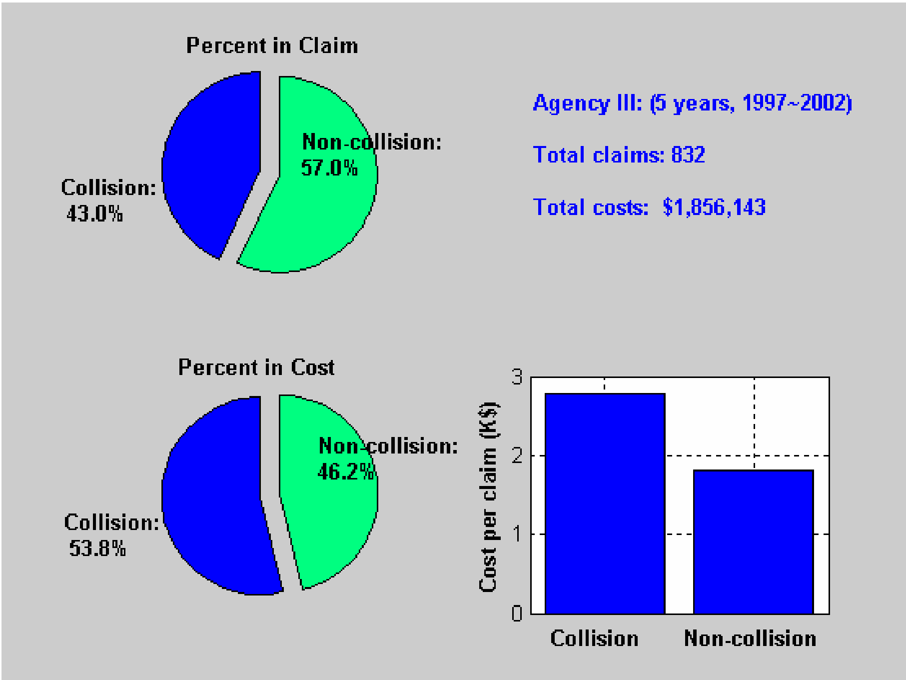

Fig. 7 Agency III: Accident costs by accident type

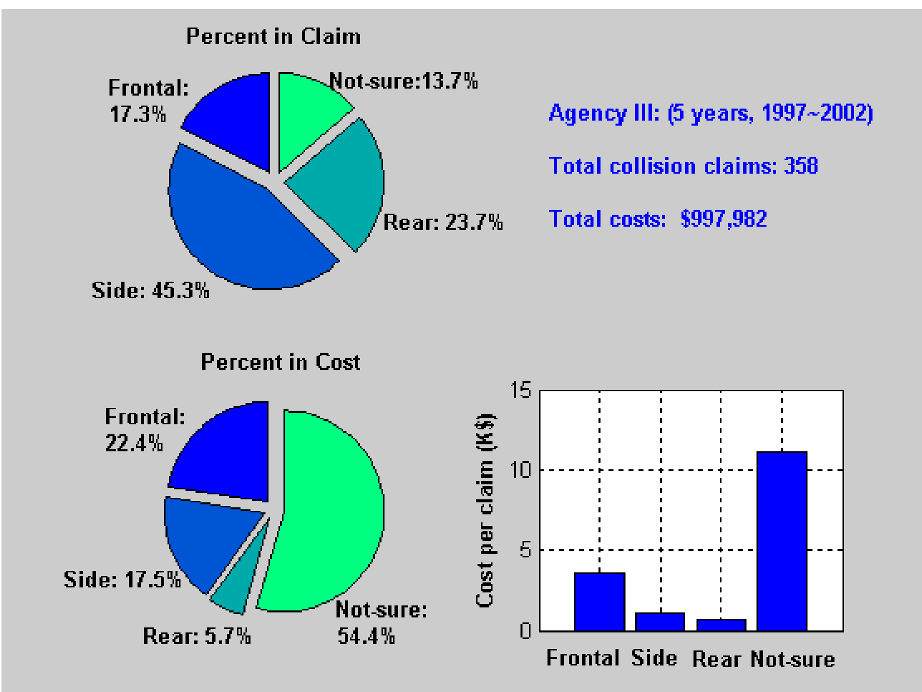

Fig. 8 Agency III: Collision accident costs by initial point of impact

1.1.4 Accident Costs of Agency IV

The accident costs for Agency IV are summarized in Figures 9 and 10.

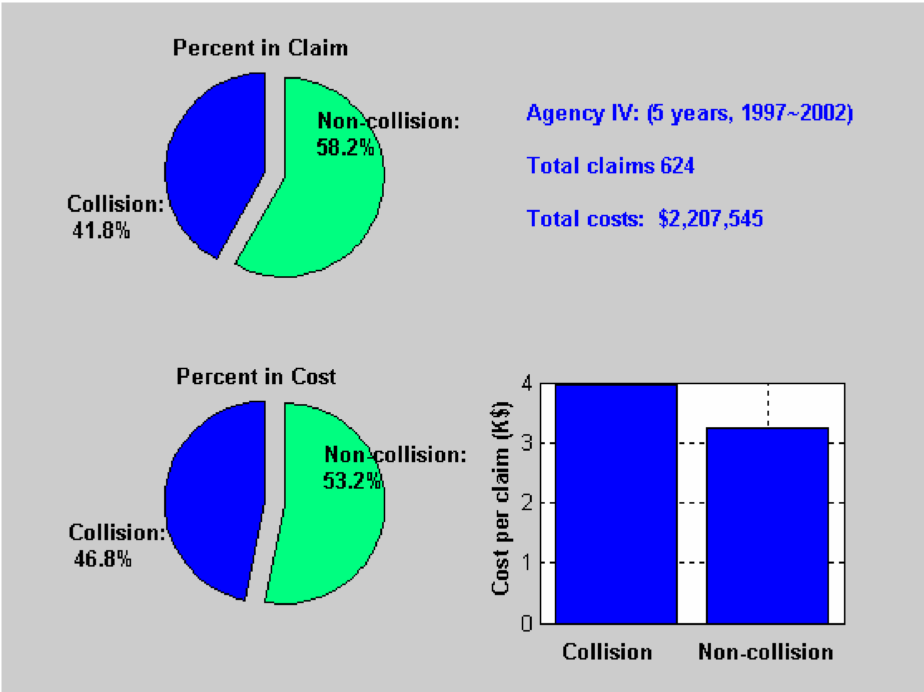

Fig. 9 Agency IV: Accident costs by accident type

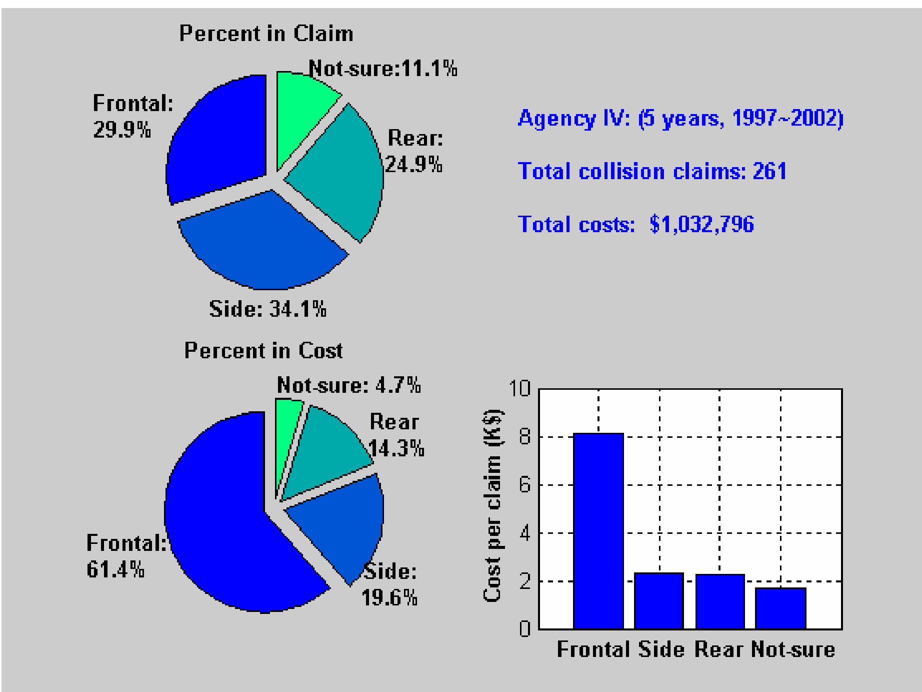

Fig. 10 Agency IV: Collision accident costs by initial point of impact

1.1.5 Distribution of Collision Claims and Costs by Loss Code

As can be seen, the cost distribution by initial point of impact varies from agency to agency. This may be due to the fact that every transit agency has its own driver training program as well as a different operating environment. These can lead to a unique collision pattern and claim distribution. Furthermore, each agency has several severe collision accidents, each costing more than $100,000, which can significantly affect the cost statistics.

Although most loss codes cannot be directly associated with an initial point of impact, it was found from the cost data that the claim distribution and cost distribution by loss code and the initial point of impact are very consistent within the four transit agencies for which detailed initial point of impact information was obtained from the original driver and police reports. The accident data of two CalTIP agencies (agencies III and IV) were selected to generate the claim and cost distributions by loss code and the initial point of impact. These distributions were then applied to the four agencies to verify their accuracy and consistency, and then extended to Agency V and other CalTIP agencies (CalTIP(30)).

There are a total of 47 loss codes that are related to collision accidents. In order to exclude the affect of severe collisions, only claims costing less than $10,000 are used to generate the claim distribution, $\text{claim\_dist}[i][j]$, and cost distribution, $\text{cost\_dist}[i][j]$, where *i* refers to the initial point of impact and *j* refers to the loss code. The original initial point of impact inputs are used for claims costing more than $10,000. For each transit agency, the generated distributions are applied to claims costing less than $10,000 as follows:

$$\text{claim\_est}[i] = \sum_j \text{claim[j]} \cdot \text{claim\_dist}[i][j]$$

$$\text{cost\_est}[i] = \sum_j \text{cost[j]} \cdot \text{cost\_dist}[i][j]$$

where $\text{claim\_est}[i]$ and $\text{cost\_est}[i]$ are estimated claim number and accident cost for point of impact *i*; and $\text{claim}[j]$ and $\text{cost}[j]$ are actual claim number and cost by loss code *j*, which are obtained from the accident data. Finally, the total claims and costs by loss code are given by

$$\text{claim\_total}[i] = \text{claim\_est}[i] + \text{claim\_review}[i]$$

$$\text{cost\_total}[i] = \text{cost\_est}[i] + \text{cost\_review}[i]$$

where $\text{claim\_review}[i]$ and $\text{cost\_review}[i]$ are actual claim number and cost by the initial point of impact for claims costing more than $10,000.

Fig. 11 shows the comparison of actual claim and cost distributions by the initial point of impact (top row), and the distributions calculated by using the statistics from Agencies III and IV (bottom row). Again, only accidents with costs less than $10,000 are considered.

Using the same statistical distributions for accidents costing less than $10,000, and taking account of those collision accidents costing more than $10,000 for which PATH acquired the initial point of impact, Figure 12 compares actual cost and claim data (top row) to statistical estimations.

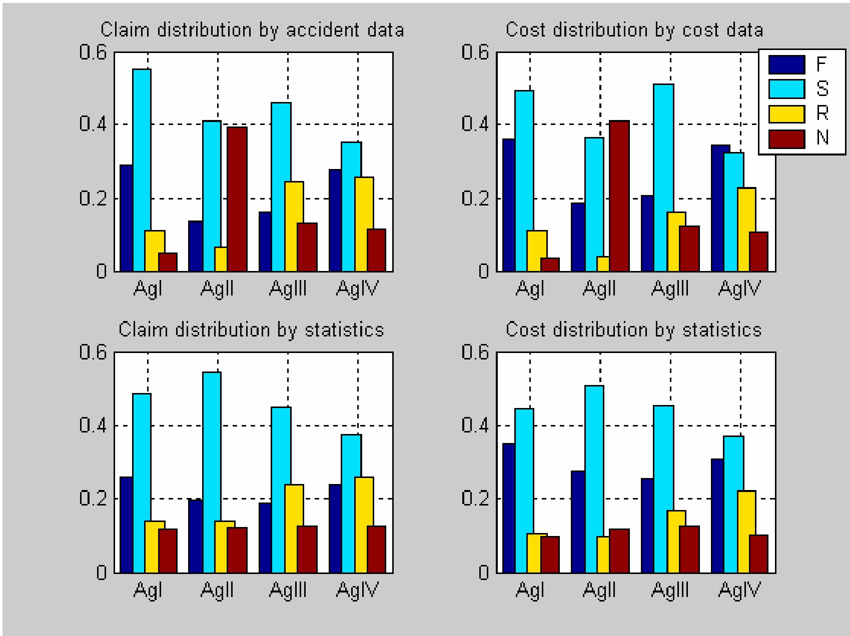

Fig. 11 Claim and cost distributions for collision accidents costing less than $10K

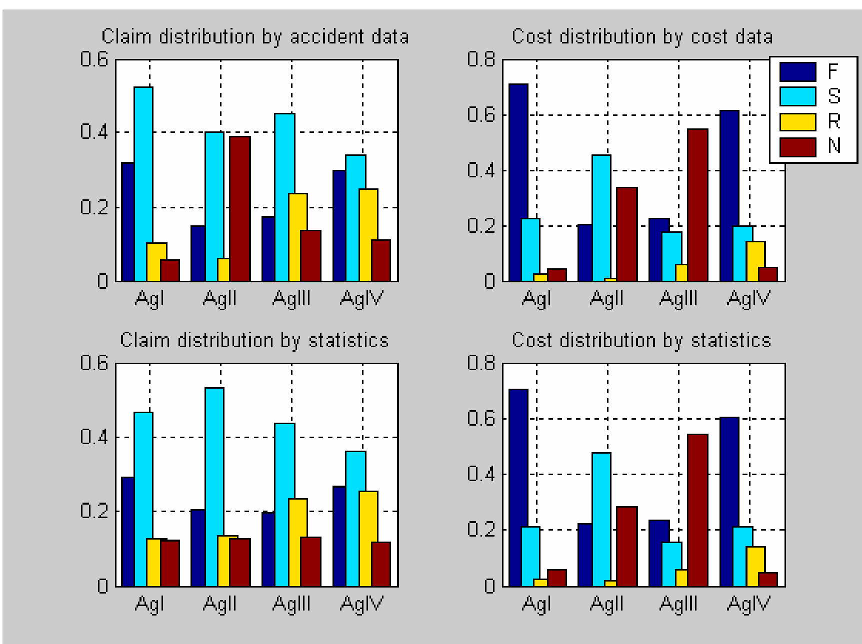

Fig. 12 Claim and cost distributions for all collision accidents

With the exception of Agency II, the derived distributions match the actual distributions quite well (error within 6%). Relatively larger variations can be found for Agency II. This is because 39.5% of its collision accidents have "not-known" initial point of impact due to the information limitation on original reports. This is much higher than other agencies.

1.1.6 Accident Costs of Agency V

The statistics from Agencies III and IV are applied to Agency V for collision claims costing less than $10,000. PATH has obtained the initial point of impact information for a total of 65 claims, which cost more than $10,000. The results are summarized in Fig. 13 and 14.

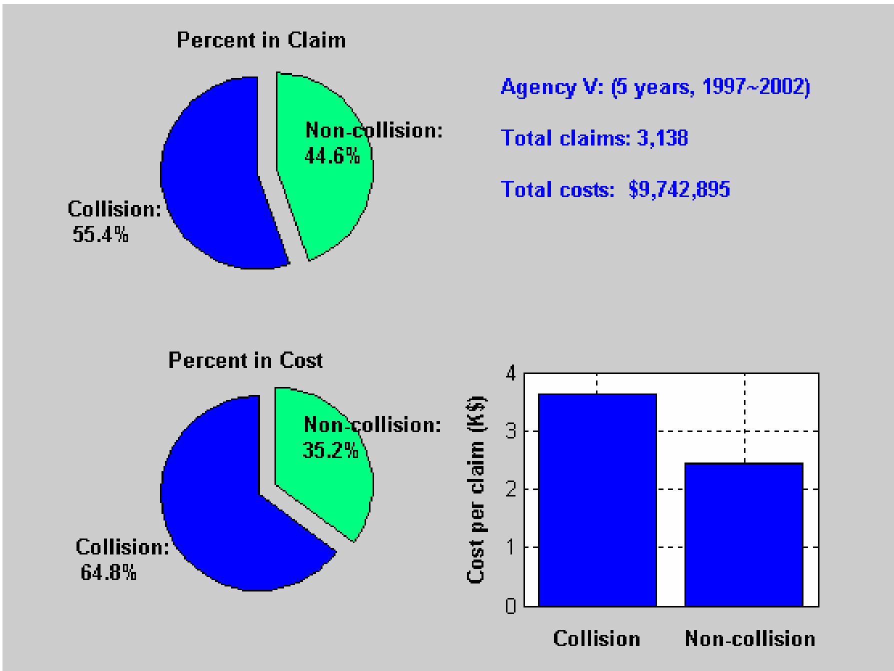

Fig. 13 Agency V: Accident costs by accident type

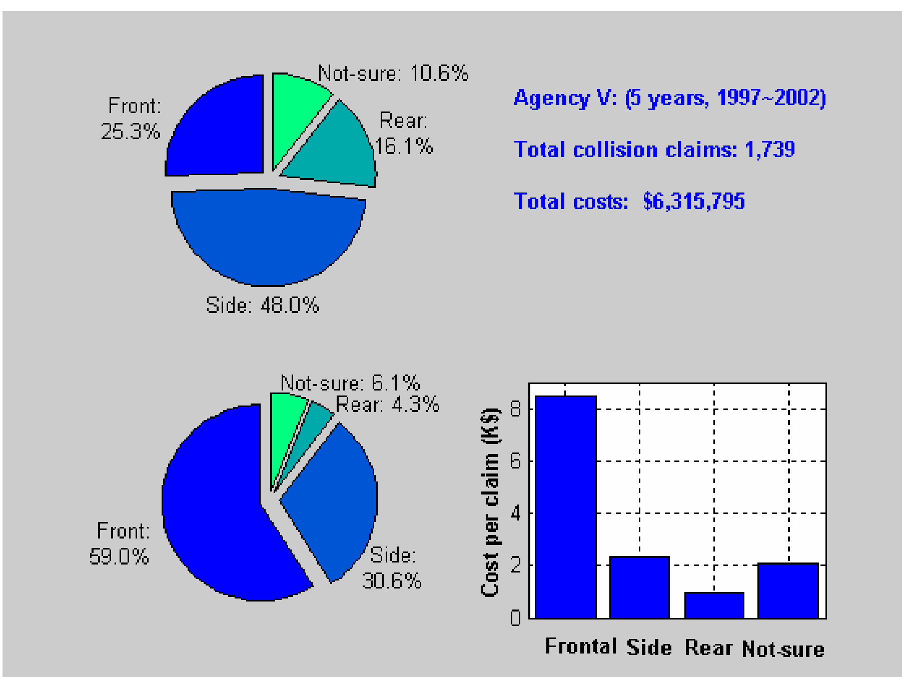

Fig. 14 Agency V: Accident costs by initial point of impact

1.1.7 Accident Costs of 30-CalTIP Agencies

Due to the prohibitive cost, in terms of both time and resources, to obtain the initial point of impact information for the 30-CalTIP members, it was decided to apply the statistics from Agencies IV and V to these agencies for collisions costing less than $10,000. PATH has obtained the initial point of impact information for all the collisions costing more than $10,000 (a total of 81 accidents). Figures 15 and 16 summarize the claim and cost data for the combined accident categories of the 30-CalTIP agencies.

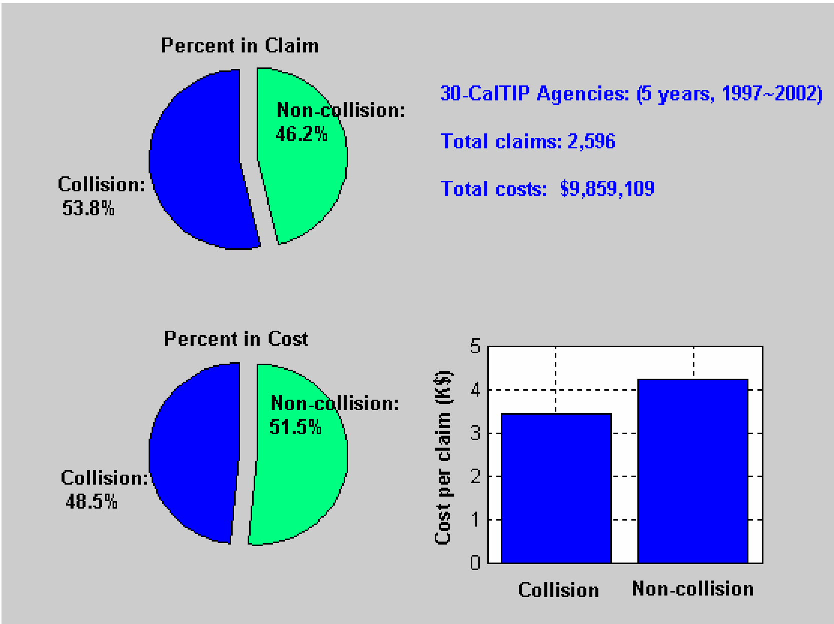

Fig. 15 30-CalTIP members: Accident costs by accident type

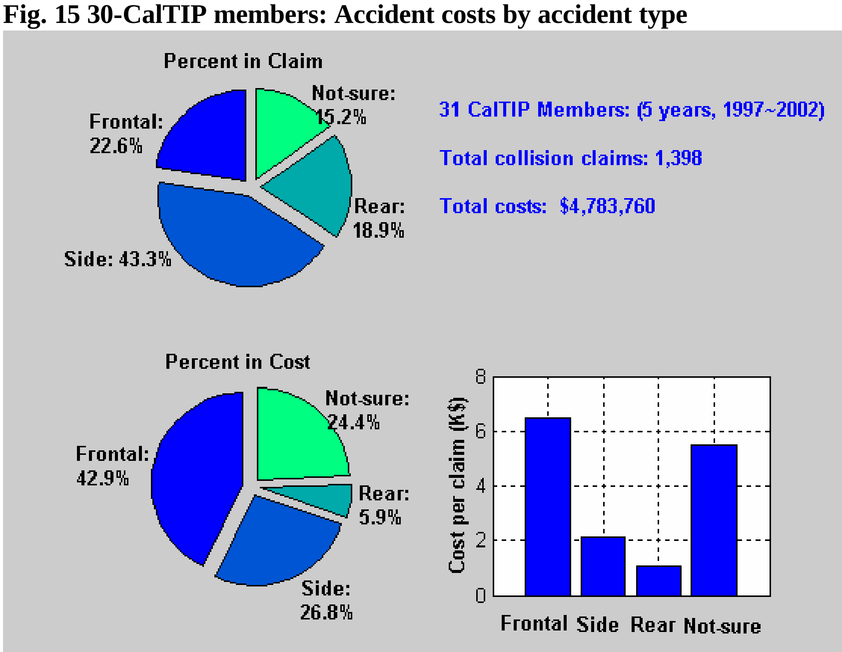

Fig. 16 30-CalTIP members: Collision accident costs by initial point of impact

1.2 IN-DEPTH COST ANALYSIS ON COLLISION ACCIDENTS

Two crash severities are defined for collision accidents: serious casualty (collision accident costing more than $100,000), and general collision accident (collision accident costing less than $100,000). Because there are so few fatalities in transit accidents, they are included under serious casualty. Table 3 summarizes the accident cost by crash severity.

Table 3 Collision accident cost data for 35-transit agencies (5 years)

	Claim		Cost	
Serious casualty (Accident costing more than $100K)	31	0.6%	$11,563,53	51.7%
General accident (Accident costing less than $100K)	5,224	99.4%	$10,790,680	48.3%
Total for 35-transit agencies	5,255	100.0%	$22,354,203	100.0%

Collision accidents account for 55.1% of claims and 62.2% of costs among all accidents, as shown in Table 4.

Table 4 Total accident cost data for 35-transit agencies (5 years)

	Claim		Cost	
Collision accidents	5,255	55.1%	$22,354,203	62.2%
Non-collision accidents	4,285	44.9%	$13,583,368	37.8%
Total for 35-transit agencies	9,540	100.0%	$35,937,571	100.0%

1.2.1 Serious Casualty

A few serious casualties account for most costs from collision accidents. In five fiscal years, there are a total of 31 serious casualties for a total cost of $11,563,523. They account for 0.6% of claims and 51.7% of costs among all collision accidents. Table 5 lists all of the 31 serious casualties, which consist of 17 frontal, 7 side, and 7 not-known initial point of impact collisions.

Table 5 Serious casualties for 35-transit agencies (5 years)

Claim	Loss Code	Initial Point of Impact	Cost	Accident description
1	2	S	$195,000	Intersection, going straight bus hit a right turn vehicle
2	9	F	$162,500	Intersection, bus failure to yield right of way
3	14	S	$203,300	Sideswipe, bus changing lane
4	19	F	$130,045	Bus struck a standing vehicle
5	19	S	$104,727	Bus struck a standing vehicle
6	23	F	$132,456	Bus rear-ending another vehicle
7	23	F	$121,335	Bus rear-ending another vehicle
8	23	F	$127,428	Bus rear-ending another vehicle
9	23	F	$236,616	Bus rear-ending another vehicle
10	23	F	$350,640	Bus rear-ending another vehicle
11	23	F	$158,908	Bus rear-ending another vehicle
12	23	F	$160.026	Bus rear-ending another vehicle
13	23	F	$100,207	Bus rear-ending another vehicle
14	24	F	$172,449	Bus rear-ending another vehicle
15	27	S	$267,223	Bus pulling from loading zone
16	30	N	$114,379	Bicyclist veered in front of bus
17	30	S	$506,313	Bus vs. Bicyclist
18	37	F	$302,307	Collision, detail unknown
19	37	N	$258,905	Collision, detail unknown
20	39	N	$163,542	Bus striking a pedestrian
21	40	S	$209,278	Bus striking a pedestrian
22	41	F	$1,642,054	Bus striking a pedestrian
23	42	N	$429,637	Bus striking a pedestrian (fatal)
24	43	S	$1,997,950	Bus striking a pedestrian
25	43	N	$906,025	Bus striking a pedestrian
26	43	F	$250,000	Bus striking a pedestrian
27	43	F	$975,000	Bus striking a pedestrian (fatal)
28	43	F	$298,015	Bus striking a pedestrian
29	43	N	$106,675	Bus striking a pedestrian
30	43	F	$326,093	Bus striking a pedestrian
31	48	N	$454,491	Collision, detail unknown (fatal)
Total			**$11,563,523**	

Two accident scenarios stand out from the others as sources of serious casualties: “bus hitting a pedestrian” (11 claims with 5 front, 2 side and 4 not-known POC), and “bus rear-ending another vehicle” (9 claims, all frontal). They account for 64.5% of claims and 76.7% of costs among all serious casualties.

1.2.2 General Collision Accident

As shown in Table 3, general accidents account for 99.4% of claims and 48.3% of costs among all collision accidents for the 35-transit agencies.

1.2.2.1 General collision accidents by initial point of impact

Figure 17 shows the claim and cost distributions by initial point of impact, and Figure 28 shows the average cost per claim for each agency. Actual accident and cost data are used for Agencies I, II, III and IV, and the generated distributions by loss code and initial point of impact are used for Agency V and CalTIP(30).

For each agency, side collisions account for the largest number of claims, while frontal collisions account for the greatest cost. Although different agencies have different claim and cost distributions for collision accidents, in general, frontal collisions account for 15~30% of claims and 30%~50% of costs while side collisions account for 35~50% of claims and 25~35% of costs. On average, each frontal collision costs more than twice as much as a side collision. The point of impact cost ranking, from most costly to least, is frontal, side, then rear collision.

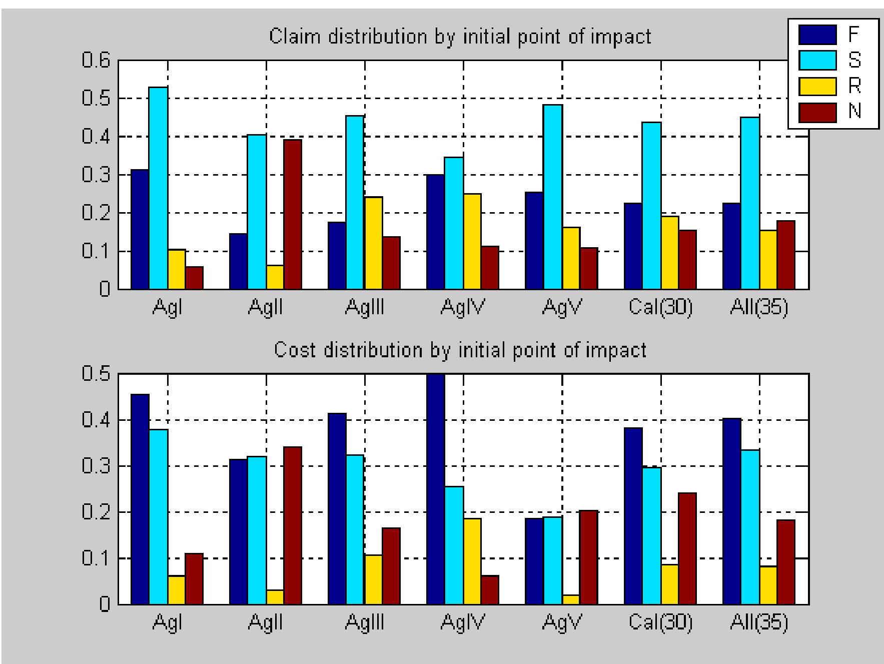

Fig. 17 35-transit agencies: General collision accident costs by initial point of impact

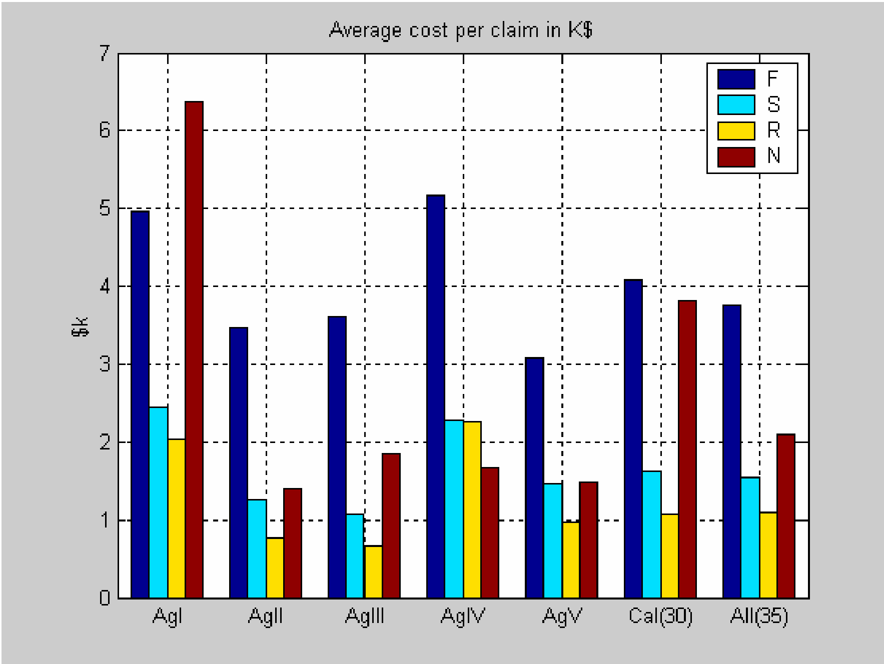

Fig. 18 35-transit agencies: Cost per claim by initial point of impact

1.2.2.2 General collisions by fiscal year

Since each transit agency has its own driver training program and operates in a different environment, it is difficult to find accident statistics that are consistent between agencies. The number of accidents and cost by fiscal year do provide interesting detail, however.

Each year, the 35-transit agencies had about 1,000 general collisions which cost $2 million. Approximately one quarter of these are frontal, and one half are side collisions. The claim costs from these two points of impact account for 40% and 35% of total costs, respectively. This is shown in Figure 19 and 20.

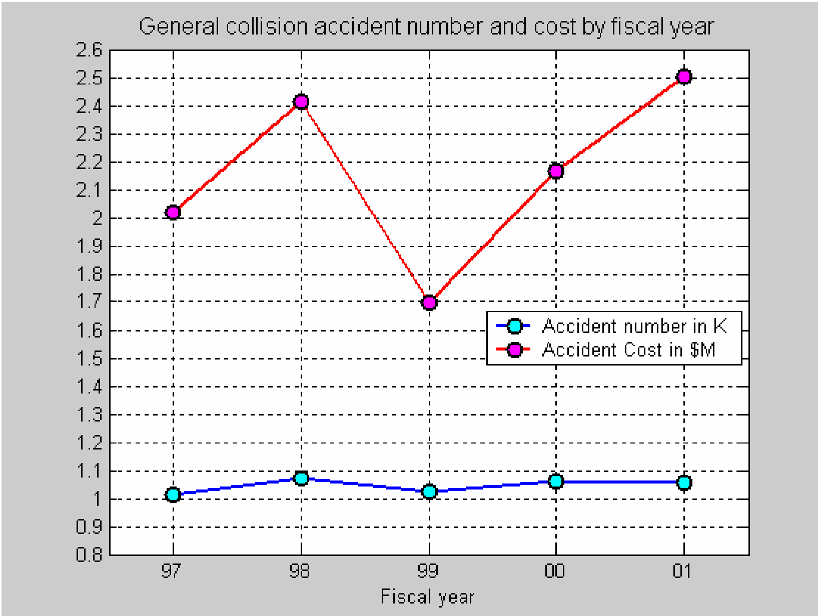

Fig. 19 35-transit agencies: General collisions by fiscal year

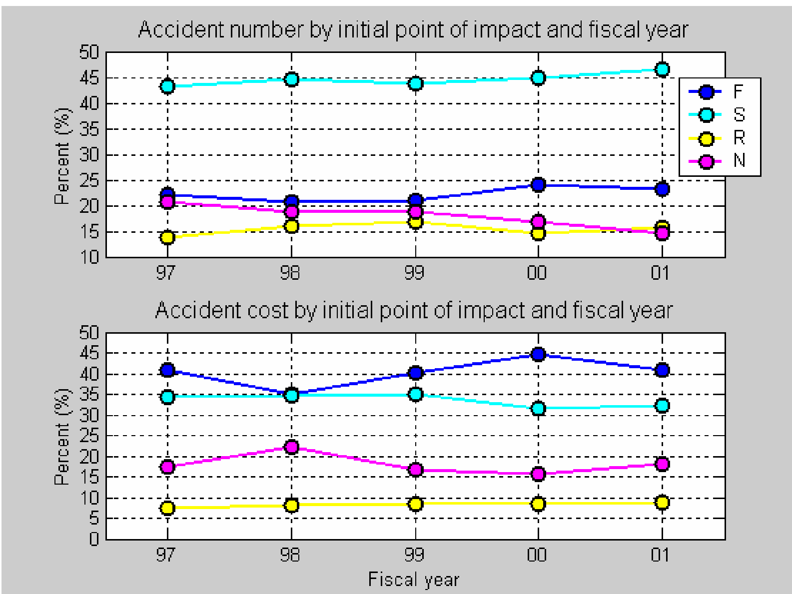

Fig. 20 35-transit agencies: General collisions by fiscal year and initial point of impact

1.2.2.3 General collision accidents by collision object

Collision objects are categorized into three groups: vehicle, pedestrian, and stationary object. Most collision accidents are vehicle collision accidents (91.2% of claims and 86.3% of costs). There are only a few pedestrian collision accidents (3.5% of claims), but they are the most costly. On average, each pedestrian collision cost $5,583 versus a per vehicle collision cost of $1,956. The results are shown in Figure 21. The ranking of collision objects, from most costly to least, is pedestrian, vehicle, and finally stationary object.

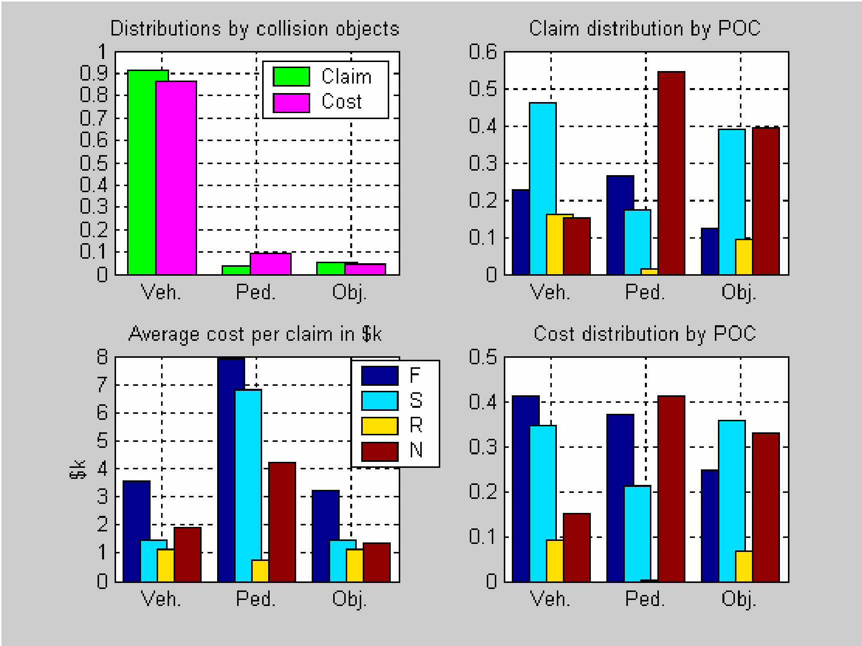

Fig. 21 35-transit agencies: General collision accident costs by collision object

1.2.2.4 Vehicle collision accidents by accident scenario

Ninety percent of collision accidents involve a bus colliding with another vehicle. The following eight accident scenarios have been considered:

Table 6 List of accident scenarios

Accident scenario	Stands for
S1	Intersection accident
S2	Bus rear-ending another vehicle (frontal collision)
S3	Collision at bus rear, including bus backing up (rear collision)
S4	Bus hit a standing vehicle
S5	Sideswipe (side collision)
S6	(Other vehicle) Cut-in accident
S7	Loading zone accident
S8	Collision between two buses
S9	Other vehicle collision accident

Five accident scenarios: intersection collision (S1), bus rear-ending another vehicle (S2), bus hitting a standing vehicle (S4), sideswipe (S5), and collision between two buses (S8), account for 65.4% of claims and 74.4% of costs among all vehicle collision accidents. This is shown in Figure 22.

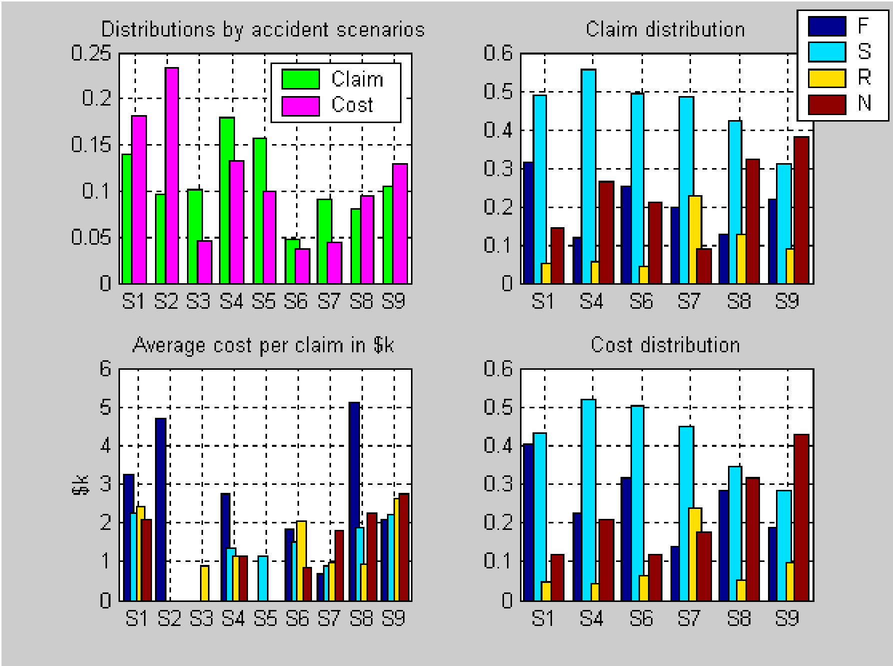

Fig. 22 35-transit agencies: General vehicle collision accident costs by accident scenario

Thirty-three percent of intersection accidents (S1) occurred while the bus was going straight (30% of costs), while 16% occurred while the bus was turning right (9% of costs) and 18% while the bus was turning left (28% of costs). The subset of accidents in which the bus was turning left and hit another vehicle (as opposed to being hit) made up 3.7% of claims and 16% of costs among all intersection accidents.

Thirty-seven percent of sideswipes (S5) occurred while the bus was passing another vehicle (41% of costs) and 45% occurred while another vehicle was passing a bus (37% of costs). Twelve percent of sideswipe accidents (18% of costs) occurred when a bus hit another vehicle while trying to turn a corner, confirming the fact that buses have a wide turning radius which often makes it difficult to avoid other vehicles.

Most standing vehicle accidents (S4) and cut-in accidents (S6) are side collisions. Twenty-two percent of loading zone accidents (S7) occurred while the bus was pulling out, accounting for 38% of costs, while 11% of claims and 13% of costs were the result of accidents while the bus was pulling into the loading zone. Two accident scenarios stand out from the others as sources of loading zone accidents: “bus pulling from zone and hitting a moving vehicle” (16% of claims and 30% of costs), and “bus pulling into zone and hitting a standing vehicle” (6% of claims and 10% of costs).

1.2.2.5 Top five vehicle collision scenarios by fiscal year

Considering accident frequency and cost, the top five collision scenarios involving a transit bus and another vehicle are, from the highest to lowest priority (severity), bus rear-ending another vehicle (S2), intersection collision (S1), collision between transit buses (S8), standing vehicle accident (S4), and sideswipe (S5).

Figure 23 shows the percentage of general vehicle collisions and general vehicle collision costs, by fiscal year, for all five accident scenarios. Figure 24 shows the same information broken out by scenario type.

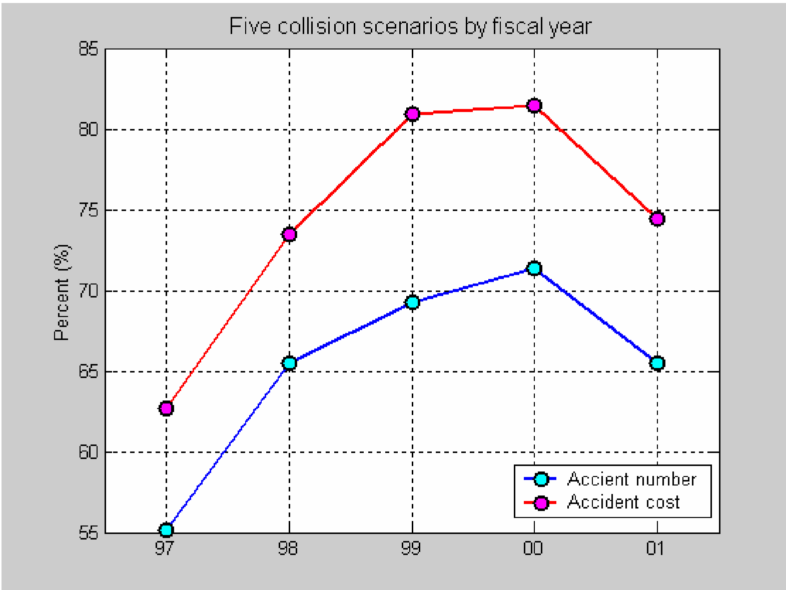

Fig. 23 35-transit agencies: Five collision scenarios by fiscal year

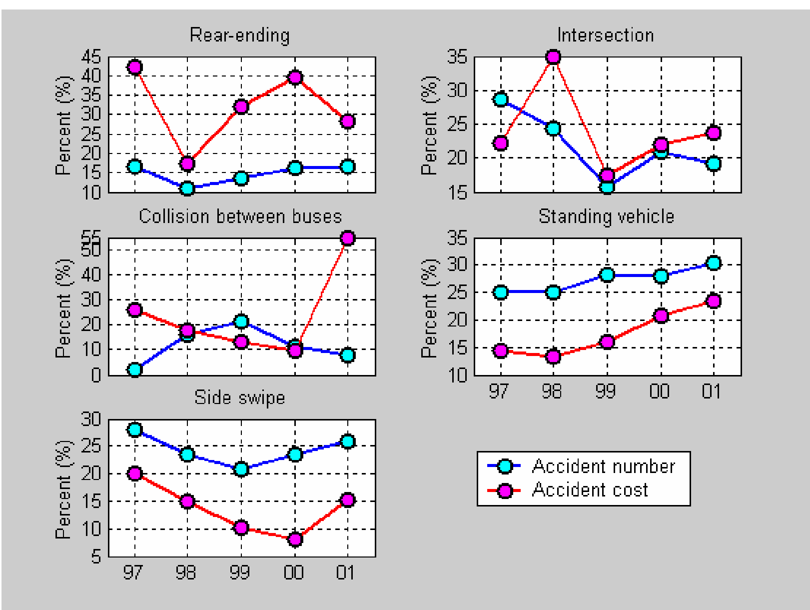

Fig. 24 35-transit agencies: Five collision scenarios

1.3 IN-DEPTH COST ANALYSIS OF PASSENGER INJURIES

For the 35 agencies, there are a total of 4,285 passenger injury accidents in 5 fiscal years with a total cost of $13,583,368, and they count for 44.7% in claim and 35.3% in cost among all accidents.

Two severities are defined for passenger injury accidents: severe for passenger injuries that cost more than $100,000; and general injury otherwise. Table 7 lists the 23 severe injuries in the five fiscal years.

Table 7 Severe passenger injuries for 35-transit agencies (5 years)

Claim	Loss Code	Cost	Accident Description
1	50	$125,017	Passenger fell on boarding
2	55	$179,512	Passenger fell on alighting
3	63	$110,196	Passenger fell due to abrupt stop
4	63	$274,079	Passenger fell due to abrupt stop
5	63	$168,105	Passenger fell due to abrupt stop
6	63	$134,281	Passenger fell due to abrupt stop
7	63	$230,531	Passenger fell due to abrupt stop
8	63	$151,000	Passenger fell due to abrupt stop
9	64	$104,965	Passenger fell on turning bus
10	65	$200,000	Passenger fell on going straight bus (walking)
11	67	$107,910	Passenger leaning out window, hit by sign
12	68	$177,175	Passenger fell, details unknown
13	68	$169,493	Passenger fell, details unknown
14	68	$427,500	Passenger fell, details unknown
15	74	$500,000	Passenger fell on running for bus
16	74	$134,494	Pedestrian fell on running for bus
17	78	$163,593	Details unknown
18	78	$164,158	Details unknown
19	78	$150,000	Details unknown
20	78	$107,500	Details unknown
21	88	$245,560	Bus vs. bicycle
22	66	$175,000	Wheelchair rolled backward on board
23	115	$165,000	Wheelchair rolled backward on board
Total		**$4,365,069**	

Two out of the twenty-three severe injuries happened at loading zones; most severe injuries occurred when passenger were on board. The scenario of “Passenger fell due to abrupt stop” stands out from the others, accounting for about 25% of both number and cost among all severe injuries.

Excluding the 23 severe injuries, the 35-transit agencies had about 900 passenger injuries and spent about $1.8 million each year. This is shown in Figure 25.

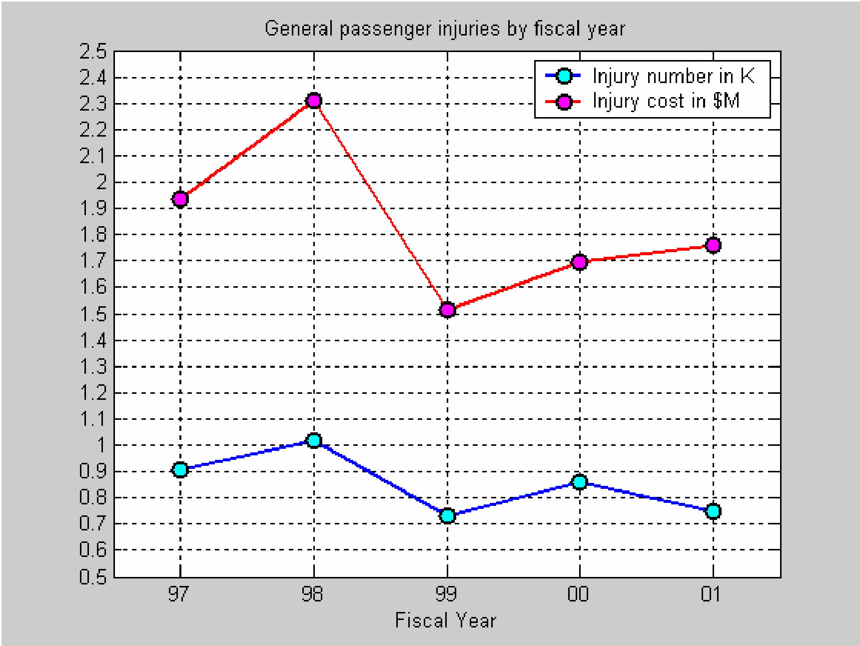

Fig. 25 35-transit agencies: General passenger injuries by fiscal year

The following eight maneuvers prior to an accident have been considered for general passenger injuries (excluding the 23 severe accidents)

Table 8 Maneuver types prior to an accident

Bus maneuver	Stand for
M1	Passenger boarding
M2	Passenger alighting
M3	Bus starting
M4	Bus stopping
M5	Bus turning
M6	Bus going straight
M7	Bus moving (others)
M8	Others

About thirty percent of general passenger injuries occurred at loading zones (boarding and alighting), which also accounted for 27.4% of costs. Twenty percent of passenger injuries occurred as a bus was stopping. This type of passenger injury has the highest severity, as it is shown in Figure 26.

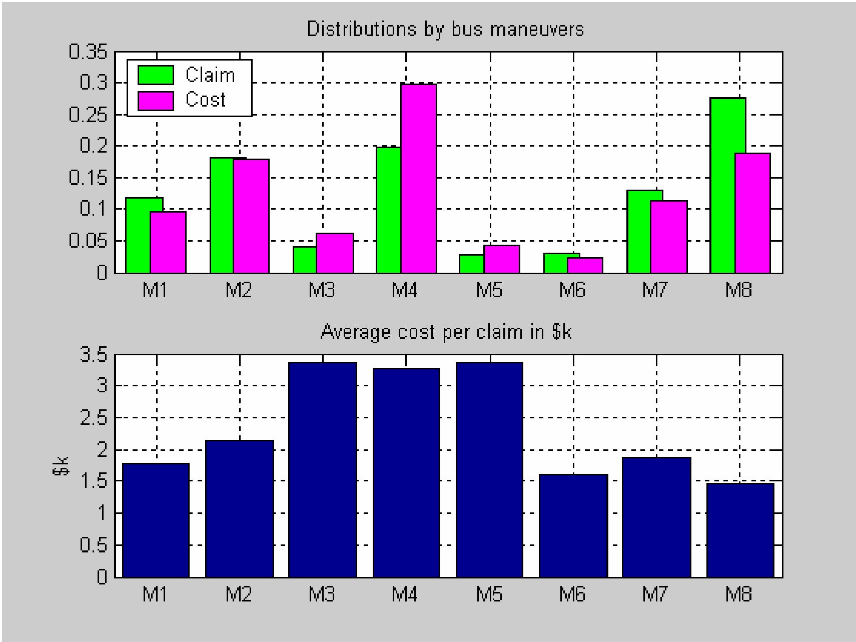

Fig. 26 35-transit agencies: Passenger injuries by bus maneuver

During the five fiscal years, there is a steady increase in the percentage of passenger injuries on stopping buses (M4) among all general injuries. This is shown in Figure 27.

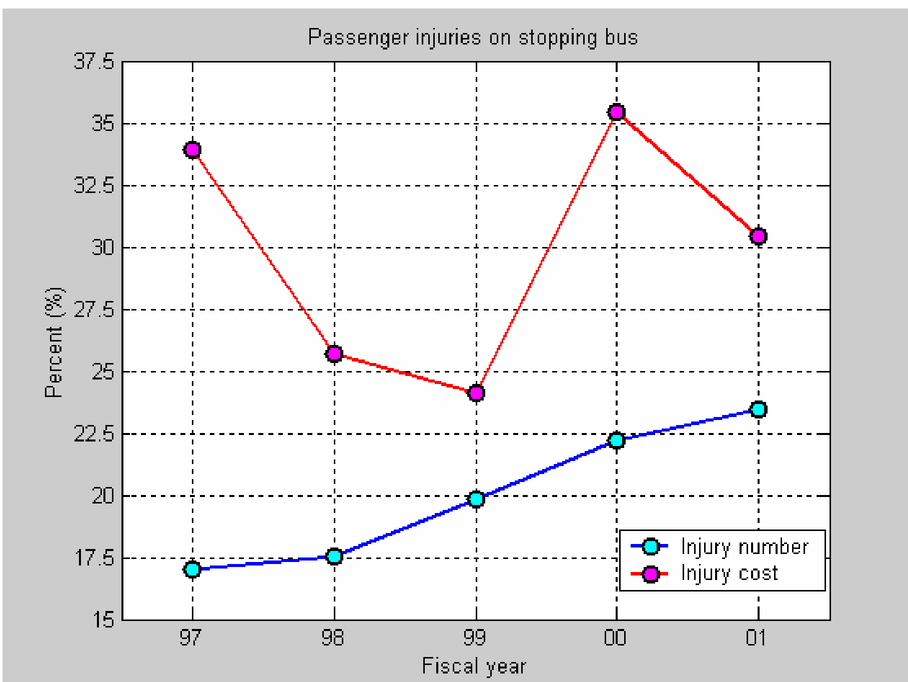

Fig. 27 35-transit agencies: Passenger injuries on stopping bus among all general injuries

1.4 SYSTEM IMPACTS

As transportation transitions into the information age with the integration of advanced and information technologies, there is a need to examine the potential impacts of new technologies such as FCWS. The focus of this task is to look at the relationship between frontal (and other) collisions and the corresponding effect(s) at both micro and macro levels. At the macro-level, how can a FCWS make a bus a safer vehicle? And at a system level, how does widespread use of FCWS or other similar technology affect the system? What are the impacts as measured by the costs resulting from death and injury and the costs from increased congestion?

Each of the core participants as well as the associate partners involved with this project has different motivations for participation. As the owner and operator of the state highway system, Caltrans is interested primarily in how vehicle-based systems will affect mobility, transportation operations, and the environment (e.g., the regional and state transportation systems). SamTrans, meanwhile, as a transit property has a greater interest in how Advanced Vehicle Control and Safety Systems (AVCSS) might improve their operations by increasing bus safety and decreasing operating costs.

The original objective of system impact task was to conduct an analysis on the potential benefit of frontal collision avoidance devices (micro) and the impact of frontal collisions involving transit buses on regional traffic systems (macro). The impact estimates were to include (a) the loss of operation time of individual buses, (b) the loss of revenue, (c) the increase of operational costs due to collisions, and (d) the interruption of traffic flow and resulting congestion.

Because of the lack of data it was not possible to connect individual accidents to changes in congestion or specific accident related costs, therefore the scope of this task had to be modified to utilize specific accident data along with aggregate state or national data on the cost of accidents and congestion. The potential impacts were categorized into two areas: cost of accidents in terms or fatalities, injuries and property damage and the impact of congestion on society including pollution, energy, health, and personal costs.

Traffic congestion can be divided into two types: recurring and non-recurring. Recurring congestion is predictable and results when the demand for transportation facilities exceeds the supply (i.e., morning and evening commutes). Non-recurring congestion is traffic slowing down as a result of accidents, stalled cars, debris, or driver distracting events adjacent to the highway (such as fires, construction, etc.). It is non-recurring congestion that is of concern in this project. Estimates as to the percentage of congestion stemming from recurring versus non-recurring causes varies between 40% and 60% and 60% and 40% respectively.

The benefit estimates will be derived from the impact analysis outlined above as well as the potential reduction of property damage, personal injury, and liability claims. This analysis will provide a foundation for the eventual cost-benefit evaluation of collision warning devices later in this project.

The benefit estimates were derived using the above mentioned baseline data. At a later date, a similar analysis with data from collision warning devices on the local transit buses shall be performed correlating the data with the baseline data.

1.4.1 Data Source

Data came from several sources:

(a) Accident data

Accident data for this analysis was obtained from the California Highway Patrol/Caltrans' Traffic Accident Surveillance and Analysis System (TASAS) [8]. The data includes location, type of accident, type of vehicle(s) involved, time-of-day, weather conditions, pavement conditions, etc.

(b) Congestion or traffic volume data

Congestion or Traffic Volume Data was obtained from three sources:

1. Texas Transportation Institute's (TTI) 1999 Urban Mobility Study, [9]
2. Caltrans, the Traffic Volumes Computer Database, and the
3. Highway Congestion Monitoring Program [10] (HICOMP) Report.

(c) Costs associated with accidents and congestion

The costs associated with accidents and congestion came from a number of sources including: TTI's Urban Mobility Study [9], The National Resources Defense Council/ Resource Futures International sponsored study "The Price of Mobility: Uncovering the Hidden Costs of Transportation," The National Public Research Institute's report Highway Crash Costs in the U.S. by Drive Age, Victim Age, Blood Alcohol Level, and Restraint Use [11], and a number of other U.S. government-sponsored reports and documents.

1.4.2 Analysis Approaches

There were three primary activities as part of this task: (1) a review of current literature; (2) a search for pertinent accident, congestion, and cost data; and (3) an analysis of these data.

TASAS Data was downloaded from Caltrans' mainframe computer system, and converted to worksheet and relational database format for subsequent analysis. Bus accident data versus time-of-day (by hour) was analyzed at three levels: statewide, for the San Francisco Bay Area, and for SR 82 in San Mateo County.

Cost estimates for fatalities, injuries, and property damage were obtained through the literature. The cost of bus accidents for California, the San Francisco Bay Area, and State Route 82 in San Mateo County was then calculated.

1.4.3 Results

(a) Cost of accidents

The cost of accidents, taken from the literature, used a comprehensive cost method known as "Willingness to Pay" to calculate the monetary value of fatalities, injuries, and property damage. While there are other methods used to determine costs associated with accidents, these values were used because they have an acceptance level within Caltrans [12] and within the broader highway transportation community including FHWA and National Safety Council advisory groups.

The comprehensive cost method includes seven cost factor areas: medical, work loss (victim), public services, employer costs, travel delay, property damage, and quality of life. The first six of these categories are self evident (i.e., public services - costs incurred by police, EMT, fire, towing, etc; property damage - costs to repair or replace vehicle or objects struck by vehicles; etc.). The seventh category Quality of Life, however, puts a value to the quality of life by quantifying pain, suffering, and quality of life for a family. The value is computed from the amount people routinely spend in dollars or time to reduce their or a family member's risk of death or injury. The amount people spend is calculated from what is commonly spent on items such as automobile air-bags, anti-lock brakes, and hazard pay for higher risk jobs.

Table 9 Accident costs 1997 dollars in California comprehensive cost method

Area	Fatality	Injury	PDO/vehicle
Rural	$3,123,603	$45,802	$2,058
Suburban	$3,123,603	$39,745	$2,058
Urban	$3,123,603	$33,688	$2,058
Average	$3,123,603	$39,745	$2,058

(b) Accidents involving buses

The number of accidents involving buses and the associated fatalities and injuries on California-owned highways was determined from the TASAS database [8]. Further investigation needs to be done in order to separate out school buses from other buses, although, informal observation indicates that the percentage of accidents involving school buses is relatively small. It also may be possible to determine what vehicle is the hitter and which was hit. This particular analysis would also go a long way toward determining the percentage of frontal collisions versus other types of collisions. The following table shows the breakdown of accidents involving buses on the state highway system.

Table 10 Accidents Involving Buses on California State Highways 1996–1998

California's Traffic Accident Surveillance and Analysis System (TASAS)[8]

Region	# of Accidents	Fatalities	Injuries
Statewide	2914	24	1066
Caltrans District 4 (S.F. Bay Area)	858	4	243
State Route 82 (In San Mateo Co.)	66	1	15

(c) Cost of accidents involving buses

The cost of accidents involving buses was calculated from the previous two tables and is shown in the following table. The numbers indicate the potential benefit that would be gained by eliminating these accidents. Property damage is calculated assuming damage to two vehicles per accident.

Table 11 Cost Estimates of Accidents Involving Buses 1996–1998

(California State Highways Only)

Region	$ of Fatalities	$ of Injuries	$ of PDO	Total
Statewide	$75M	$36M	$12.M	$123M
CT District 4 (S.F. Bay Area)	$12M	$8.2M	$3.5M	$24M
State Route 82 (In San Mateo Co.)	$3.1M	$0.51M	$0.27M	$3.9M

(d) Accidents and congestion

There was a rough proportionality between the number of accidents involving buses and traffic volumes (i.e. morning and evening commutes) in that there more bus accidents occur in higher traffic volumes. While it is obvious that accidents impact traffic flow by reducing the capacity of the highway, it is not apparent whether congested traffic conditions cause more accidents because they are more hazardous (i.e., speed differentials created by alternating free-flowing and stop-and-go traffic flow) or if the increases are simply due to the fact that there are more vehicles on the road. Many different methods have been used over the years to estimate the cost of congestion.

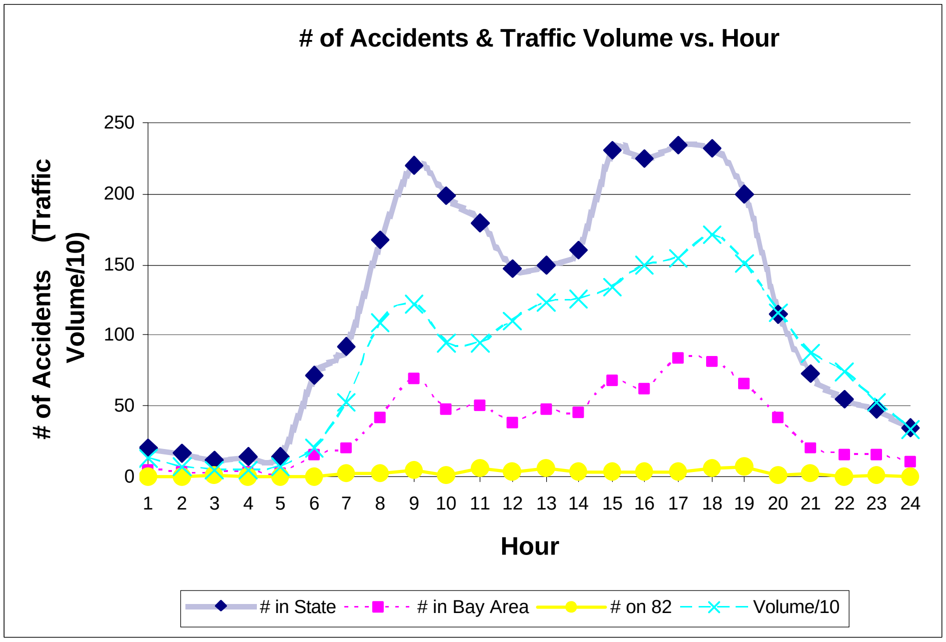

Fig. 28 Number of accidents and traffic volume vs. hour

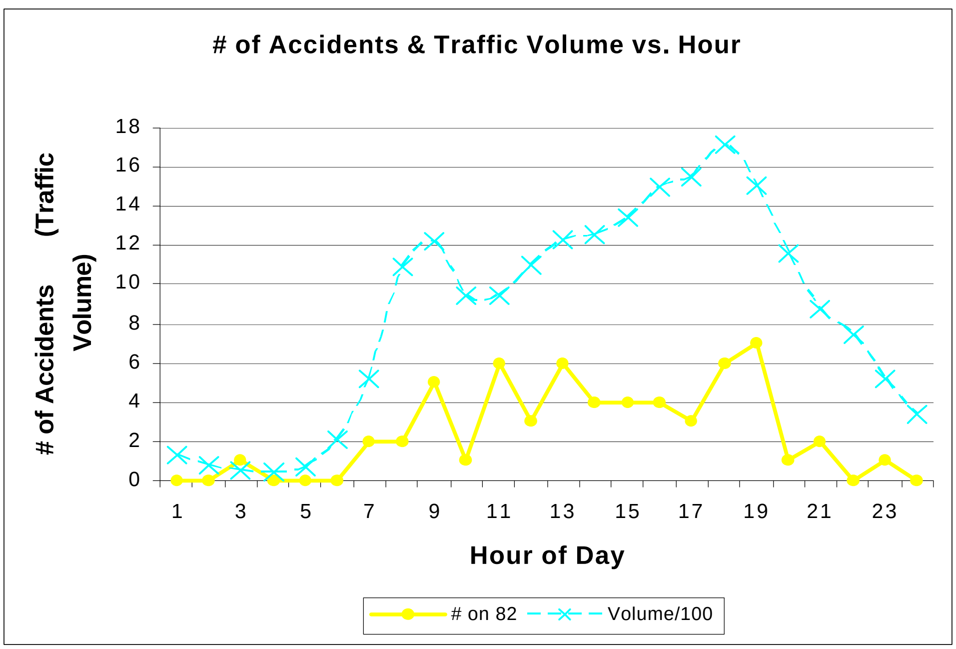

Fig. 29 Number of accidents and traffic volume vs. hour

Dealing with lack of data is perhaps the greatest difficulty when trying to perform this type of analysis. In addition to the fact that congestion data is generally aggregate and averaged over days or weeks or months, accident data, whether it be the physical data surrounding the accident or the subsequent medical and legal costs, are considered very sensitive and therefore difficult to obtain. Additionally, each agency has a different system for collecting and archiving safety data, varying from paper records to archaic computer databases to modern database systems. Also, congestion data was available only for California highways, whereas, most transit agencies operate their vehicles on local streets and roads. This data was generalized data that was averaged out over weekly or monthly periods so there was no way to correlate what effects specific accidents had on traffic flow.

Regardless of the perspective of the person looking at accident statistics, it is apparent that accidents, especially those leading to death or injury, are very expensive. Also, they get more expensive, at least in terms of dollars, as one transitions from the individual to the transit agency to the insurance company to state and federal governments and to society at large. Although the transit industry has the safest drivers when compared to commercial vehicle operators and the driving public, the costs of bus related accidents warrants the investigation and development of devices or systems to mitigate crashes, which is over one million dollars per year on only one state route in San Mateo County.

Because of the uncertainty in quantifying the costs related to accidents (i.e., congestion, air pollution, pain and suffering, public relations, etc.) it is important to consider measures other than dollars when deciding on whether to research, develop and eventually deploy collision warning and collision avoidance systems.

Baseline statistics proposed as benchmarks in measuring the effectiveness of projects in these areas should include, but not be limited to: frequency and severity of accidents, injuries and fatalities, vehicle role, corrective action, movement prior to critical event, critical event, and damage costs. An effective benchmark would be a reduction in critical factors: overall incidents, injuries/fatalities, and costs.

1.5 OBSERVATION AND CONCLUSIONS

This transit accident and cost analysis was conducted using actual accident data from 35 transit agencies in California for the most recent five fiscal years. These agencies operate buses in a wide range of regions and operating environments, including one of the most congested areas in the United States, the San Francisco Bay Area. We have confirmed that accident claim and cost distributions vary from agency to agency due primarily to the fact that every agency has its own driver training program and a different operating environment. We have also shown that the accident and cost distributions by loss code and the initial point of impact are very consistent between transit agencies.

The statistics obtained are consistent with the national bus accident statistics:

- 0.6% of collision accidents involved serious casualties of which 54.8% were frontal collisions and 22.6% were side collisions. NHTSA[5] reports 0.6% fatality, of which 68.4% were frontal and 16.8% were on the side for bus collision accidents (school, intercity and transit).

- 91.2% of collision accidents involved another motor vehicle, 5.3% involved an object, and 3.5% involved pedestrians. NHTSA[5] reported 83.5% of accidents with a vehicle and 16.2% with an object.
- Excluding not-known initial point of impact collisions, 27.1% of collision accidents are frontal collisions, 54.3% are side and 18.6% are rear collisions while NHTSA [5] reported 28.2% front, 47.6% side and 22.9% rear.

The cost benefit analysis confirmed the recommendation by transit IVI Committee on the need for IVI technologies:

- Excluding the costs for serious casualties and not-known point of impact collisions, 49% of collision costs are for frontal collisions, 41% are for side, and 10% are for rear collisions. These numbers may be significantly reduced by frontal/forward, side and rear warnings.
- Passenger injuries (not collision related) account for one third of all accident costs. Passengers injured due to the bus coming to an abrupt stop have the highest priority both in frequency and severity (19.8% of claims and 28.1% of costs). This type of accident may be avoided with smoother operation from FCWS.
- 56% of passenger injury costs are related to moving buses, while 21% are from boarding and alighting. Those numbers may be significantly reduced with Lane assist/precision docking.

This analysis also shows the specific needs for IVI technologies:

- Bus backing accidents are not a critical scenario for the 35 agencies.
- Forty-four percent of serious casualty costs are for pedestrian accidents, which also account for 15% of all accident costs. This shows the critical need for pedestrian detection and avoidance service.
- Considering accident frequency and cost, the top five collision scenarios involving a transit bus and another vehicle are, from the highest to lowest priority (severity): bus rear-ending another vehicle, intersection collision, collision between transit buses, standing vehicle accident, and sideswipe. These five accident scenarios account for 65.4% of claims and 74.4% of costs among all general vehicle collision accidents (excluding serious casualties).

Several observations can be concluded from the review of numerous accident reports in the course of this study:

- The speed of buses prior to the accident occurrence was generally modest as recorded in the incident reports, for example below 30 mph. This is due to the fact that the transit buses operate on suburban corridors, local streets, and among transit stations and typically they are not expected to run at high speeds for transportation purposes. For incidents near bus stops, traffic lights, or intersections, the speed can be considerably lower. Since the operating environment of transit buses covers a variety of local streets and corridors in urban and suburban environments, they generally see heavy traffic and frequently encounter street objects such as pedestrians, bicycles, and parked vehicles. It is essential to examine carefully the performance and capability of sensors under these circumstances. Thus, the first phase of data collection and the evaluation of sensing signals and noises will be extremely important.

- Among the reviewed accident reports, many incidents involved the bus making contact with a neighboring vehicle at the front corners at relatively low speeds. This may happen when the bus is pulling out from a stop or turning at an intersection, or an adjacent vehicle is moving aggressively ahead of the bus. The incident may be classified as a frontal or a side impact in reports. This implies that the implementation of corner sensors may be essential to alert the drivers of such obstacle presence. The corner sensors can also be useful for detecting cut-in vehicles.
- The operating speed of buses on local streets, near traffic lights, or bus stops is low and the distance to other vehicles or obstacles are short. Under these operating circumstances, it may be challenging to provide a warning signal that is timely yet not frequent enough to distract the driver.
- In the selection process of warning signal types and driver-machine interface, it should be taken into consideration that transit bus drivers are working under heavy work loads.

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2 Field Data Analysis

The accident data provides a knowledge base for determining the type and frequencies of frontal collision accidents. As transit accident data relies on recall from the parties involved, the data may not accurately describe the cause and time sequence of events in enough detail to enable a detailed accident analysis. In order to better understand the bus operating environment and time sequence of events in potential accidents, the team determined that it was critical to collect field data so that bus accident scenarios can be constructed. Significant efforts were devoted to the development of a data acquisition system.

The objectives of the Data Acquisition System (DAS) are to: (1) help understand the environment that the Frontal Collision Warning Systems will operate in, (2) provide a basis for an analysis using a dynamic vehicle model to predict potential collision courses, (3) facilitate the development of the collision warning system, and (4) enable before-and-after data comparison to determine if there is any change in driving behavior with the introduction of the system. It is understood that the likelihood of the buses instrumented with the data acquisition system being involved in an accident is extremely small. However, the large amount of data collected on these buses will provide an accurate description of the relative movement of buses and the surrounding vehicles. In the absence of collisions, hazardous conditions that potentially can lead to accidents can be identified and driver reactions to these hazardous conditions can be analyzed. In-depth understanding of the bus operating environment and hazardous conditions through collection and analysis of field data is a critical portion in determining the specification of performance requirements for a transit bus FCWS.

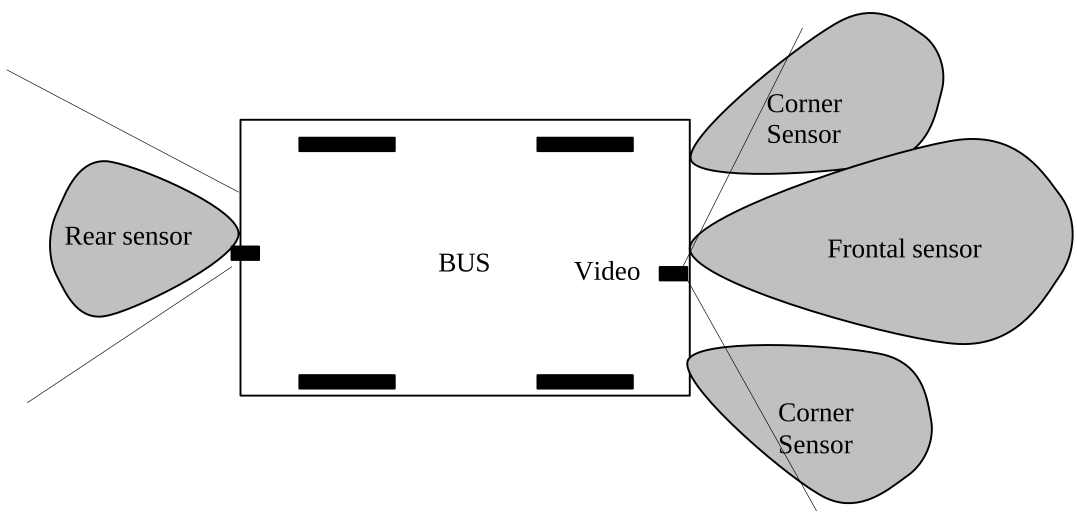


Fig. 30 Sensor arrangements of the Data Acquisition System

Based on the data acquisition needs, a sensor arrangement for the DAS is designed to include sensors to detect frontal and frontal corner obstacles and to monitor steering angle movement, brake and throttle motion, vehicle velocity and acceleration (Figure 31) provides the DAS configuration. Detail description of the development of data acquisition system can be found in Appendix V.

The hardware configuration of the DAS can also be used as the hardware platform of the FCWS. Minor changes in sensor layout and computer configurations may be required to do this. The data acquisition function and the collision warning function can both be implemented in software. They can run in parallel in a multi-task system. This means the DAS will be still running after the FCWS has been installed on the bus. This allows us to analyze driver adaptations by comparing the data collected before the FCWS is installed with the data after installation.

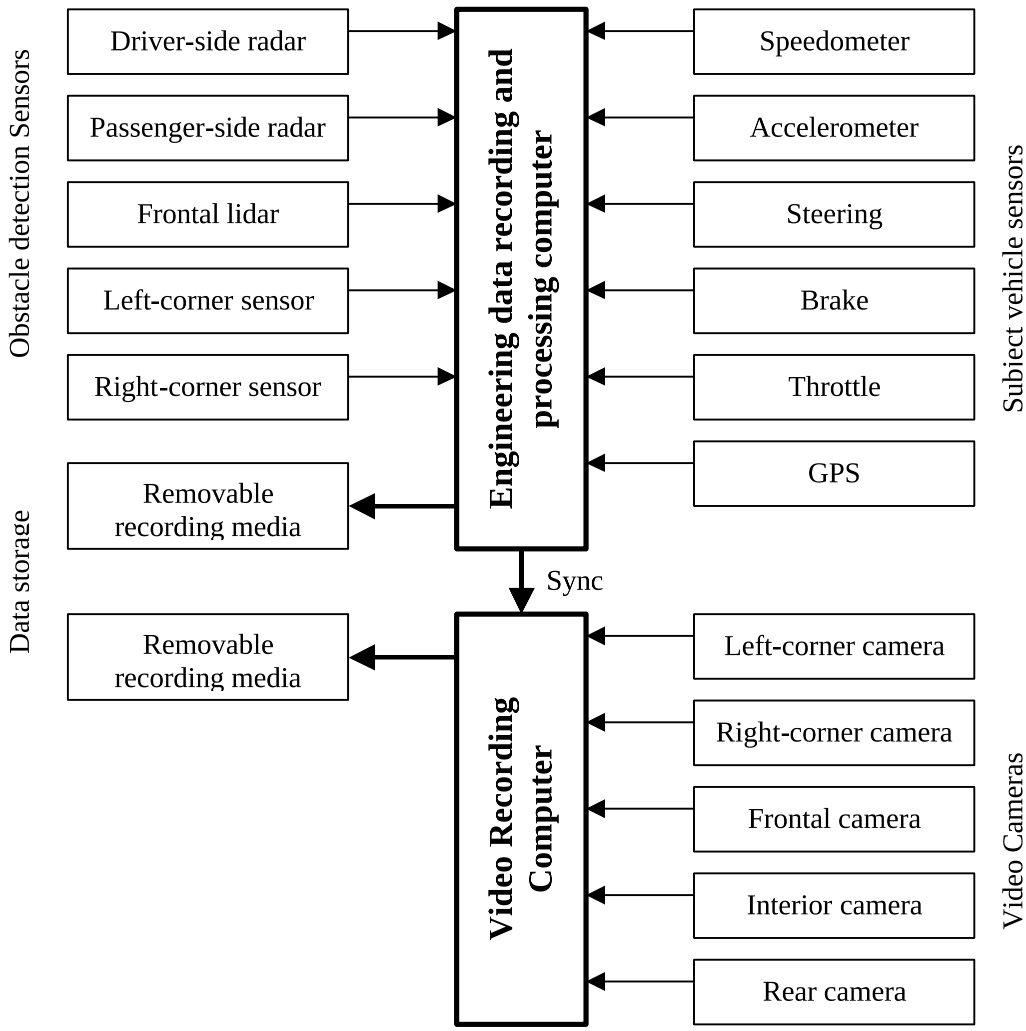


Fig. 31 Diagram of the data acquisition system

Using 3 buses instrumented with this data acquisition system, field data were collected since early 2001. The data was analyzed at three different levels: 1) manual review with the data playback tool which is a Windows™ program developed by PATH, 2) histogram analysis of specific parameters by simply counting the numbers of samples in the data, and 3) event-related histogram and clustering analysis by applying filtering algorithms to the data to detect events (e.g. braking onset) and estimate parameters. These approaches are discussed in detail in the following sections.

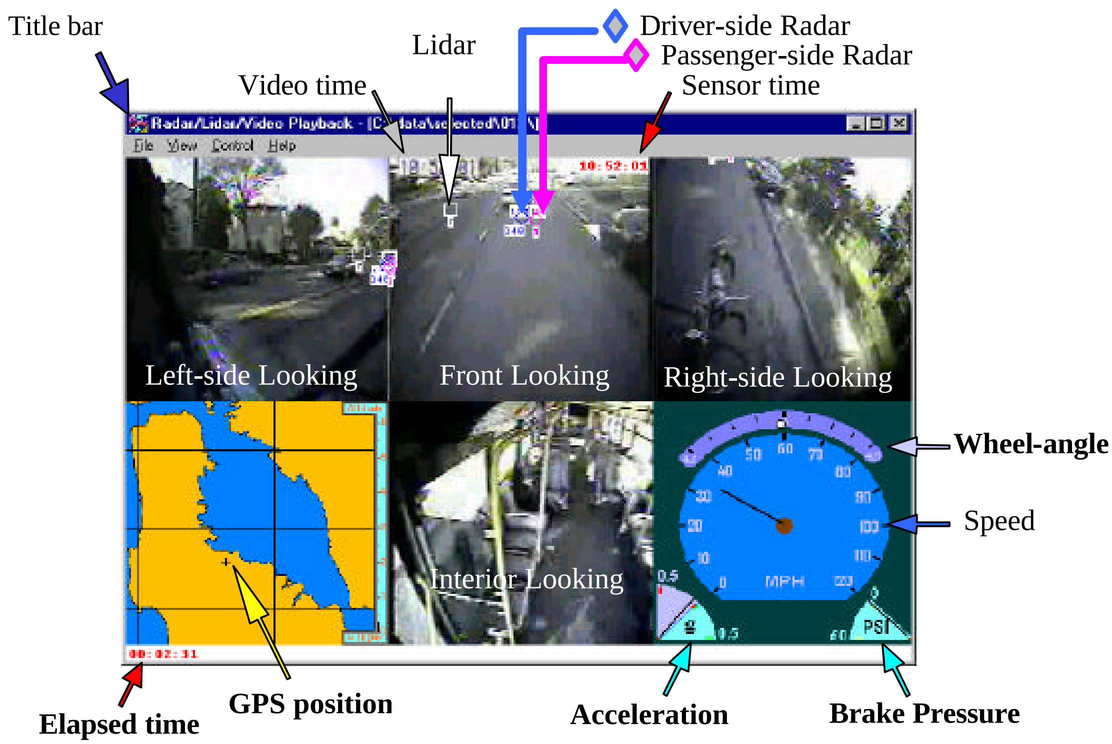


Fig. 32 Snapshot of the data playback tool window

To facilitate data analysis, PATH has developed a data playback tool, a program running in a Windows™ environment. The tool was developed in May 2000 and has been updated several times. The tool can decode and play back MPEG movies in Windows™. It displays bus states, such as speed, acceleration, brake pressure, front wheel angle and GPS location, simultaneously during video playback. It projects the radar and lidar targets into the video frames, using simple visual marks to indicate which objects in the frames have been detected by which radars or lidars. Fig. 32 is a snapshot of the data playback window. It can be seen that the display is divided into six sub-windows. Video from each camera is displayed in one sub-window. The GPS location and altitude are displayed in the lower left-hand sub-window. Other subject vehicle states, i.e. wheel angle, speed, acceleration and brake pressure, are displayed in the lower right-hand sub-window.

This tool provides the data reviewer a complete view of all the data collected at the same time. The tool provides the ability to understand sensor behavior, traffic scenarios, and the characteristics of targets. For example, the tool has been used to verify different sensor performance; see below for radar and liar information verified by the tool:

Micro-wave radar disadvantages

- Nearly stationary targets can not be detected;
- Target signal drops;
- Low azimuth accuracy.

Micro-wave radar advantages

- Working well in all weather;
- Accurate range;

Lidar disadvantages

- Saturation facing sun ;
- False alarms with rain, fog and grime on lens;
- Dependent range-rate estimate;
- More stationary roadside targets;
- Occasional target split.

Lidar advantages

- Able to detect stationary targets;
- Accurate two-dimensional position measurements;
- Large view angle;
- Fewer target drops.

The tool also provided a software platform to develop and test the warning algorithms.

2.1 ANALYSIS OF DATA SAMPLES

The field data used for this analysis was recorded on the first bus (SamTrans bus No.600) from August 1, 2000 thru April 16, 2001. There was 80 days of data. The bus was operated for average 7.5 hours a day. The experimental bus was on normal service in San Mateo County, California. The drivers who drove the bus were not specified or selected. The bus and the service routes were assigned to them by the dispatch center of SamTrans according to normal crew assignment schedules. 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 cities. Different weather conditions including rain, fog and wind, were encountered. The bus was usually put on service in the early morning before daybreak, until the late afternoon around sunset, with a few scheduled breaks. The 80-day data covers the representative drivers, routes, weather, time-of-day and level of traffic.

2.1.1 Approaches

For each parameter x, the possible distributed value region I was divided into n equidistant intervals I_i $(i = 0,1,...,n-1)$. The step size is $\Delta = I/n$. The data is scanned to accumulate the number of samples of x that fall into each interval. This is like generating histogram bins. Since the Data Acquisition System (DAS) has a fixed sampling rate, the number of samples in each bin, b_i, is proportional to the total time that x stays on the value interval. The following normalized parameter (B is the total samples of x):

$$p_i = \frac{b_i}{\mathrm{B} \cdot \Delta} \qquad i = 0,1,\ldots,n-1$$

is proportional to the total time that x stays on the value interval i. It has the property that:

$$\sum_{i=0}^{n-1} p_i \Delta = 1$$

$p_i \ (i = 0,1,\ldots,n-1)$ is the relative frequency distribution. It is not necessarily an approximation of a Probability Density Function (pdf) of x, because the adjacent samples may not be independent. However it still gives out the probability distribution characteristic of x.

The initial step size, $\Delta = I/n$, is small to preserve the resolution of the relative frequency distribution. In the case that the step size is too small to accumulate sufficient samples in the bins, a moving window average method was used to combine the bins. Assuming the size of the moving window is $(2N+1)\Delta$, the smoothed relative frequency distribution is defined by:

$$q_i = \frac{\sum_{j=i-N}^{i+N} p_j}{2N+1} \qquad i = 0,1,\ldots,n-1.$$

It is also true that:

$$\sum_{i=0}^{n-1} q_i \Delta = 1 \qquad i = 0,1,\ldots,n-1.$$

In practice, the moving window size is selected by trying different window sizes to smooth p_i.

2.1.2 Bus Speed

For bus speed, the value region $I = [0,40]$ m/s (1m/s = 2.25 mph) was divided into 2000 intervals with step size of $\Delta = 0.02$ m/s. It was found from the data that the minimum speed sensor measurement, except 0, is 0.55m/s, hence a bus stop/running threshold is set at 0.5m/s. Speed above/below this threshold indicates when the bus is moving/stopped.

When the bus is running, the minimum speed measurement is 0.55m/s, and the maximum measurement is 31.3m/s. The maximum speed occurred in the case that a bus was running at highway speed. There are in total 20,890,161 samples. The estimated relative frequency distribution of bus speed, $p(v)$, is shown in Fig. 33 in red with dashed line.

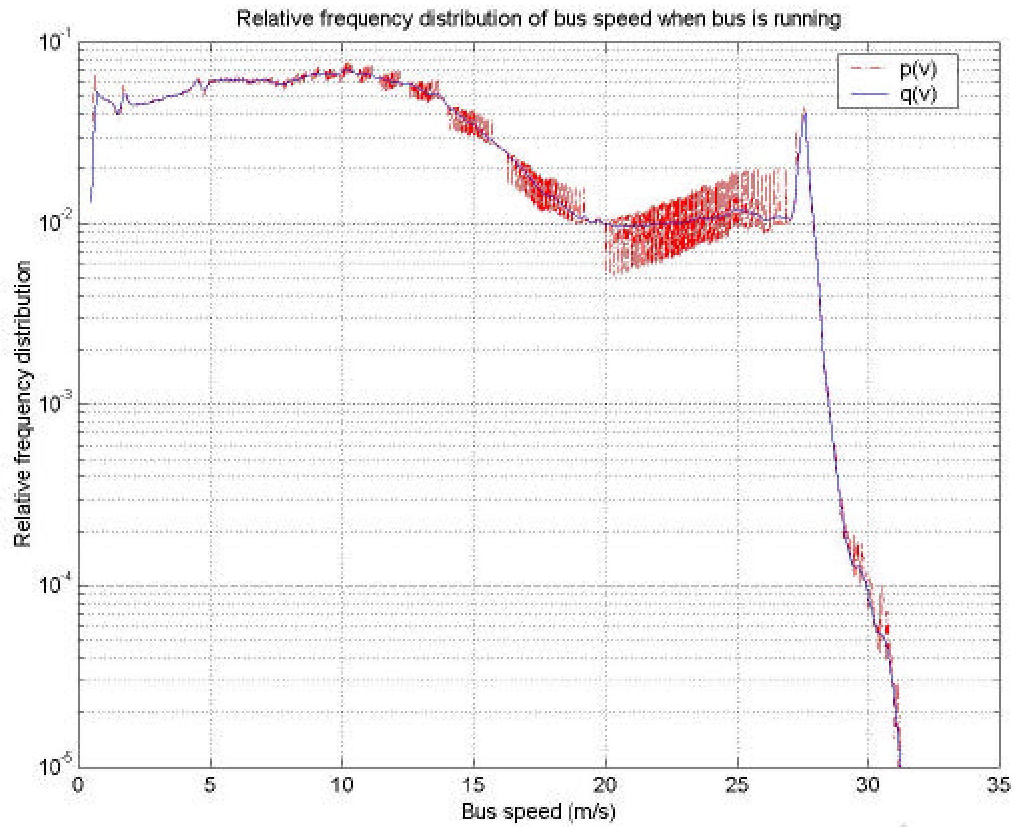


Fig. 33 Relative frequency distribution of bus speed when bus is moving

As we can see, the plot of $p(v)$ is quite noisy. To smooth the plot and keep the peak at 27.5m/s, two different window sizes were used. One window with $N = 2$ was applied on the intervals within $[27,28]$ m/s, and the other window with $N = 5$ was applied to everything else. The smoothed relative frequency distribution $q(v)$ is shown in Fig. 33 with a blue solid line.

As can be seen from Fig. 34, the bus mostly travels in four main speed ranges, 8~12m/s, .55~5m/s, 5~8m/s and 12~15m/s.

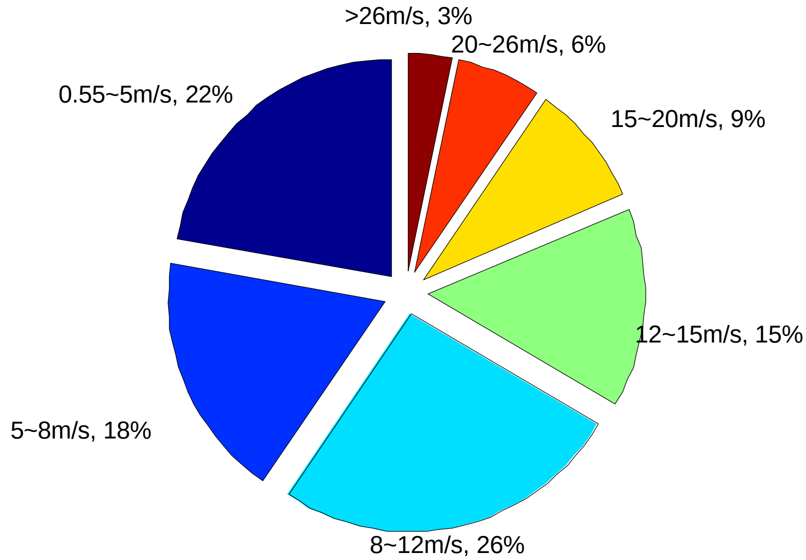


Fig. 34 Percentage of time for bus speed

2.1.3 Bus Acceleration

For bus acceleration, the value region $I = [-1,1]g$ ($g = 9.8\text{m/s}^2$) was divided into 133 intervals with step size $\Delta = 0.015g$. It was found from the field data that the maximum acceleration value is 0.523g, and the minimum acceleration value is –0.692g (deceleration).

The relative frequency distribution of bus acceleration $p(a)$ is shown in Fig. 35 (in total 20,890,161 samples). Since the plot is pretty clean, no moving widow was applied to it. The highest peak locates at –0.01g. In the positive half, there is another peak at 0.028g. Although the maximum decelerating and accelerating found in the field data are quite large, there is a very limited likelihood that bus has acceleration values below $-0.4g$ ($< 2e^{-3}\%$) in slowing down or greater than $0.4g$ ($< 2e^{-4}\%$) in speeding up. As shown in Fig. 36, the bus has a higher probability with acceleration valued from $-0.1g$ to $0.g$ for decelerating and valued from $0.g$ to $0.12g$ for accelerating. Fig. 36 shows the percentage of time that the bus is operated with different acceleration levels. The percentage of time that the bus acceleration is greater than $0.2g$ is 0.2%, this is not displayed in the pie chart.

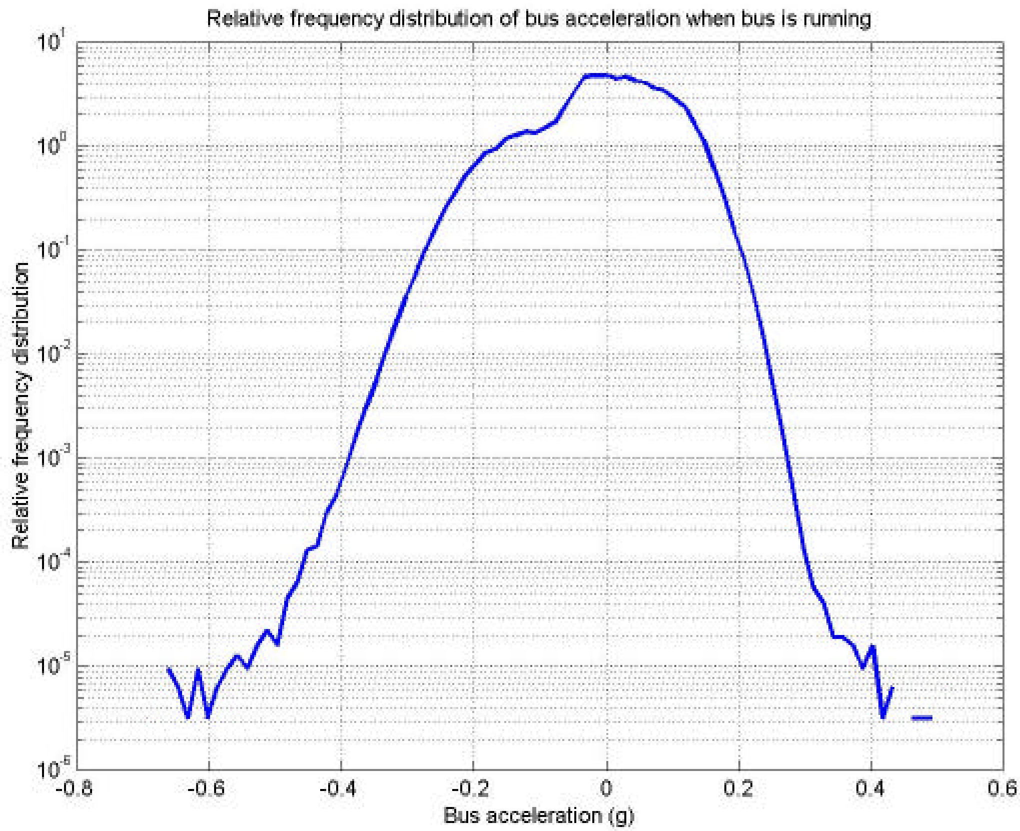


Fig. 35 Relative frequency distribution of bus acceleration when bus is moving

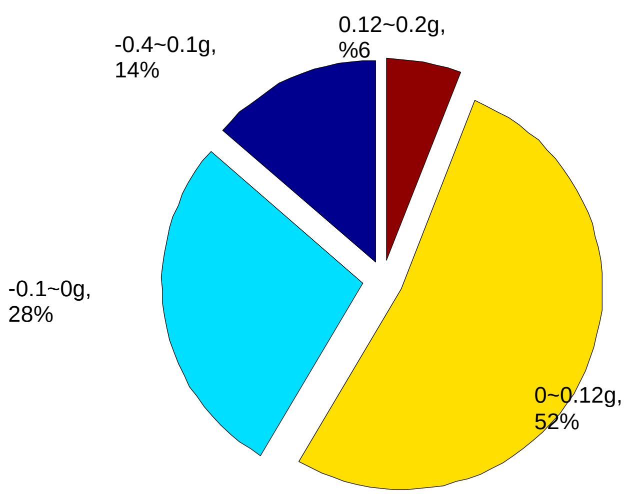


Fig. 36 Percentage of time for bus acceleration

The total time spent speeding up is longer than spent slowing down (58%:42%). 67% of deceleration occurs within -0.1~0.0 g, while 90% of acceleration occurs within 0~0.12g.

2.1.4 Brake Pressure

For brake pressure, the value region $I = [0,100]$ psi was divided into 1,000 intervals with step size $\Delta = 0.1$ psi. When the bus is stopped, bus drivers sometimes step on the brake harder. This would affect the overall statistics of brake pressure. Hence, only the data from when the bus is moving was considered. There are a total of 20,890,161 samples. It was determined from the field data that 1.3 psi is an appropriate threshold to separate brake-on samples from no-brake data. Fig. 37 shows the percentage of time for brake-on vs. no-brake when the bus is moving.

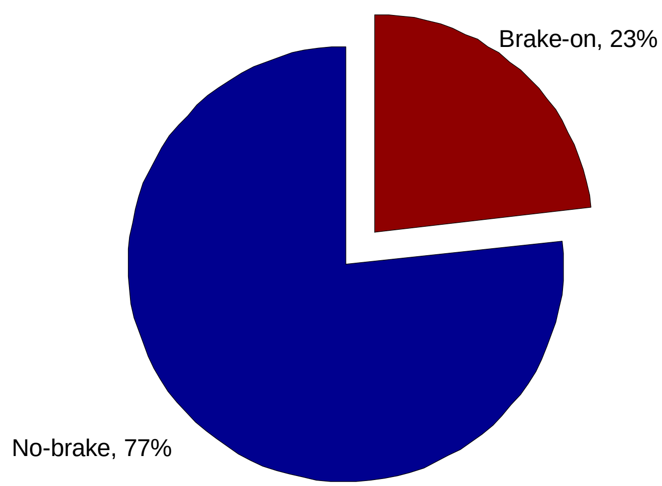


Fig. 37 Percentage of time for no-brake vs. brake

The maximum brake pressure in field data when the bus is moving is 81.7 psi, in this case the driver braked in an emergency to avoid hitting a child and a dog that had suddenly run across the street. Fig. 38 shows the relative frequency distribution of brake pressure $p(press)$ (when brake is on) in red with dashed line. A moving window with $N = 10$ was applied, the smoothed $q(press)$ is displayed with a blue solid line.

The highest peak is at 9 psi. When the brake is on the most commonly occurring frequency of brake pressure is 6 to 12 psi. Fig. 39 shows the percentage of time for brake pressure in different levels. It should be noted that brake pressure is above 50 psi less that 0.2% of time.

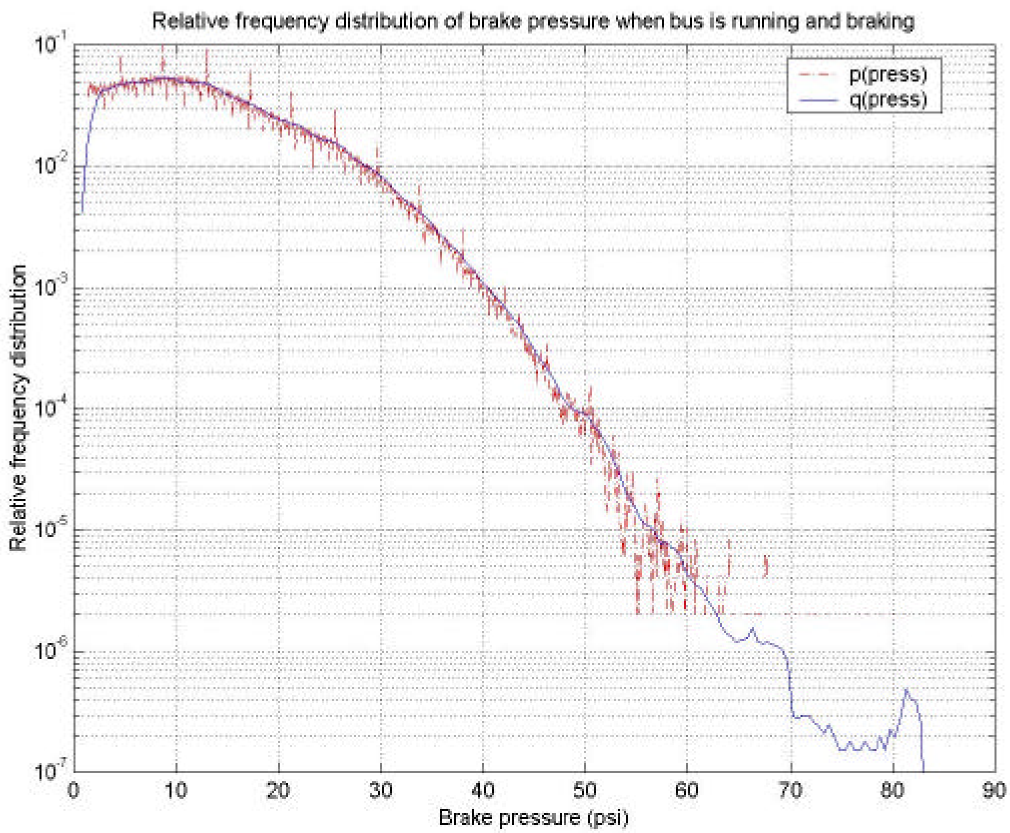


Fig. 38 Relative frequency distribution of brake pressure

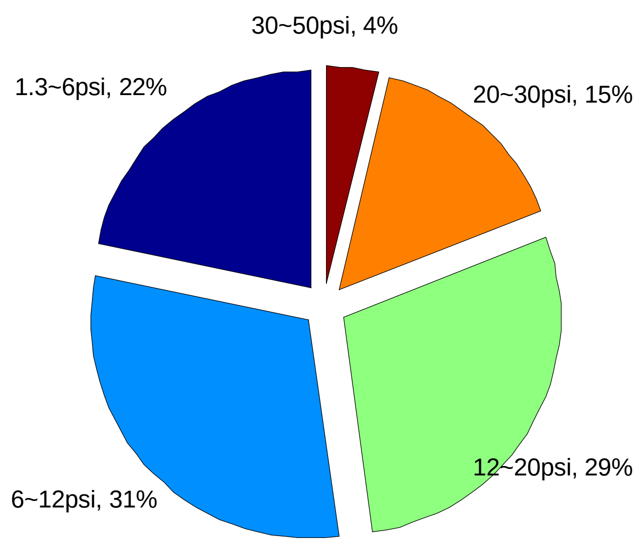


Fig. 39 Percentage of time for brake with different pressure levels

2.1.5 Front Wheel Angle

For front wheel angle, the value region $I = [-60,60]$ deg was divided into 800 intervals with step size $\Delta = 0.15$ deg. When the bus is stopped, bus drivers sometimes hold the steering wheel at certain non-zero angles. This would affect the overall statistics of wheel angle. Hence, only the data when the bus is moving (speed > 0.5m/s) was considered. In field data, the maximum front wheel angle is 45.5 deg to the right and 50.1 deg to the left.

The relative frequency distribution of front wheel angle, $p(angle)$, is shown in Fig 40 with a red dashed line. Left is positive and right is negative. To smooth the plot and to maintain the peak at 0 degree, two moving windows were used. One window with $N = 1$ was applied to the region of –6~ +6 deg, and the other window with $N = 10$ was applied to everything else. The smoothed relative frequency distribution, $q(angle)$, is shown with a solid green line. The highest peak locates at 0 degrees, this indicates that most of time the bus is moving straight forward.

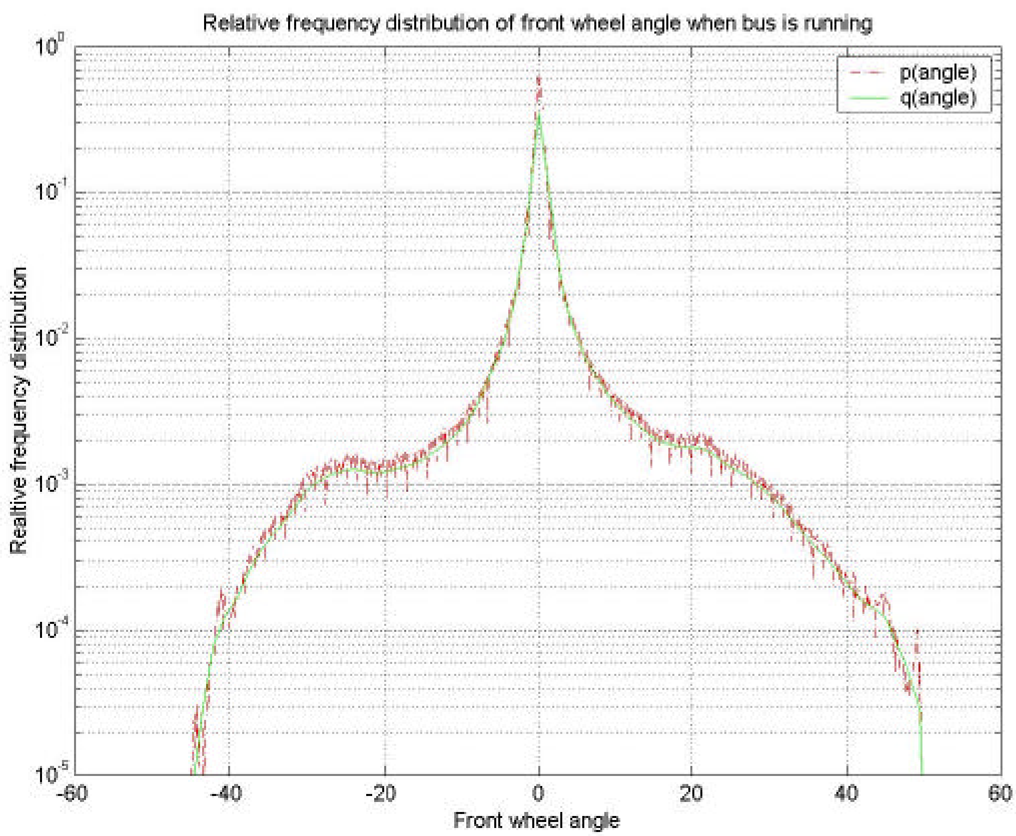


Fig. 40 Relative frequency distribution of front wheel angle (+left/-right)

2.1.6 Minimum Following Distance and Corresponding Closing Rate

Lidar can detect up to 8 targets simultaneously. Only those targets that are running in the same direction as the bus with 2-meter (about half a lane) or closer lateral distance to the bus center line were picked up. The minimum following distance is the minimum longitudinal distance from the bus frontal bumper to targets. The corresponding closing rate is the closing rate of the target at the minimum distance. Closing rate equals negative range rate. Positive closing rate means that the bus is approaching a forward target.

For minimum following distance, the value region $I = [0,200]$ m was divided into 2000 intervals with step size $\Delta = 0.1$ m. Again, only those samples from when the bus was moving were considered. There are in total 6,494,755 samples. The closest minimum following distance in the field data is 0.078m, which occurred in a case that bus was following a leading car in stop-and-go movement. The maximum value of minimum following distance found is 160.1m, which is the maximum range that the Lidars can detect.

The relative frequency distribution of minimum following distance, $p(r)$, is shown in Fig 41 with a red dashed line. A moving window with $N = 12$ was applied to it to smooth the plot. The smoothed relative frequency distribution, $q(r)$, is displayed with a blue solid line. The highest peak locates at 22m.

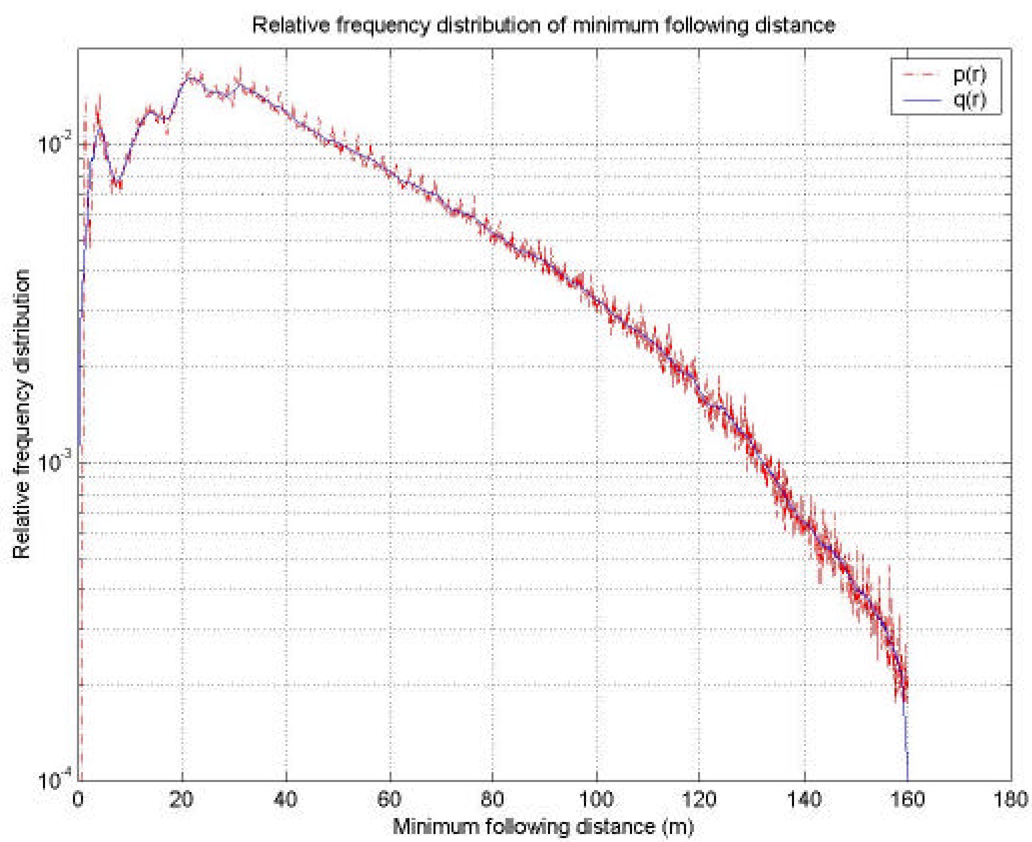


Fig. 41 Relative frequency distribution of minimum following distance

For the corresponding closing rate, the value region $I = [-100, 100]$ m/s was divided into 2,000 intervals with step size $\Delta = 0.1$ m/s. The maximum value of closing rate is 29.6m/s, when the bus was approaching a target. The minimum value of closing rate is –65m/s. This negative closing rate is doubtful because while it is possible it is very rare for a vehicle to move that fast. Furthermore, it is not clear in the video data if there is such a target. However, the Lidar did report such a target with a relative speed of 65m/s. Sensor noise, or other targets that are not in the camera's field of view might cause this. We are still not sure what caused this problem, and need to do further investigation.

The relative frequency distribution of closing rate, $p(rate)$, is shown in Fig 42 with a red dashed line. The highest peak locates at 0. There is another peak at 2.75m/s. It is also found that there is no data falling in the region of 1.45~2.45m/s. This is another issue that cannot be explained at this moment. Further investigation is needed.

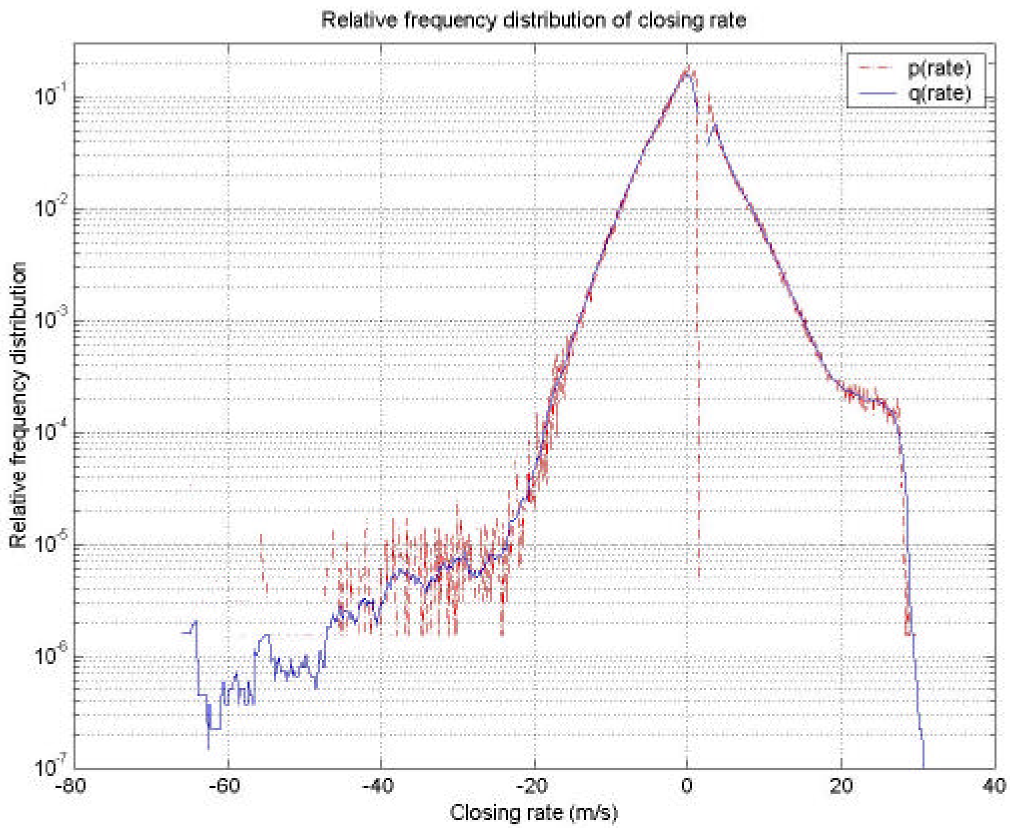


Fig. 42 Relative frequency distribution of closing rate

Two moving windows were used to smooth the plot. A window with $N = 0$ was applied to the region of 1.45~2.45m/s, and another window with $N = 10$ was applied to everything else. The smoothed relative frequency distribution is displayed with a blue solid line. Fig 43 shows the percentage of time for different closing rate levels. The percentage of time that closing rate is above 20m/s is 0.15%. The percentage of time that the closing rate is below –20m/s is 0.02%. Neither of these two closing rates are depicted in the pie chart.

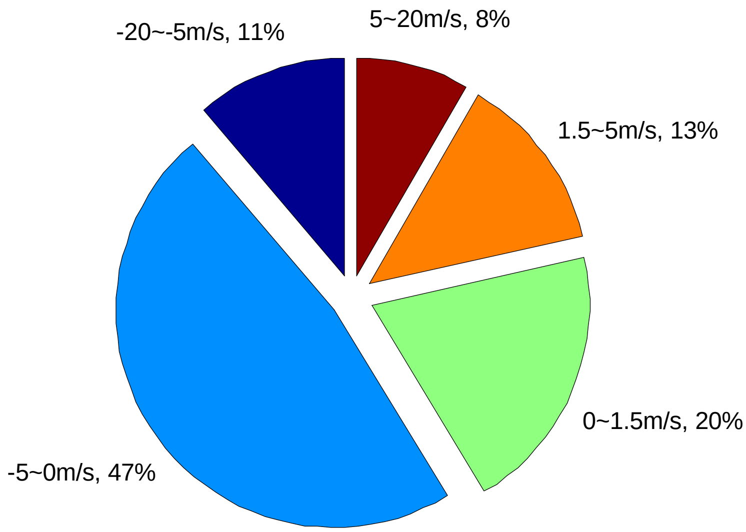


Fig. 43 Percentage of time for closing rate

2.2 BRAKING ONSET ANALYSIS

The data that is used in the braking onset analysis was collected from September 2000 to February 2001, 77 days of data were used. The experimental bus was on normal service in San Mateo County, California. The drivers who drove the bus were not specified or selected. The bus and the service routes were assigned to them by the dispatch center of SamTrans according to normal crew assignment schedules. The service routes 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 cities. Different weather conditions including rain, fog and wind, were encountered. The bus was usually put on service in the early morning before daybreak, until the late afternoon around sunset, with a few scheduled breaks. The 77-day data covers representative drivers, routes, weather, time-of-day and traffic.

2.2.1 Data Collection

The braking onset data is picked up from the 77-day data set. The lidar data, steering angle and bus speed are all processed with Kalman filtering to remove noise. The steering angle data is converted to the front-wheel angle. The target speed is transformed from relative speed to absolute speed. The time sequence of the braking pressure samples is compared with a threshold of 3 psi, producing a string of 0's (under the threshold) and 1's (over the threshold). Once four 1's are found in five consecutive samples, and the preceding five consecutive samples are all 0's, a braking onset is declared. The first of the five samples containing four 1's is the braking onset. The lidar data at the braking onset is examined to find the closest target in front of the bus. If there is a target in front of the bus, and the bus speed is greater than 1m/s, and the Time-To-Collision (TTC) is smaller than 40s and greater than 0s, then the braking-onset data is picked up and saved in a data file for further processing. TTC is calculated as [1]

$$TTC = R/(Vb - Vt) = R/Vb(1 - Vr)$$

where R is the closest range, Vb is the bus speed, Vt is the target speed, and Vr is the Vt-to-Vb ratio. The front wheel angle is sampled five points later than the braking onset. In total 25,387 braking onset cases are extracted from the data.

2.2.2 Histogram Analysis of Braking Onset Parameters

The following pictures are histograms of bus speed, target speed, target range, initial brake pressure and TTC, all at braking onset.

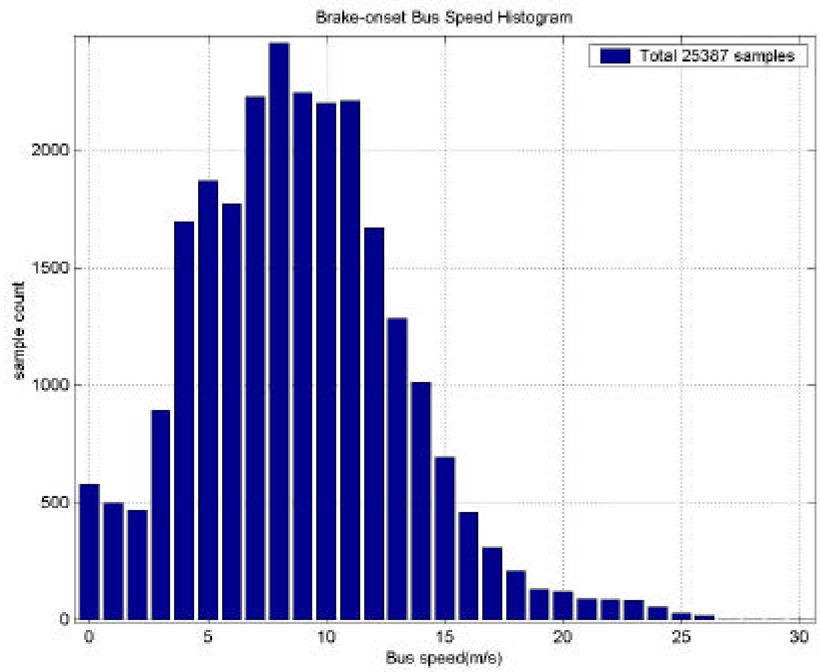


Fig. 44 Bus speed histogram

Most brakes are initiated at 4~12m/s (9~27mph), see Fig 46. Frequency of brakes at higher speed (over 16m/s or 36mph) is significantly smaller than those at lower speed. For stop-and-go situations when the bus speed is slower than 3m/s (6.5mph), the lower the speed, the higher the number of brake applications.

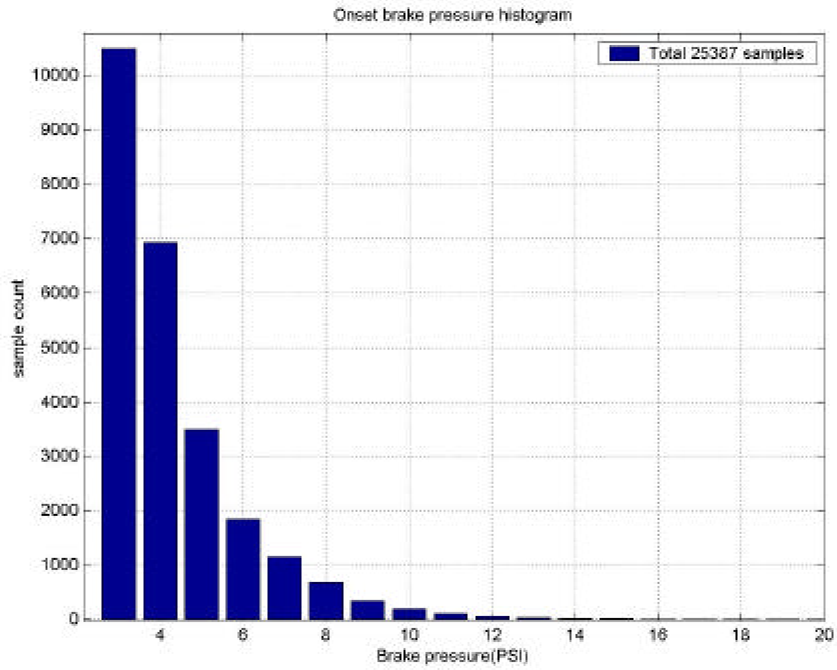


Fig. 45 Onset brake pressure histogram

In most cases, as seen in Fig. 47, the onset (initial) brake pressure is small (<10psi). This indicates that the bus drivers usually brake smoothly.

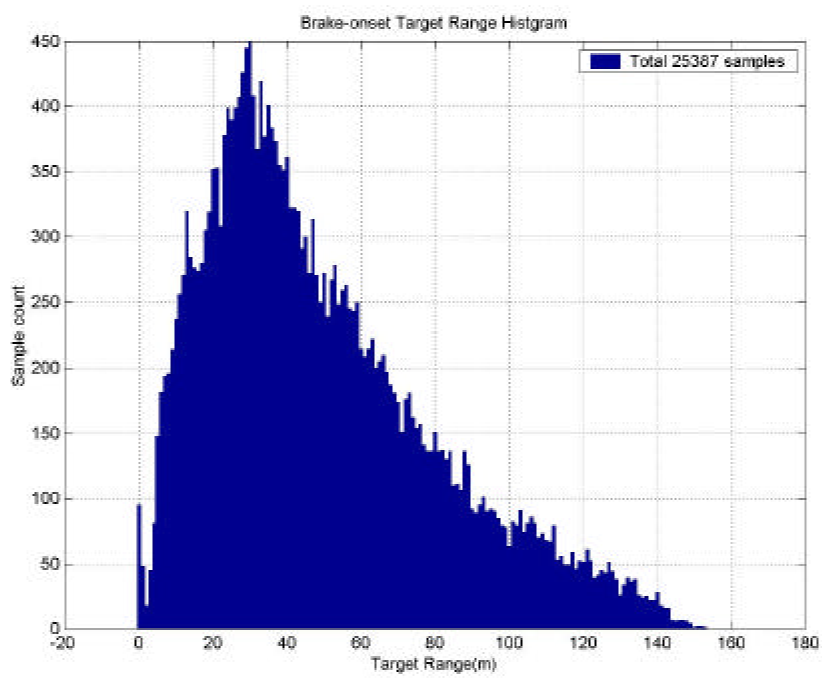


Fig. 46 Target range histogram

The maximum range of the closest target at braking onset is between 20 and 40 meters. There is a small peak at zero range as shown in Fig. 46. The data of those cases were checked. The target is either a very close object or a false target. In most cases the target is a false target (rain or fog).

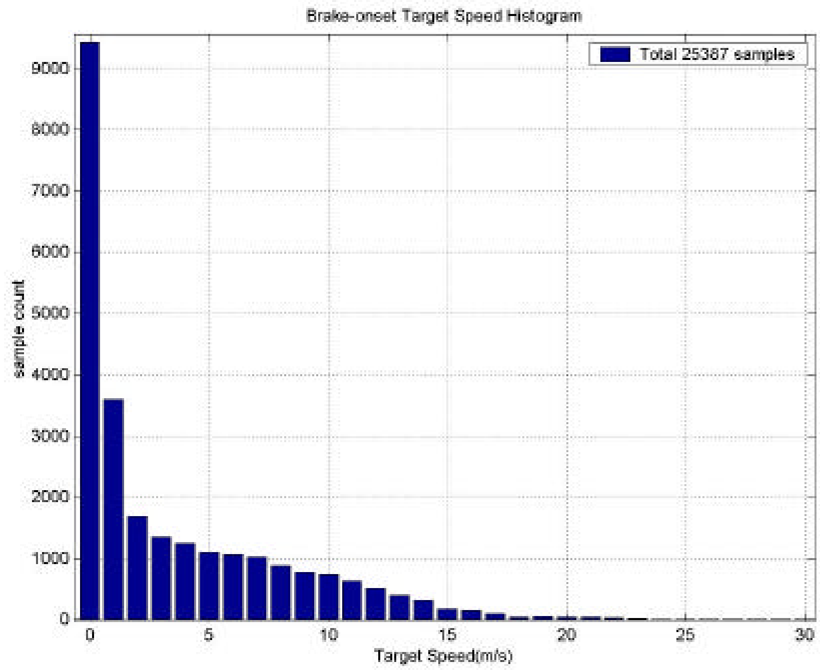


Fig. 47 Target speed histogram

In more than half of the cases, the closest targets in front of the bus at braking onset were stationary or slowly moving (<3m/s or <6.5mph), see Fig. 47. It should be noted that the target is not necessarily the direct cause of the brake. In other words, the driver might not be reacting to the target but something else at that moment. One example is where a lead vehicle speeds up after stopping at a stop sign, while the bus driver has to brake to stop at the same stop sign. It is not the lead vehicle but the stop sign that forces the bus driver to brake. Another example is where a car is parked at a corner of a curved road, while the bus driver has to slow down before turning at the corner. It is not the parked car but the curve that forces the bus driver to brake. In both examples, the cars are picked up as targets. But the bus driver is not responding to them.

This point is very important to understand in the TTC histogram of Fig. 48. The TTC does not imply the timing of drivers' decision making in braking. It is merely a distribution of TTC at the moment the bus drivers initiate braking. It is informative in that false positives will not be avoided if we use TTC as a measure of severity. Whatever TTC threshold is set, there must be false positives, because in the cases where the TTC is smaller than the threshold, a warning is triggered before the drivers decide to brake, but the drivers would not consider this situation requiring a warning.

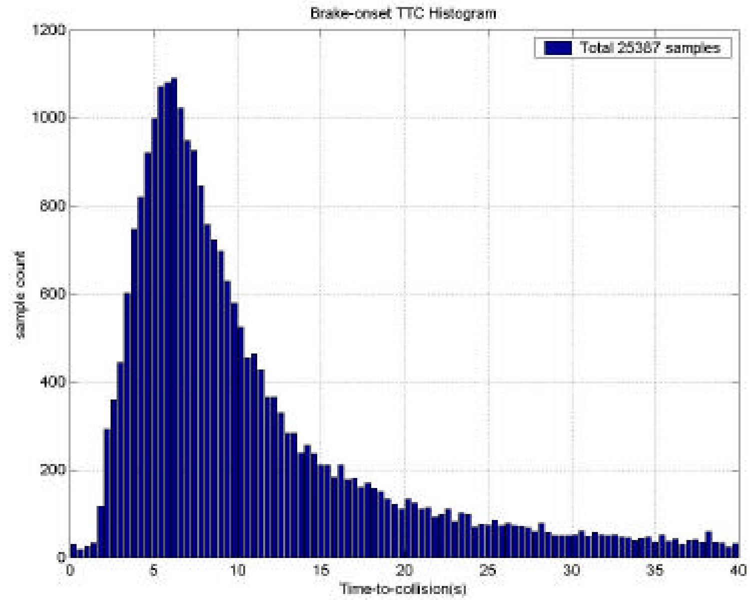


Fig. 48 Time to-collision histogram

2.2.3 Clustering of Target Following Scenarios

In the definition, TTC is proportional to the following range *R*. If the bus speed and the target speed are given, *R* is equivalent to TTC in characterizing the braking onset timing. For this reason, we focus on clustering of *Vb* and *Vr* hereafter.

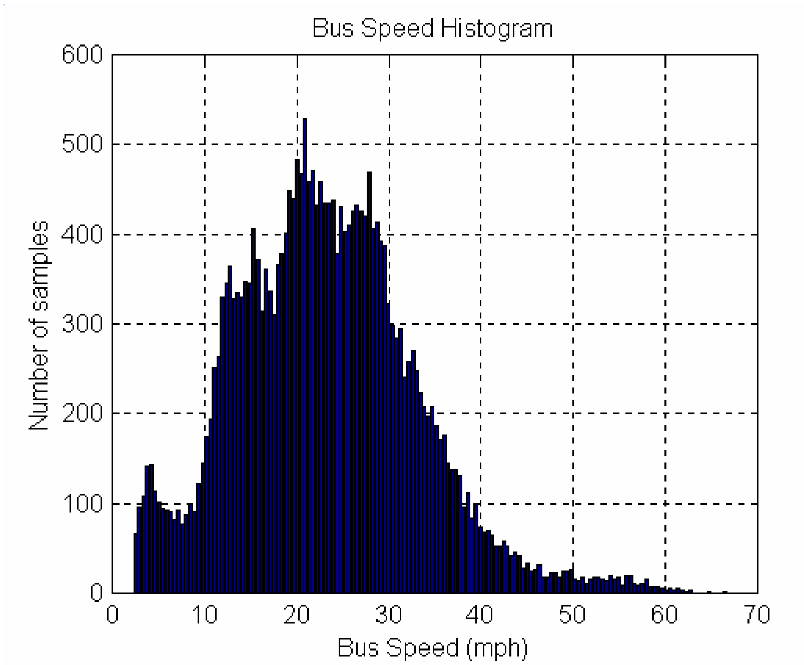


Fig. 49 Bus speed histogram

Fig. 49 is the refined histogram of *Vb*. There are several peaks. They are approximately at: 4.0-, 15.0-, 21.0-, 28.0-, 32.5- and 50.0-mph. This is not surprising, because the California speed limits are usually 5mph on congested areas with pedestrians, 15mph at blind intersections or in alleys, 25mph in business or residence areas, 30-, 35-, 40- or 45-mph for broader divided two-ways, and 55-65mph for freeways. The main body of the histogram is between 10- to 40-mph. This says that the bus mainly runs on low speed roads. The frequency that the bus runs below 7.5mph is high. The reason is probably that the bus needs to stop at the bus stations which are usually in congested areas, e.g. BART and Caltrain stations. The frequency becomes zero when bus speed approaches zero. This is because we didn't pick up those data when bus speed is smaller than 1m/s.

We empirically divide the bus speed into five categories in the following table.

Table 12 Categories of bus speed

Category	B1	B2	B3	B4	B5
Vb(mph)	0-7.5	7.5-17	17-31	31-45	>45

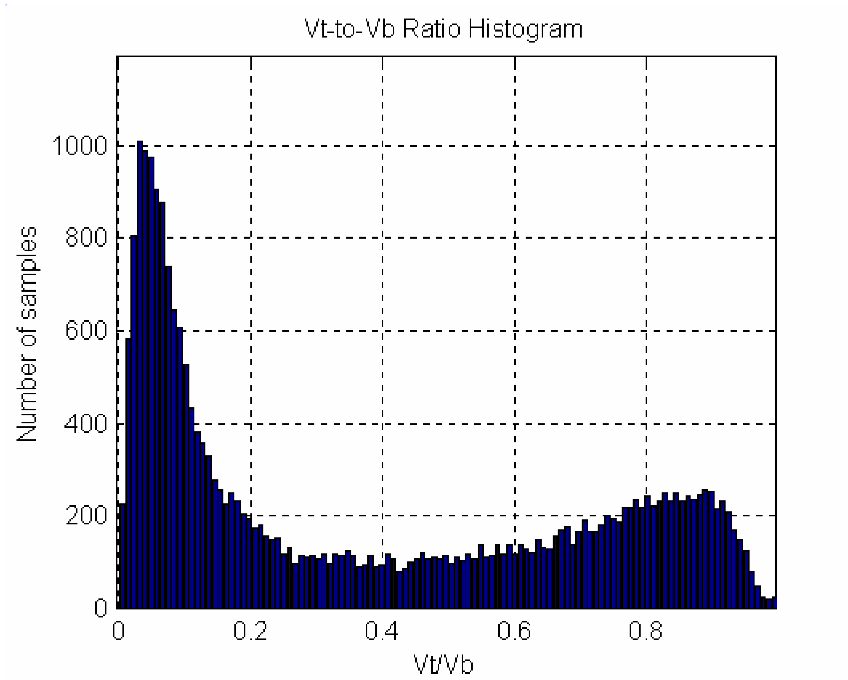


Fig. 50 *Vt*-to-*Vb* ratio histogram

Figure 50 is the histogram of the *Vt*-to-*Vb* ratio. There are two peaks. One is at approximately 0.04, the other is around 0.9. This indicates that most of the targets from which the bus is trying to keep away are either very slow or at the similar speed of the bus. The big peak at 0.04 shows that the bus usually faces a great amount of slow-speed or stationary targets.

We empirically divide the ratio into three categories in the following table.

Table 13 Categories of speed ratio

Category	T1	T2	T3
Vt/Vb	0-0.25	0.25-0.7	0.7-1

Combining the bus speed categories with those of speed ratio, we get 15 clusters. This is shown in Fig. 50. Each braking onset case is represented by a dot in the 2-D plot. The dot density represents the concentration of the clusters. This is a reasonable clustering except the B5-T2 combination. There are too few dots in this region to form a cluster.

The numbers of the cases that fall into each cluster are listed in the following table.

Table 14 Total numbers of cases in each cluster

	T1	*T2*	*T3*	***Subtotal***
B1	573	525	138	**1,236**
B2	3112	1642	1033	**5,787**
B3	7151	3057	3230	**13,438**
B4	1761	798	1750	**4,309**
B5	290	45	282	**617**
Subtotal	**12,887**	**6,067**	**6,433**	**25,387**

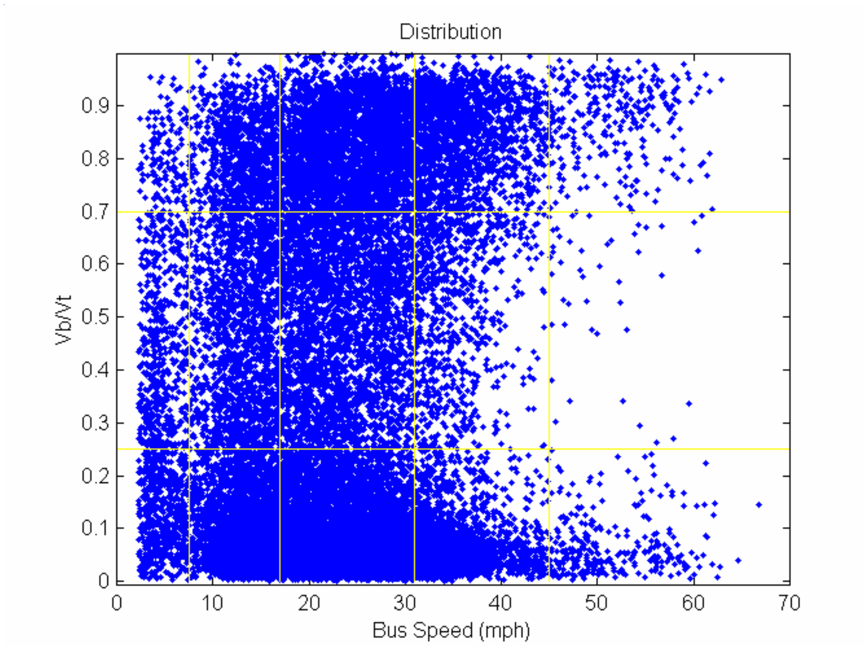


Fig. 51 Clusters of target following scenarios

The clustering in Fig. 51 provides a natural categorization of braking onset scenarios. Each cluster may follow different statistical characteristics. This provides a way to improve the collision warning performance.

2.3 FUTURE WORK

Further analysis of the field data requires complex algorithms to pick up specific scenarios or targets. Development of the scenario recognition algorithms will help to improve the performance of the collision warning system. PATH will focus its efforts on algorithm development in the future phase of the project. The data will be reviewed with the improved algorithms.

PATH has developed a prototype CWS on SamTrans buses. PATH is collecting data on these buses. Another task of data analysis would be to figure out drivers' adaptations to the system, i.e. change of drivers' behaviors after cooperating with the FCWS. Future work will also include comparing operators driving performance behavior prior to the introduction of the FCWS to after implementation.

References

1. Hayward J.C., Near misses as a measure of safety at urban intersections. Doctoral dissertation, Pennsylvania State University, 1971.

Section Two

Development of Prototype Transit Frontal Collision Warning Systems

3 DEVELOPMENT OF A PROTOTYPE TRANSIT FCWS

In order to conduct field testing of different elements of the FCWS and for validation of the final requirement specifications, three prototype collision warning systems were developed. Because of the technical challenge for a transit FCWS to deal with the diversity of obstacles and the different traffic patterns in the urban environment, the emphasis of the prototype system development is placed on the investigation of a detection and warning algorithm. Based on a JDL data fusion model, a preliminary detection algorithm was developed that can track different obstacles within the field of sensor views and decouple the bus motion from the sensor measurements. A warning algorithm was also developed to incorporate a warning threshold synthesized from the drivers' normal braking behavior.

This section will present the key tasks undertaken by PATH in the development of a prototype FCWS on SamTrans buses.

3.1 HARDWARE CONFIGURATION

The prototype transit FCWS was developed on a similar hardware platform as that of the DAS, which PATH had developed and installed on the SamTrans buses. In evaluating the data acquisition needs, an evaluation of existing DAS's was conducted. It was determined through the study that no commercial or government developed system (including DASCAR) was available that would meet all the performance requirements. PATH therefore designed a system that is composed of two distinct systems - one system records engineering data and the other records video data. The engineering data is recorded with a PC based computer. The computer used is an Industrial Computer Systems 9300™ series bench top computer using ISA/PCI architecture. This computer records the output from a variety of sensors. The sensors selected by PATH to capture the environment around the bus include commercially available mono-pulse millimeter-wave radars and scanning infrared lasers. Both the radar and scanning laser measure distance and azimuth angle for multiple targets. The radar units are mounted on the front bumper, one on each end, pointing forward. Ultrasonic sensors were originally used as corner sensors, however they did not work well for two reasons. Firstly, the ground was being picked up as a target as the sensitivity was adjusted to a high level. Secondly, as ultrasound transceiver surface was not water proof it was decided that they were not appropriate as corner sensors. It was then decided that Denso LIDAR sensors would be better for this role, so several of these were acquired from Denso. Three lidar units are mounted on the bumper. The units mounted at each end of the bumper are pointing out 20 degrees and the one mounted near the center is pointing straight ahead. Other sensors record the driver inputs to the bus, such as steering wheel angle, brake line pressure, throttle position, and turn signal activation. Other sensors include an accelerometer and a GPS system. The radars, lidars, and GPS data are recorded using RS232 communication protocol. The remaining sensors are recorded using an analog to digital board and anti-aliasing filters.

Fig. 52 Sensors installed on a bus

Video data is recorded using a commercially available digital video system. The first digital video recording system implemented saved the video as a series of still images in an encrypted proprietary format. This limited the level of compression and allowed only three days of data to be collected before the removable hard disks had to be changed. This also required that the video data first be converted to a standard still-picture format, and then be converted to a standard moving-picture format (MPEG-1). This was a very time consuming manual process. The video recorder was not reliable such that it crashed the flash-ROM system several times. A Loronix™ video system was found that offered several improvements over the previous system. This system records video in a standard still format (AVI) and allows for automated conversion to MPEG-1 format. Much less time is required to convert the video data now that the process is automated. The system also has greater storage capacity than the previous one, allowing one week of data collection before the removable hard disks need to be changed. This system was retrofitted on the first bus and has proven to be much more reliable and easier to use. The video cameras in the originally developed system were too obtrusive, and easily damaged or moved by passengers. A different style of video camera was selected to replace them. These cameras have a form factor that allowed them to be installed in the destination window of the bus. This makes them less obtrusive and prevents them from being tampered with. This system records up to six cameras in AVI format onto a PC hard drive. Four miniature "board cameras" capture video images around the bus. The cameras capture the front road scene, the left and right front corner road scene, and the passenger compartment of the bus. The video streams from the four cameras are combined into one video stream by a quad image combiner to extend the hard drive storage capacity.

Synchronization between engineering and video data is very important for later playback. The first item of information for synchronization is the time stamp recorded in the video frame as a title. This time stamp is generated by a title generator which receives the clock time from the engineering computer. This title allows for manual synchronization. The engineering computer also sends three synchronization signals to the video recorder through the alarm inputs. These signals and their triggering time stamps are recorded separately by both the engineering computer and the video recorder. The signals are triggered every one minute, 15 minutes and 60 minutes respectively. By matching the signal records in the engineering data with the records of alarms in the video recorder, time difference between the two computers can be determined. Once the computer time difference is matched, the video clips can be synchronized with the engineering data streams. The synchronization occurs as part of the process of transferring the data from the removable hard disks to a permanent data base storage system. The permanent data base storage system is composed of a Redundant Array of Inexpensive Disks (RAID). Once the data base has been synchronized and broken into small data clips each set of data clips is saved in one folder for easy access.

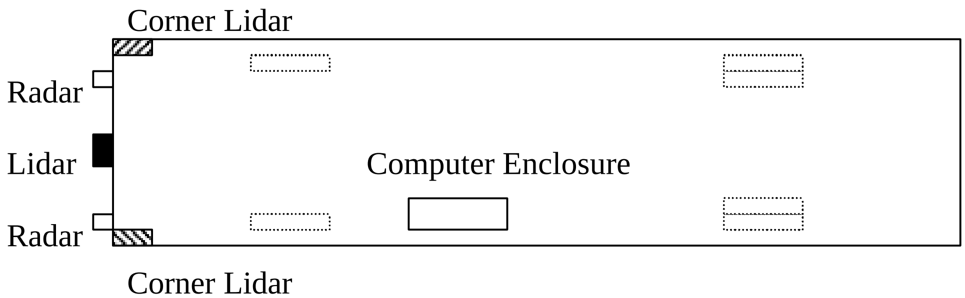


Fig. 53 System layout on the bus

The data acquisition system has been installed on three buses in the SamTrans fleet. A fourth system has been prepared for installation on a yet to be determined bus from another agency in the Bay Area. The first system started collecting data in August 2000. The second system started collecting data in April 2001. After the second system started running, the first system was updated with the new design. The third bus started collecting data in January 2002.For a full review of the development issues see Appendix V. Additional modifications to the DAS hardware arrangement included adjustment of sensor locations and the installation of the Driver-Vehicle-Interface (DVI).

To mitigate the influence of sensor errors upon algorithm performance evaluation, the prototype FCWS uses only lidars for object detection. The lidars' measurement of object lateral position is much more accurate than that of the micro-wave radars. The micro-wave radars' azimuth angle measurement is less satisfying. The bus speed and the steering angle information are used to predict the bus motion in the improved algorithm (the 2nd generation algorithm). All other sensors, the GPS, the accelerometer, the cameras, the throttle position sensor, and the brake pressure sensor, are not used in the algorithm and the data from these sensors is recorded. The data acquisition program runs in parallel with the prototype collision warning program on the same hardware platform. Raw data is recorded in the removable hard disks. The data is not only useful to verify the warnings, but also allows for collection of driver behavior changes in adaptation to the warning system.

3.2 THE TRANSIT FCWS ALGORITHM ARCHITECTURE

The prototype FCWS algorithm was developed based on the data fusion and decision making model developed by the Joint Directors of Laboratories (JDL) data fusion sub-panel.

3.2.1 The JDL Data Fusion Process Model

The JDL data fusion model provides a top-level framework of data fusion systems, and defines terms commonly used in different areas. The top level of the JDL data fusion process model [2] is shown in Fig. 54. A summary of the JDL data fusion process components is shown in. Table 15.

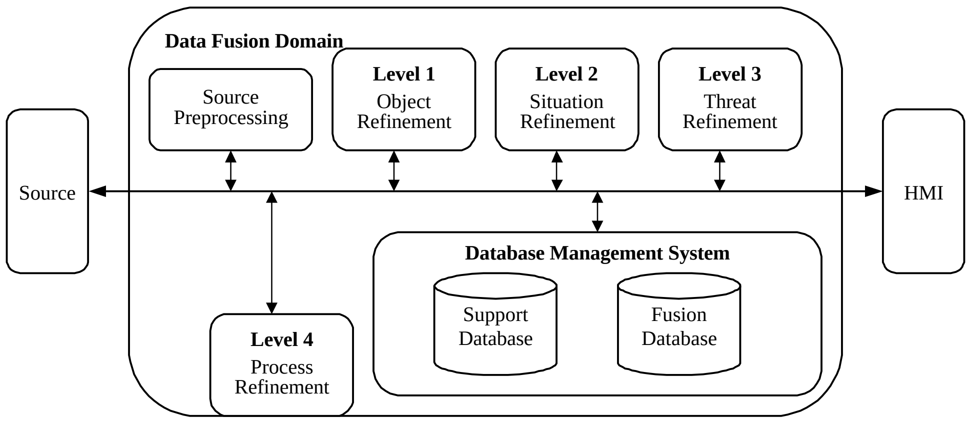


Fig. 54 JDL data fusion process model

Table 15 JDL process model components summary

SOURCE	The sources provide information at a variety of levels ranging from sensor data to *a priori* information from databases to human input.
PROCESS ASSIGNMENT	Source preprocessing enables the data fusion process to concentrate on the data most pertinent to the current situation as well as reducing the data fusion processing load. This is accomplished via data pre-screening and allocating data to appropriate processes.
OBJECT REFINEMENT (Level 1)	Level 1 processing combines locational, parametric, and identity information to achieve representatives of individual objects. Four key functions are: • Transform data to a consistent reference frame and units • Estimate or predict object position, kinematics, or attributes • Assign data to objects to permit statistical estimation • Refine estimates of the objects identity or classification
SITUATION REFINEMENT (Level 2)	Level 2 processing attempts to develop a contextual description of the relationship between objects and observed events. This processing determines the meaning of a collection of entities and incorporates environmental information, *a priori* knowledge, and observations.
THREAT REFINEMENT (Level 3)	Level 3 processing projects the current situation into the future to draw inferences about the enemy threats, friendly and enemy vulnerabilities, and opportunities for operations. Threat refinement is especially difficult because it deals not only with computing possible engagement outcomes,

[2] For details of JDL model, please refer to 'Multisensor Data Fusion' by E. Waltz and J. Llinas (Artech House, 1990).

	but also assessing an enemy's intent based on knowledge about enemy doctrine, level of training, political environment, and the current situation.
PROCESS REFINEMENT (Level 4)	Level 4 processing is a meta-process, i.e., a process concerned with other processes. The three key level 4 functions are: • Monitor the real-time and long-term data fusion performance • Identify information required to improve the multi-level data fusion product, and • Allocate and direct sensor and sources to achieve mission goals.
DATABASE MANAGEMENT SYSTEM	Database management is the most extensive ancillary function required to support data fusion due to the variety and amount of managed data, as well as the need for data retrieval, storage, archiving, compression, relational queries, and data protection.
HUMAN-COMPUTER INTERACTION	In addition to providing a mechanism for human input and communication of data fusion results to operators and users, the Human-Computer Interaction (HCI) includes methods of directing human attention as well as augmenting cognition, e.g., overcoming the human difficulty in processing negative information.

The JDL model is a generic model for common understanding and discussion. It has defined levels of processes to identify functions and techniques. The model has built a common base for researchers and system developers working in different areas. With the help of this model, we can adopt a lot of approaches and techniques developed for other applications, such as robotics, Computer Integrated Manufacturing Systems (CIMS), airport surveillance and air traffic control, etc., to develop a CWS.

The JDL model however, is not a universal architecture for real applications. It does not specify the level of data fusion. Data fusion level is an application-specific problem. To define the collision warning system architecture, analysis of the system function requirements is needed.

3.2.2 Function Requirements of Bus FCWS

All the functions defined in the JDL model, except level four are required in the bus FCWS. First of all, the source preprocessing must be performed to eliminate the unwanted signals and to detect the objects of interest. The sources here may include object sensors such as RADARs, LIDARs, SONARs, CAMs, GPSs, etc., and subject vehicle sensors such as speedometers, accelerometers, steering angle and braking pressure sensors, etc. Sensors are used to convert the measurable elements of the physical processes of the environment into electric parameters. The process to convert the physical process elements into electric parameters is observation. Some unwanted signals, such as pavement clutter, road-side trees and traffic signs, etc., and interference from the same kind of sensors mounted on other vehicles or from other sources, as well as noise from internal components of the sensor, must be suppressed, to pickup the real object signals. The preprocessing is the process to figure out, from one or more observations, whether an object exists or not, and to measure the status of the existing object.

The process to find out whether an object exists or not, is defined as detection. It is a probabilistic test of hypotheses. In the simplest situation, we have two hypotheses, H1 and H0, representing the object's presence and absence respectively. The probability of being H1 while the object does exist, viz. probability of correct detection (Pd), is always less than 1. The probability of being H1 while the object does not exist, viz. probability of false alarm (Pfa), is always greater than zero.

The process to measure 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 comes from single or multiple observations. Measurements, as functions of time, are stochastic processes in reality. Level 1 processing should then be performed to detect the processes and to estimate parameters of the processes. It is assumed in most cases that false alarms are less possible than real objects to form continuous processes. The detection of the process will eliminate the false alarms and determine when a process begins and when it ends. The estimation of the process will refine the measurements. The results of detection and estimation of processes are called tracks. The process to initiate, manipulate and end tracks is called tracking.

A track represents a stochastic process converted by a sensor from the physical process of an object. The parameters of a stochastic process are correspondent to the parameters (as functions of time) of an individual object. To develop a description of the current relationship among multiple objects and events in the context of their environment, level two processing is needed. Tracks from different sensors may represent the same object. These tracks must be fused into one track. This process is called track-to-track fusion, and the fused track is called the system track. After fusion, a system track usually is a refined unique representation of an object. The history of the tracks and the relationship among the tracks as an aggregation represents the scenario of the traffic. Once the scenario is described, level three processing is needed to assess the threats. Threat assessment is the process whereby the current situation is projected into the future to assess the severity of a potential traffic accident. Knowledge about vehicle kinematics, traffic, and the environment is needed for the assessment. Human behavior may also be used for this assessment. Once a potential threat is detected, a warning will be sent to DVI. Level four processing is not needed in an FCWS, because the developers of the system and the vehicle drivers will perform this function outside of the system.

3.2.3 Architecture of the Bus Collision-Warning Algorithm

Studies on collision warning/avoidance during the past few years have built a good foundation for the bus FCWS design. Individual sensors such as RADARs [3] and LIDARs [4] have been developed. Some sensors have been integrated with built-in Digital Signal Processors (DSP). The DSP's can perform source preprocessing with some also able to perform level 1 processing. It is convenient to adopt these intelligent sensors in the bus FCWS. Threat assessment algorithms have been studied and various severity measures have been proposed, e.g. TTC [5,6], warning distance [7], warning boundaries [8, 9].

To develop a collision warning algorithm architecture from the JDL model, one of the key issues is to decide where in the data flow to fuse the data. We prefer the track-to-track fusion that matches the state-of-the-art technology of the sensors and helps us to concentrate our efforts on higher level processing. Fig. 55 is the block diagram of the bus collision warning algorithm architecture. For some sensors, lower level processes (source preprocessing and object refinement) may be implemented inside the sensors, though they are drawn apart from the sensors in the block diagram.

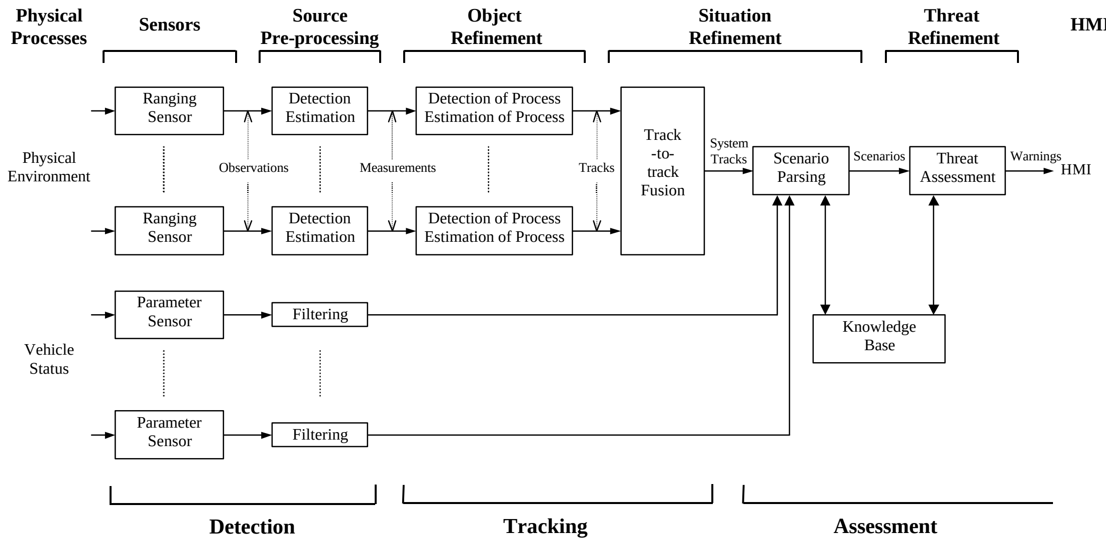


Fig. 55 Bus collision-warning algorithm architecture

3.3 THE PRELIMINARY TRANSIT FWCS ALGORITHM

The algorithm framework was proposed on the basis of the JDL model. The functional requirements of the bus FCWS are partitioned into hierarchical levels in the algorithm framework, as illustrated in Fig. 56. This framework is almost the same as that in Fig. 55, except that in the preliminary FCWS algorithm, the gray background module, which is denoted by 'linear long-term prediction', replaces the scenario-parsing module. The linear prediction is based on the kinematical model and is scenario independent.

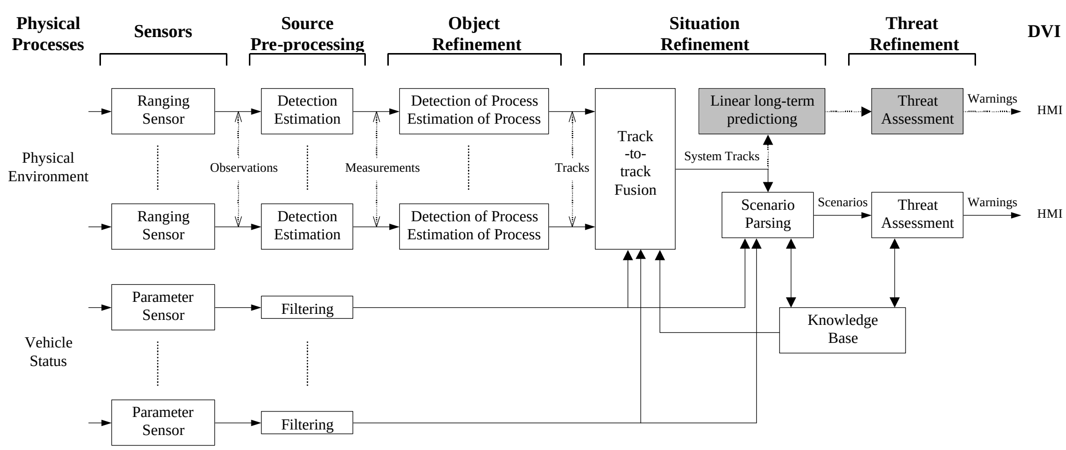


Fig. 56 Algorithm framework

The hierarchical framework determines the processing functions in the transit FCWS. It defines FCWS as a specific application of the multi-sensor data fusion JDL model described in the previous section. This makes it possible to utilize in the FCWS techniques already developed in a wide scope of data fusion research areas.

Object sensors, such as micro-wave radars and lidars, have built-in front-end signal processing functions. The algorithm to detect an object and that to measure the kinematic parameters of an object are not included in this report. Summarized in this report are the tracking algorithm and the threat assessment algorithm.

3.3.1 Tracking Algorithm

The block diagram of the tracking algorithm is illustrated in Fig. 57.

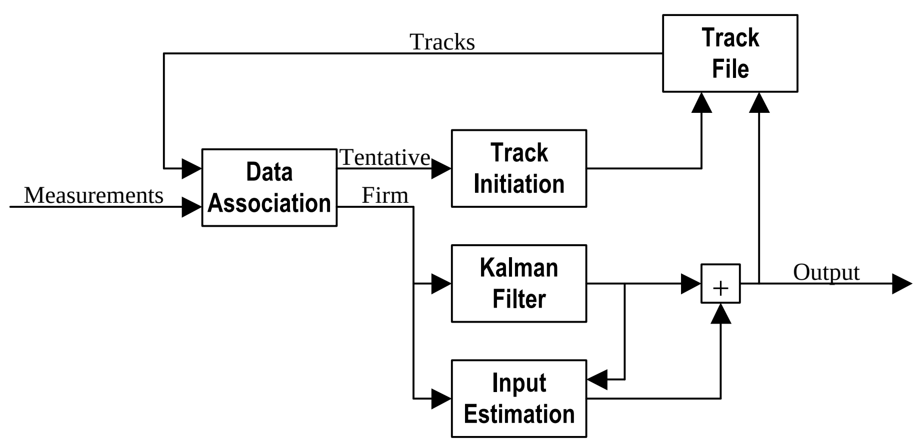


Fig. 57 Tracking algorithm diagram

In the diagram, the "track file" is a list of targets currently being tracked. Each target has a unique identification (ID), a status flag (tentative or firm), and a set of parameters estimated in the last step. The key module in the diagram is the "Kalman filter". The system model for the Kalman filter is:

$$\begin{cases} x_{k+1} = Ax_k + w_k \\ y_k = Cx_k + u_k \end{cases}$$

where, x is the system state vector, whose elements are positions and velocities, y is the measurement vector, A is the state transition matrix, C is the measurement matrix, w and u are zero-mean white system and measurement noises respectively.
The filtering algorithm is:

$$G_k = P_{k/k-1}C^H\left[CP_{k/k-1}C^H + R\right]^{-1}$$
$$\hat{x}_{k/k-1} = A\hat{x}_{k-1}$$
$$a_k = y_k - C\hat{x}_{k/k-1}$$
$$\hat{x}_k = \hat{x}_{k/k-1} + G_k a_k$$
$$P_k = P_{k/k-1} - G_k C P_{k/k-1}$$
$$P_{k+1/k} = AP_k A^H + Q$$

where, R and Q are covariance matrices of measurement and system noises, respectively, a_k is the innovation vector, representing the new information in the latest measurement, G_k is the innovation gain matrix, which is determined by the noise covariance matrices. The above Kalman filter assumes zero-mean noise input. This is usually not true for an automobile. Any kind of maneuvers, e.g. accelerating, decelerating or turning, may be non-zero-mean, and should be regarded as input. The "input estimation" module estimates maneuvers of the targets from the Kalman filtering error:

$$e_k = y_k - C\hat{x}_k$$
$$\bar{e}_k = a\bar{e}_{k-1} + (1-a)e_k$$

where e_k is the Kalman filtering error, $\bar{e}_k$ is the estimated input vector which is used to correct the Kalman filter output. This input estimator is a first order integrator.
The corrected output is saved in the track file under the ID of the corresponding target. If a target has not been updated for a certain number of cycles, it will be dropped out of the track file. In multiple target circumstances, there might be multiple measurements. It is unknown which measurement is generated by which target. This problem is solved in the "data association" module using the Nearest Neighbor (NN) data association criteria [10]. The measurements that are associated with tracks are sent to the Kalman filter. Those that are not associated with any targets are processed in the "track initiation" module to start new tracks.

Fig. 58 shows how the tracking algorithm manipulates multiple targets. The dots are measurements from a lidar in six second periods. The solid lines are tracks in the track file. At most sampling instances, there are multiple measurements. Accordingly, at most times during the six second period, there are multiple tracks. Each solid line links together a series of discrete dots, indicating good tracking. Sometimes, the measurement dots deviate from the tracks. The deviation is due to measurement errors, hard-to-track maneuvers and some unknown reasons.

Fig. 59 plots out the trajectories of these multiple targets on a 2D plane. The two axes represent lateral and longitudinal positions respectively. The dots are measurements. The solid lines are tracks. It is clear in this plot that the measurements are well associated with the tracks.

The tracking algorithm has been coded in C language in Windows™ environment. After a thorough test, the codes have been ported to the QNX™ environment.

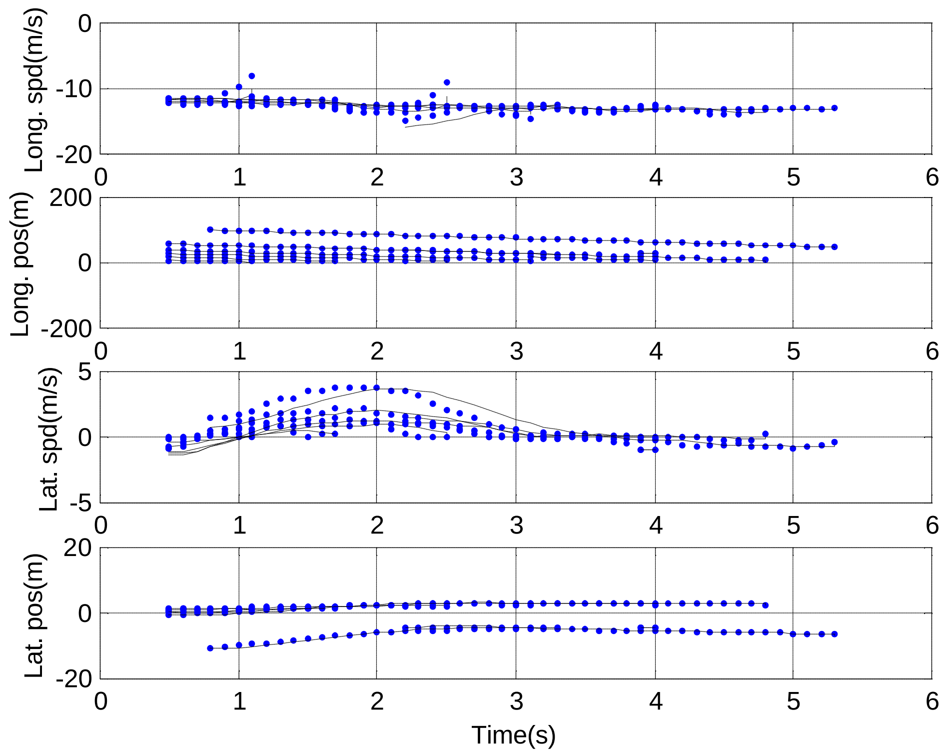


Fig. 58 Multiple target tracking result

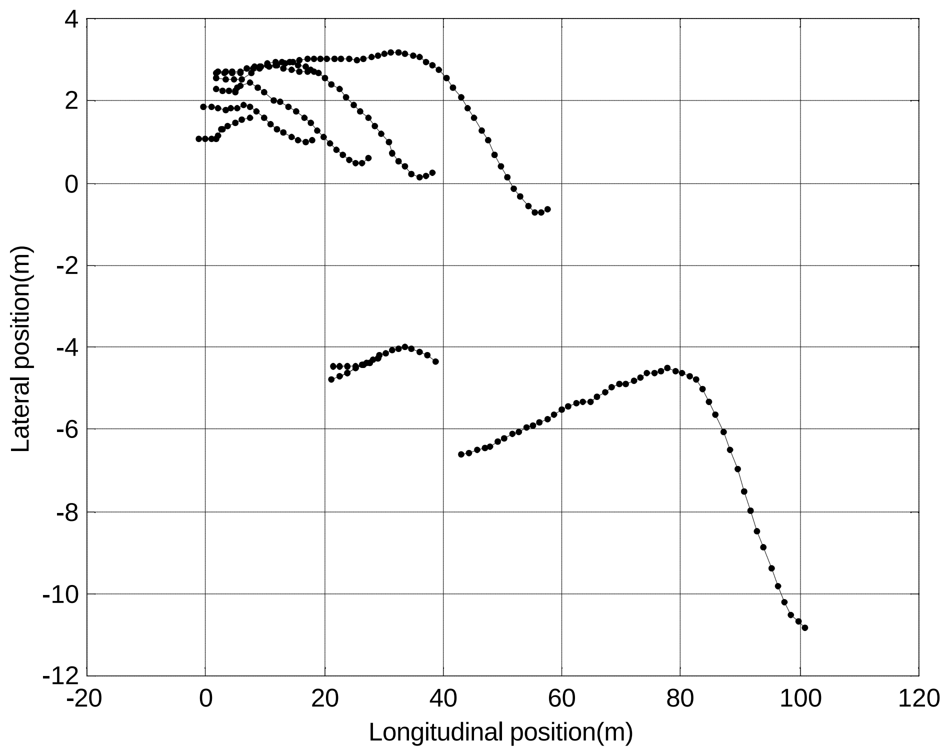


Fig. 59 Multiple target trajectories

3.3.2 Threat Assessment Algorithm

There are two common measures to assess the threat of a target in ground traffic applications, Distance-To-Collision (DTC) and Time-To-Collision (TTC). In highway applications, the warning distance, or DTC is usually used. When the target is slowing down, the DTC is defined by the Stopping Distance Algorithm (SDA) [7]:

$$DTC_{SDA} = \frac{v_s^2}{2a_s} + v_s T - \frac{v_o}{2a_o}$$

When the target is running at constant speed but the subject vehicle is closing up, the DTC is defined by the Closing Rate Algorithm (CRA) [7]:

$$DTC_{CRA} = \frac{(v_s - v_o)^2}{2a_s} + (v_s - v_o)T$$

where, v_s, v_o, a_s, a_o are speeds and deceleration rates of the subject vehicle and the object (the target) respectively, *T* is the total system delay time including processing delay, driver's reaction time and the brake delay time. Burgett, et al. proposed more detailed scenario separations [9]. The SDA assumes that the target is slowing down to stop and the subject vehicle will slow down after the warning is given to the driver. The DTC is defined as the minimum distance between them that the subject vehicle needs to stop without colliding with the target. The CRA assumes that after the warning is given to the driver the subject vehicle will slow down to the same speed that the target is running at. The DTC is defined as the minimum distance the subject vehicle needs to slow down without colliding with the target.

DTC is a good measure of severity. When DTC is smaller than the actual distance, it is safe. When DTC is greater than the actual distance, a warning should be given. In this case, the larger the DTC is, the higher the degree of threat. However, the relationship between DTC and degree of threat depends on the speed. For the same DTC, the higher the speed is, the higher the encountered threat degree. To decouple the threat measure from speed, TTC is used. TTC is defined as the smaller positive root of the following equation:

$$r = (v_s - v_o)(t + T) + \frac{1}{2}(a_s - a_o)t^2$$

where v_s, v_o, a_s, a_o are speeds and acceleration rates of the subject vehicle and the object (the target) respectively, *T* is the total system delay time, *r* is the actual distance. If TTC does not exist, there will not be a collision.

Define $\begin{cases} v_r = v_o - v_s \\ a_r = a_o - a_s \end{cases}$ as relative speed and relative acceleration. TTC should satisfy the following equation:

$$r + v_r(t + T) + \frac{1}{2}a_r t^2 = 0$$

This definition of TTC using the Range-Speed-Acceleration (RSA) model is straightforward and convenient to use, because sensors usually measure range and range-rate, which can be directly substituted into the equation as distance and relative speed. When the motion of both the subject vehicle and the target is restricted to translation only, this definition of TTC is a good measure of threat level. The shorter the TTC is, the higher the threat level is. However, when the subject vehicle turns, i.e. the motion includes rotation, use of the above definition will lead to an incorrect estimation of TTC. The reason is that in this case the sensor is mounted on a non-inertial system and kinematic laws do not exist.

To consider rotation, which happens frequently in urban streets, a more complex model is needed. Let $\vec{r}_m$ and $\vec{v}_m$ represent the measured position and velocity, the relative position and relative velocity in an inertial reference coordinate system can be derived as:

$$\begin{bmatrix} \vec{r} \\ \vec{v}_r \end{bmatrix} = R \begin{bmatrix} \vec{r}_m \\ \vec{v}_m \end{bmatrix}$$

where R is the rotation matrix of the sensor coordinate system in the reference coordinate system. In two-dimensional case, R can be defined by the rotating angle q :

$$R = \begin{bmatrix} \cos q & -\sin q \\ \sin q & \cos q \end{bmatrix}.$$

And the rotating angle satisfies:

$$\frac{dq}{dt} = w,$$

where w is the angle speed.
TTC should satisfy the following equation:

$$\vec{r} + \int_0^t \vec{v}\,dt = R\vec{r}_m + \int_0^t \vec{v}\,dt = 0$$

where $\vec{v}$ satisfies:

$$\begin{cases} \vec{v}(0) = \vec{v}_r = R\vec{v}_m \\ \dfrac{d\vec{v}}{dt} = \vec{a} \end{cases}$$

It is very difficult to find a universal analytic solution to this equation. Under the assumption that the driver's control of the vehicle remains constant, i.e. the wheel slip angle and the tangential acceleration rate are constant, the equation can be simplified as:

$$\vec{r} + Q_o\vec{v}_o - Q_s\vec{v}_s = 0$$

where $Q_o = \begin{bmatrix} q_{o1} & -q_{o2} \\ q_{o2} & q_{o1} \end{bmatrix}$ and $Q_s = \begin{bmatrix} q_{s1} & -q_{s2} \\ q_{s2} & q_{s1} \end{bmatrix}$, and

$$q_{o1} = \frac{1}{k_o v_o} \sin k_o \left(v_o t + \frac{1}{2} a_{To} t^2 \right)$$

$$q_{s1} = \frac{1}{k_s v_s} \sin k_s \left(v_s t + \frac{1}{2} a_{Ts} t^2 \right)$$

$$q_{o2} = \frac{1}{k_o v_o} \left[1 - \cos k_o \left(v_o t + \frac{1}{2} a_{To} t^2 \right) \right]$$

$$q_{s2} = \frac{1}{k_s v_s} \left[1 - \cos k_s \left(v_s t + \frac{1}{2} a_{Ts} t^2 \right) \right]$$

where k is a constant related to the wheel slip angle, a_T is the constant tangential acceleration. This model is a non-linear model based on the Constant-slip-Angle and Constant-tangential-Acceleration (CACA) assumption. When $k \to 0$, this CACA model is simplified to a linear RSA model.

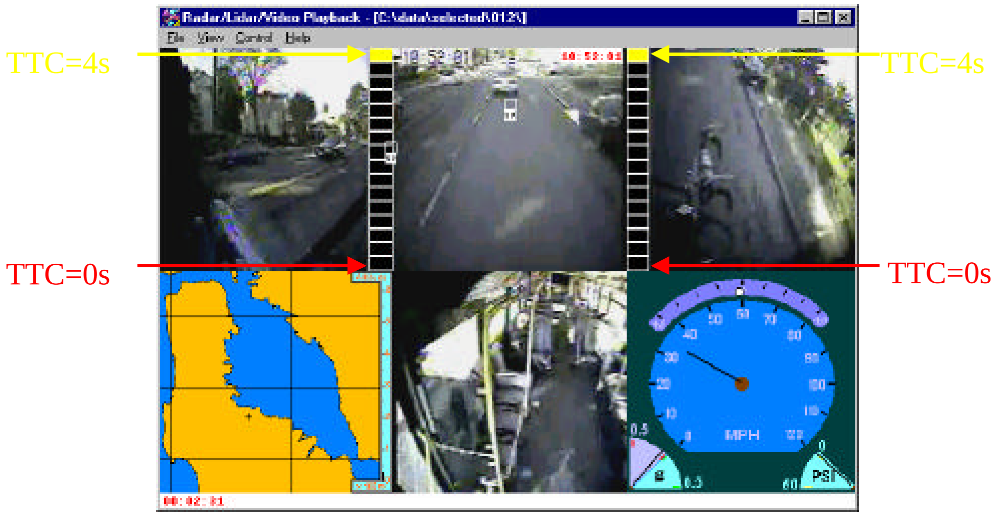
3.3.3 Test of the Preliminary Algorithm

The CACA model was used in the preliminary algorithm to estimate TTC. The preliminary algorithm, including the tracking and threat assessment algorithms, was coded in C in the Windows™ environment. The collected data was then used to debug and test the program. After thorough testing, the algorithm was integrated into the data playback software which was developed earlier to review the data. On both sides of the frontal-looking video sub-window in the playback display, two bars of boxes are added to simulate the LED-bar Driver Vehicle Interface (DVI). As is depicted in Fig. 60, if time-to-collision is shorter than four seconds, the bars are lit up downward from the top. The number of boxes that are lit up is linearly related to the TTC value. The shorter the TTC value, more boxes are lit up. Color of the boxes also changes from yellow to orange to red, as TTC becomes shorter and shorter. The data playback tool integrated with the preliminary warning algorithm is called the warning playback tool.

The collected data was mostly reviewed with the warning playback tool. By playing back the collected data, both true warnings and false warnings were experienced. The true alarm rate (the probability that a target in front of the bus would have collided with the bus if the bus driver had not taken action) was relatively high, but the false positive rate (the probability that a target in front of the bus would not collide with the bus at all but a warning was given – nuisance alarm, or that a warning was given but no target at all was present – false alarm) was too high to be accepted. Almost all the false positives are nuisance alarms. The nuisance alarms mainly happen in the following situations:

- the bus is turning while the object is static or moving in the opposite direction
- the bus is running along a straight road but slightly yawing, while the object is static or moving in the opposite direction
- the bus is running at higher speed on highways or freeways which causes the sensors to vibrate, this vibration makes it appear to the sensors as though the object is moving at one time measurement and then static in the next.

The static objects encountered are mainly parked cars, trees, traffic signs, fences, and poles.



TTC = Time-to-collision

Fig. 60 Display of the preliminary algorithm in Windows™ environment

There are many causes of the nuisance alarms. The non-linear CACA model is based on the assumption that the bus driver would maintain the current turn angle and tangential acceleration rate. This is usually not true. The warning algorithm doesn't have the information about the structure of the road or the type of the object. This makes it difficult to discriminate between true warnings and false warnings. The problem with a high false warning rate is that the drivers may loose trust in the system and ignore alarms. The following section will discuss the improvements made in the algorithm to deal with this problem.

3.4 IMPROVEMENT OF TRANSIT FCWS ALGORITHM

The transit bus FCWS algorithm was improved in two main aspects. Firstly, the bus motion is decoupled from the radar measurements, so that the motion of the objects can be described with a simple kinematic model. This unique approach simplifies the algorithm and improves the precision of position prediction. Secondly, bus drivers' normal braking behavior is used to set up the warning detection threshold. The threshold is friendlier to human operators.

3.4.1 Decoupling of Bus Motion from Radar Measurements

In a bus FCWS, radars and lidars are mounted on a bus. The bus is a moving platform. When the bus is moving, of course, all the sensors on the bus are moving together with the bus. When the bus is turning, all the sensors are also turning. A radar is a positioning sensor, observing the environment in its own coordinate system, the so-called reference system. What a radar observes is the relative position and motion of the objects in this reference system. When a radar is turning with the bus, its own coordinate system becomes a rotating reference system. In a rotating reference system, a phenomenon called the Coriolis effect is introduced. At this moment, in the radar's measurements, a static object looks like it is moving, and an object that is moving along a straight line looks like its path is curving. This occurs because a nonlinear component is introduced into the measurements because of the Coriolis effect. This nonlinear component makes it harder to predict the future positions of the objects.

There are two approaches to deal with the nonlinear component. One is to model the Coriolis effect with a nonlinear kinematic model. The other is to transform the measurements into an inertial reference system, thus to remove the Coriolis effect from the measurements. It is not impossible to predict the future positions of the objects with a non-linear kinematic model. However the algorithm becomes too complex to do so. To simplify the algorithm, we can use simplified solutions proposed by the CACA model in the previous section. However the assumptions for the simplification are usually not practical. In order to decouple the bus motion from the sensor measurements, we developed a new approach. As the Coriolis effect is caused by the bus motion, once the bus motion is decoupled, the sensor measurements are equivalent to those transformed into the ground coordinate system, which is an inertial reference system. In this inertial system, both the bus and the objects can be modeled with a simple linear kinematic model. This makes the algorithm much simpler. After decoupling, the bus motion is described with a linear kinematic model. This provides the possibility of estimating the driver's status from the bus motion parameters. The decoupling also gives us the individual motion of both the bus and the objects, which provides more information about the dynamic relationship between the bus and the objects, than observations can tell.

Fig. 61 is an exemplar plot of the raw trajectories of objects in the radar's own coordinate system. Fig. 62 is from the same data but after decoupling.

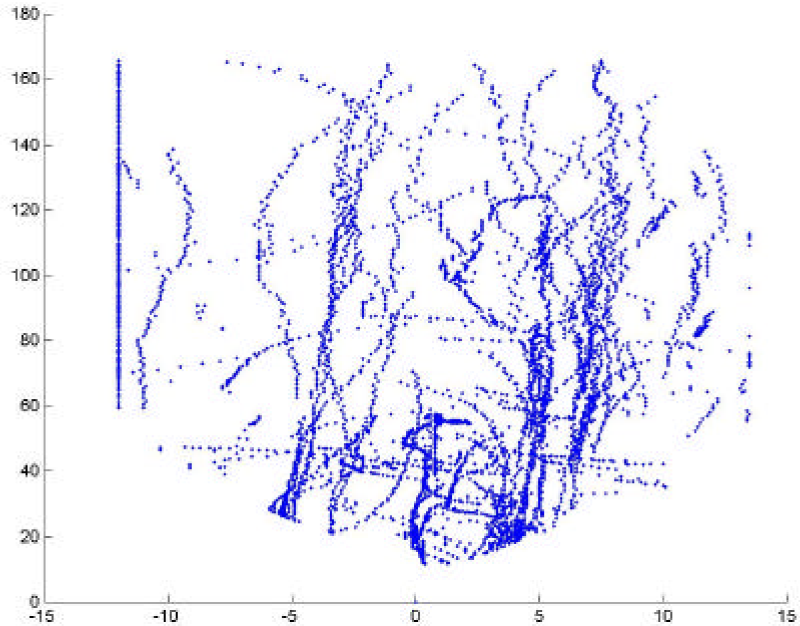


Fig. 61 Trajectories of objects in radar's coordinate system
(Horizontal axis: lateral position in meters; Vertical axis: longitudinal position in meters)

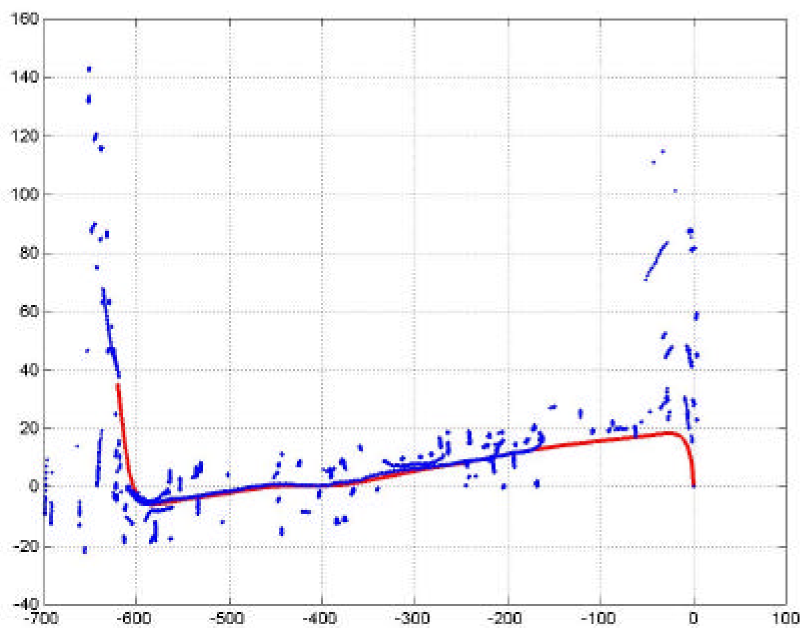


Fig. 62 Trajectories of objects (blue) and the bus (red) in the inertial system
(Horizontal axis: x-axis of the inertial reference system (m); Vertical axis: y-axis of the inertial reference system (m))

3.4.2 Human-Cooperative Threshold for Warning Detection

In a FCWS, the bus operator plays an important role. The operator not only controls the bus by accelerating, braking or turning, but also observes the environment, detects the potential threats and makes decisions. Before a FCWS is put on the bus, it is assumed that the operator had been independently, working well on the bus. The FCWS is supposed to give warnings only when the driver is inattentive, i.e., when the driver is distracted by something else, consequently unaware of the imminent threat ahead. The warnings are supposed to be given early enough, so that the operator has time to react and take control of the bus, either to fully avoid the threat or to lessen the impact of an unavoidable accident. The condition for activating a warning when the operator is inattentive must be emphasized herein. Research has shown that people tend to match their response rate to the reliability of the warnings. High levels of unreliable warnings tend to induce users to ignore all warnings. A warning that is given when the driver has already recognized the potential threat through his own observation provides very limited information. If too often the warnings are given when the driver is already aware of the potential threat, the reliability of the warning system will become too low for the driver to respond to it. In this case, drivers may consciously, and very rationally, decide not to comply with the warning, or even to disable the warning system. Bus operators are experienced drivers who are usually very attentive when driving. Although no quantitative result shows how often the bus drivers are inattentive, it is assumed that the rate of distraction is a low-probability event. This means, if warnings are activated disregarding the driver’s attentiveness level, most of them provide very limited information for the driver, because the driver is already aware of the potential threat. This greatly impairs the reliability of the FCWS. The approaches that simply use distance, closing rate, or TTC to detect a threat are subject to such a reliability problem. To solve this problem, the driver’s status (attentiveness) must be considered in the FCWS design.

We found from the collected data that the bus drivers’ normal braking onset timing drops into a certain safety region on the range-to-range-rate plot. Fig. 63 is the range-to-range-rate plot from the data we collected from August, 2000, to February, 2001. Each dot in this plot represents a braking case, in total 25,387 cases. The range and range-rate of each case are sampled at the onset of braking. A safety region can easily be identified in this plot. The safety region represents the normal timing that the drivers brake for to avoid accidents. We use the lower boundary of this safety region to define the threat detection threshold. This threshold is more human-cooperative, because it is from the data we have collected. It represents the safety limit of normal driver operations.

The improved algorithm was tested on SamTrans Bus 601 for one week, with six drivers involved. The threshold was slightly adjusted after the test. The test shows that false warnings are greatly suppressed.

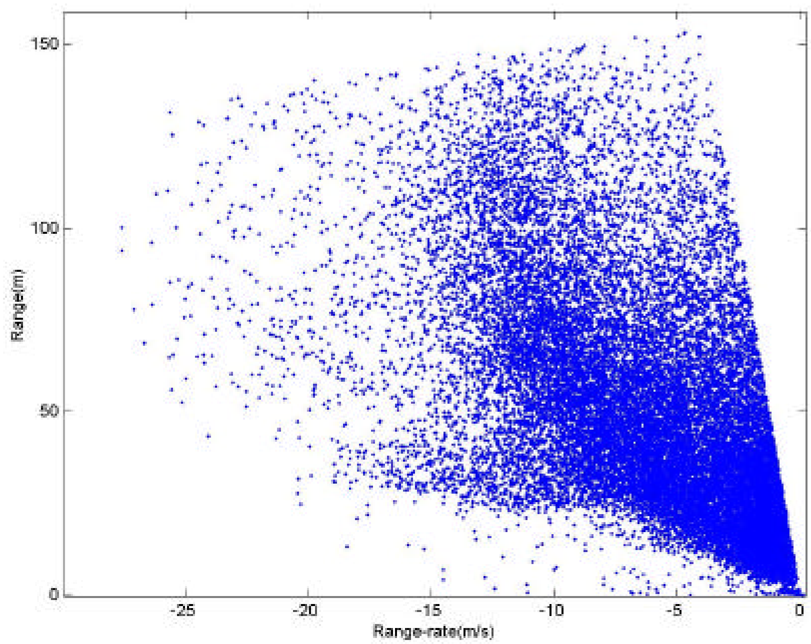


Fig. 63 Clustering of braking onset timing

3.4.3 Track File StructureTrack list

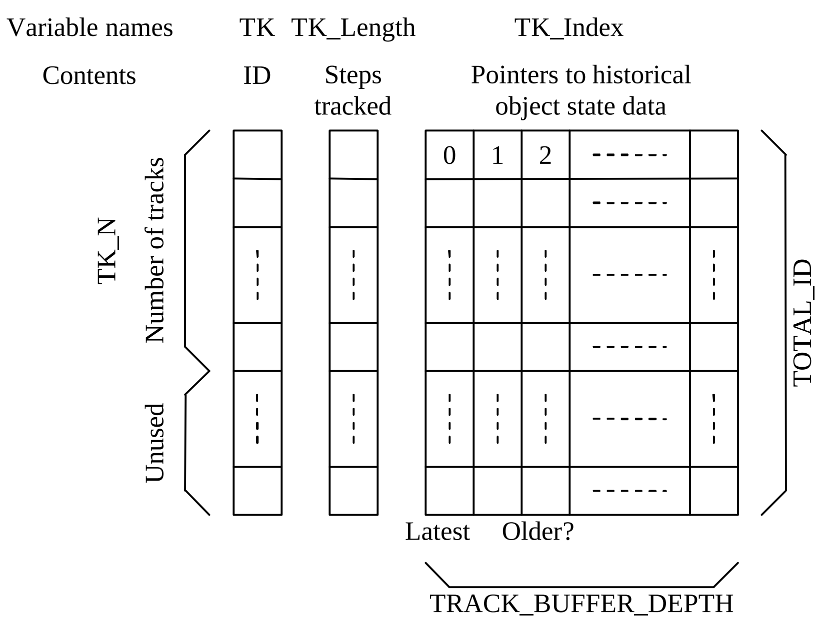


Fig. 64 Track file structure

The top-layer structure of track file is a linear list (see the following figure). Each entry of the list is a track, which contains an ID, a count of steps tracked, and a fixed-length FIFO of most-recent pointers to historical data. Track file is a static structure. Its size is defined by two constants: TOTAL_ID and TRACK_BUFFER_LENGTH. Each sensor has its own track file.

ID queue

Unused ID's are saved in a queue (see the following figure). Whenever a new track is initiated, an ID is pulled out from the queue (pointed by ID_Tail) and assigned to this track. Whenever an old track is dropped out, an ID is released and pushed into the queue. The queue is a static structure. Its size is defined by the constant TOTAL_ID. Upon initialization, the queue is preset with integers from 1 to TOTAL_ID.

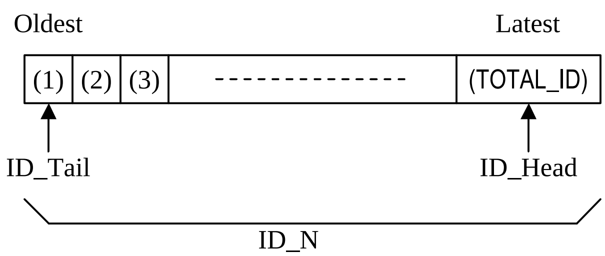


Fig. 65 ID queue structure

Object state buffer

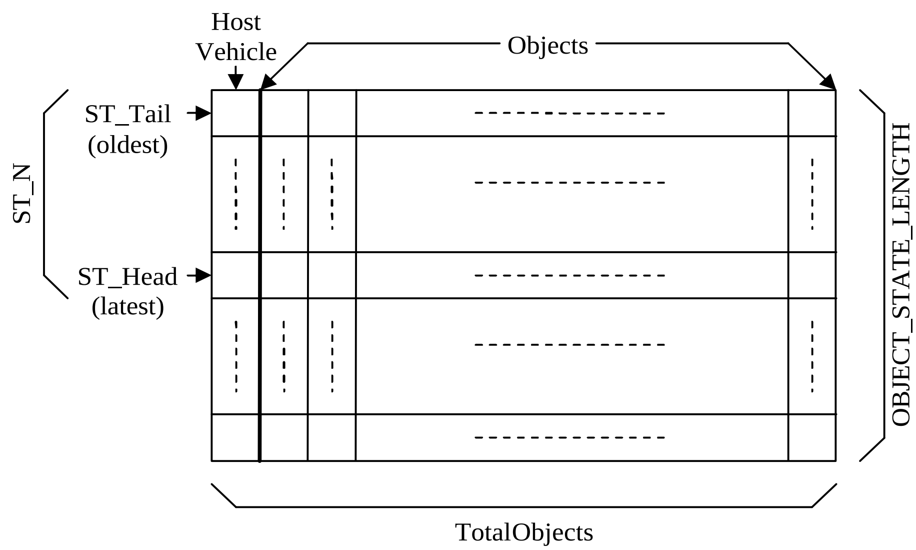


Fig. 66 Object state buffer structure

Object state buffer is a 2D array (see the following figure). The first dimension is implemented as a circular queue; the second dimension is a fixed-length sub-array. The first column of object state buffer is for storing host-vehicle states. Size of object state buffer is defined by two constants: OBJECT_STATE_LENGTH and TotalObjects. Each entry of object state buffer is an OBJECT_STATES structure.

Object state data structure

```
typedef  struct {
        double stime;
        int state,ID;
        double m1,m2;
        double x,y;
        double v;
        double A,C;
        double al,ac;
} OBJECT_STATES;
```

where “stime” is the time when the observation is received from the sensor, “state” and “ID” are track properties, “m1” and “m2” are observations (e.g. range and lateral position), others are estimated states (smoothed states).

Additional information

Additional information may be saved in the track file as well. Currently the time stamp of processing and GPS locations are saved in the track file as additional information.

3.4.4 Data association

Data association for tracking is the process to figure out the correlation between observations and tracks, i.e. to associate observations with existing tracks.

Association metrics

An association metric is a measure of distances between observation-track pairs. An association metric must satisfy the following three criteria:
Distinguish ability: Given any two entities *a* and *b*, the distance between them must satisfy

$$d(a,b) \geq 0$$
$$d(a,b) = 0 \quad \Leftrightarrow a = b$$

Symmetry: Given any two entities a and b, the distance between them must satisfy
$d(a,b) = d(b,a)$;

1. *Triangle Inequality*: Given any three entities a, b and c, the distances between them must satisfy

$d(a,b) + d(b,c) \geq d(a,c)$;

We define the distance measure in 2D space (*x*,*y*) as:
$d(a,b) = |x_a - x_b| + |y_a - y_b|$, where (x_a, y_a) and (x_b, y_b) are coordinates of entities a and b in 2D space.

Gating and assignment

Gating is the process to remove those obviously impossible correlations between observation-track pairs. Multiple observations may fall in the gate of one track. One observation may fall in the gates of multiple tracks. Assignment is the process to determine the appropriate correlations.

Distance matrix

First of all, we calculate the distances between all observation-track pairs, which form a matrix.

Table 16 Distance matrix

Tracks	Observations			
	1	2	----	N
1	d(1,1)	d(1,2)	----	d(1,N)
⋮	⋮	⋮	----	⋮
K	d(K,1)	d(K,2)	----	d(K,N)

where K is the total number of tracks, N is the total number of observations.

Gating

For each observation-track pair, if one of the following criteria is satisfied

1. $if\ TK\_Length < 5\ and\ d(\ ) > 5m;$
2. $if\ 5 \le TK\_Length < 10\ and\ d(\ ) > 4m;$
3. $if\ TK\_Length \ge 10\ and\ d(\ ) > 3m;$

the observation is immediately declared not belonging to this track.

Assignment

We assume that one observation can only be correlated to one track and vice versa.
The assignment logic is:
if $d(k,n) = \min_{i=1\cdots K} d(i,n) = \min_{j=1\cdots N} d(k, j)$, assign observation n to track k.

3.4.5 Host vehicle Data Filtering

Host vehicle state observations are longitudinal wheel speed and steering wheel angle. Host vehicle model is a nonholonomic bicycle model.

Nonholonomic constraint and kinematic model

Nonholonomic constraint means the wheels cannot move sideways. The nonholonomic bicycle model is illustrated in the following figure, where q is front wheel turning angle, L is the wheel-base of host vehicle, v is longitudinal speed of front wheel, R is the turning radius. We have the following equations:

$$C = \frac{1}{R} = \frac{\sin(q)}{L}$$
$$w = vC$$

where C is the curvature, w is the yaw-rate.

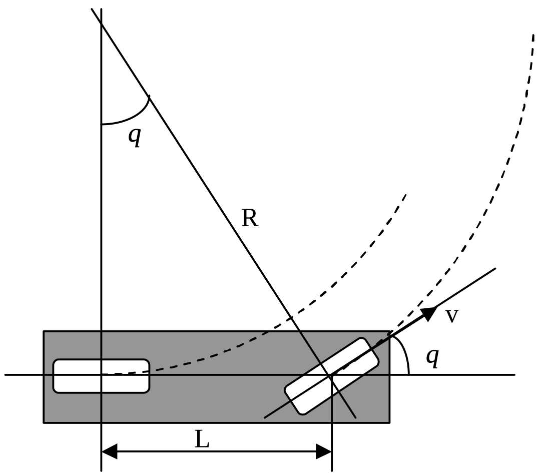


Fig. 67 Vehicle kinematic model

The host vehicle kinematical model with nonholonomic constraint is:

$$\begin{cases} \dot{x} = v \cdot \cos(A) \\ \dot{y} = v \cdot \sin(A) \\ \dot{A} = w = v \cdot C \\ \dot{v} = a_l \\ C = \frac{\sin(q)}{L} \end{cases}$$

where (x,y) is vehicle's position in ground coordinate frame, A is vehicle's headway in ground coordinate system, a_l and q are driver inputs.
This model can be illustrated in the following input-output format.

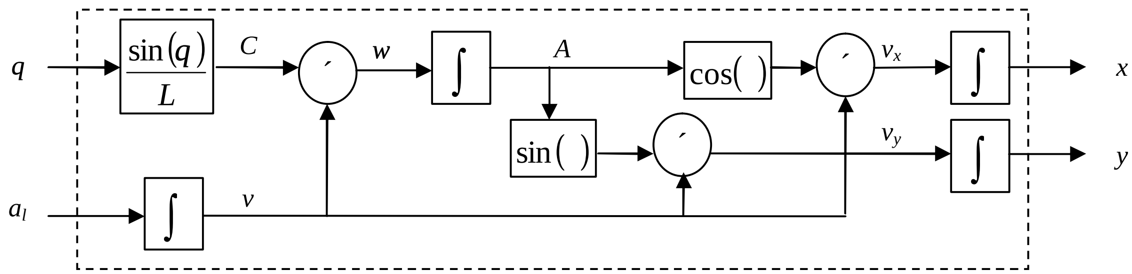


Fig. 68 Vehicle state model

Filtering

Initialization

$$\begin{cases} x(0)=0 \\ y(0)=0 \\ v(0)=v_0 \\ C(0)=\sin(q_0)/L \\ A(0)=0 \\ a_l(0)=0 \\ a_c(0)=0 \end{cases}$$

where v_0 is the initial wheel speed, q_0 is the initial front wheel angle.

Prediction

$$\begin{cases} \hat{x}(k+1)=x(k)-v(k)\cdot dt\cdot\sin(A(k)) \\ \hat{y}(k+1)=y(k)+v(k)\cdot dt\cdot\cos(A(k)) \\ \hat{v}(k+1)=v(k)+a_l(k)\cdot dt \\ \hat{C}(k+1)=C(k)+a_c(k)\cdot dt \\ \hat{A}(k+1)=A(k)+C(k)\cdot v(k)\cdot dt \\ \hat{a}_l(k+1)=a_l(k) \\ \hat{a}_c(k+1)=a_c(k) \end{cases}$$

Update

$$\begin{cases} v(k+1) = a \cdot \hat{v}(k+1) + b \cdot \tilde{v}(k+1) \\ C(k+1) = a \cdot \hat{C}(k+1) + b \cdot \sin\left(\tilde{q}(k+1)\right)/L \\ a_l(k+1) = a \cdot \hat{a}_l(k+1) + b \cdot [v(k+1) - v(k-T)]/[t(k+1) - t(k-T)] \\ a_c(k+1) = a \cdot \hat{a}_c(k+1) + b \cdot [C(k+1) - C(k-T)]/[t(k+1) - t(k-T)] \\ A(k+1) = \hat{A}(k+1) + [C(k+1) \cdot v(k+1) - C(k) \cdot v(k)] \cdot dt/2 \\ x(k+1) = x(k) - [v(k)/2 + v(k+1)/2] \cdot dt \cdot \sin(A(k)/2 + A(k+1)/2) \\ y(k+1) = y(k) + [v(k)/2 + v(k+1)/2] \cdot dt \cdot \cos(A(k)/2 + A(k+1)/2) \end{cases}$$

If $k < T$,

$$\begin{cases} a_l(k+1) = \hat{a}_l(k+1) \\ a_c(k+1) = \hat{a}_c(k+1) \end{cases}$$

3.4.6 Motion Decoupling

Coriolis effect

If Newton's laws of motion are used in a rotating system, the Coriolis effect appears. It introduces apparent components in the motion equations.

Let X_I be the position of a point in an inertial system, T the coordinate of the origin of a rotating system, R the rotation matrix from the rotating system to the inertial system, X_R the observed position of the same point in the rotating system, we have

$X_I = RX_R + T$ or $X_R = R^{-1}(X_I - T)$.

where

$R = \begin{bmatrix} \cos a & -\sin a \\ \sin a & \cos a \end{bmatrix}$ and $R^{-1} = \begin{bmatrix} \cos a & \sin a \\ -\sin a & \cos a \end{bmatrix}$.

See the following figure.

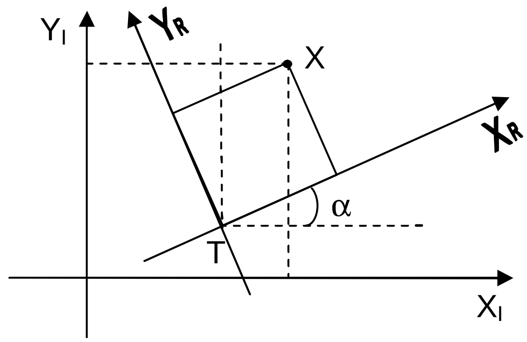


Fig. 69 Coordinate transformation

Then we have

$$\frac{d}{dt}X_R = \frac{d}{dt}R^{-1}(X_I - T) + R^{-1}\frac{d}{dt}(X_I - T)$$

where

$$\frac{d}{dt}R^{-1} = \begin{bmatrix} -\sin a & \cos a \\ -\cos a & -\sin a \end{bmatrix} \cdot w = R^{-1}\begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \cdot w$$

w is the yaw rate of the host vehicle.

Let

$$V_C = w\begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}(X_I - T),\ V_I = \frac{d}{dt}X_I,\ V_T = \frac{d}{dt}T \text{, and } V_R = \frac{d}{dt}X_R,$$

then

$$V_R = R^{-1}(V_C + V_I - V_T) \text{ or } V_I - V_T = RV_R - V_C.$$

When $w = 0$, $V_C = 0$, the relative speed observed in the inertial frame is equal to the speed observed in the rotating frame rotated by the rotation matrix. When $w \neq 0$, $V_C \neq 0$, after the speed observed in the rotating frame is rotated by the rotation matrix, it is not equal to the relative speed observed in the inertial frame. There is an extra component V_C in the rotated non-inertial observation. This is the component caused by the Coriolis effect.

Decoupling algorithm

The problem could be solved by means of augmented state-space modeling which involves both the states of the target and the state of the host vehicle (sensor platform). However the augmented model is computationally complex. To simplify computation, we estimate rotation matrix and position of the host vehicle separately, then the results are used as known to estimate the states of the target. From the states of host vehicle, the rotation matrix and the position of host vehicle are unknown as:

$$R(k) = \begin{bmatrix} \cos A(k) & -\sin A(k) \\ \sin A(k) & \cos A(k) \end{bmatrix}$$

$$T(k) = \begin{bmatrix} x(k) \\ y(k) \end{bmatrix},\ V_T \text{ is the observation.}$$

$$X_I(k) = R(k) X_R(k) + T(k),\ \ X_R(k) \text{ is the sensor observation.}$$

We can now use X_I as observation for target state estimation. In this decoupling algorithm, we have used the initial position and orientation of the host vehicle as the origin and orientation of the reference inertial frame.

3.4.7 Target data filtering

Kinematic model

Primarily we want to detect vehicle-like targets. Target data filtering is based on the same bicycle model as used for host vehicle data filtering.

Filtering

Initialization

$$\begin{cases} x(0) = x_I(0) \\ y(0) = y_I(0) \\ v(0) = 0 \\ C(0) = 0 \\ A(0) = 0 \\ a_l(0) = 0 \\ a_c(0) = 0 \end{cases} \qquad \text{where } \begin{bmatrix} x_I \\ y_I \end{bmatrix} = X_I = RX_R + T .$$

Prediction

Update

$$\begin{cases} v_x = [x(k+1) - x(k-T)]/[t(k+1) - t(k-T)] \\ v_y = [y(k+1) - y(k-T)]/[t(k+1) - t(k-T)] \\ v(k+1) = \sqrt{v_x^2 + v_y^2} \\ A(k+1) = \arctan(v_y / v_x) - p / 2 \\ a_l(k+1) = [v(k+1) - v(k-T)]/[t(k+1) - t(k-T)] \\ C(k+1) = \lfloor A(k+1) - A(k-T) \rfloor_{2p} /[t(k+1) - t(k-T)]/[v(k+1)/2 + v(k-T)/2] \\ a_c(k+1) = [C(k+1) - C(k-T)]/[t(k+1) - t(k-T)] \\ x(k+1) = x(k) - [v(k)/2 + v(k+1)/2] \cdot dt \cdot \sin(A(k)/2 + A(k+1)/2) \\ y(k+1) = y(k) + [v(k)/2 + v(k+1)/2] \cdot dt \cdot \cos(A(k)/2 + A(k+1)/2) \end{cases}$$

If $k < 3T$, then

$$a_c(k+1) = \hat{a}_c(k+1);$$

if $k < 2T$, then

$$\begin{cases} a_c(k+1) = \hat{a}_c(k+1) \\ C(k+1) = \widehat{C}(k+1) \\ a_l(k+1) = \hat{a}_l(k+1) \end{cases};$$

if $k < T$, then

$$\begin{cases} a_c(k+1) = \hat{a}_c(k+1) \\ C(k+1) = \widehat{C}(k+1) \\ a_l(k+1) = \hat{a}_l(k+1) \\ v(k+1) = \widehat{v}(k+1) \\ A(k+1) = \hat{A}(k+1) \end{cases};$$

if target is stationary, then

$$\begin{cases} a_c(k+1) = 0 \\ C(k+1) = C(k) \\ a_l(k+1) = 0 \\ A(k+1) = A(k) \end{cases}.$$

3.4.8 Warning Detection

1. Look into the table in Apendix VI; find the threshold corresponding to the speeds: T(vl,vb); and divide the distance D by the threshold:

   d=D/T(vl,vb)

2. The DVI is designed with seven segments. Warnings are accordingly divided into seven levels. Let mi (i=1,…,7) be the factors in the following lists:

   for least sensitivity (%): 148,132,116,100,84,68,52

   for medium sensitivity (%): 156,140,124,108,92,76,60

   for most sensitivity (%): 164,148,132,116,100,84,68

   and wi (i=1,…,7) be the corresponding warning levels, find the smallest mi that is greater than or equal to d, the corresponding warning level is wi. If d is greater than the m1, no warning is needed, the corresponding warning level is w0.

3.5 SUMMARY

Based on the data fusion model, viz. the JDL model, a preliminary algorithm was developed and integrated into the data playback tool. By playing back the collected data with the warning playback tool, false positive patterns are experienced and analyzed. The algorithm was then improved by decoupling the bus motion from the sensor measurements and by setting the warning threshold according to the drivers' normal braking behavior. As the warning threshold is changed, the leading time of the warning to the potential collision may become shorter than is needed to avoid the collision. This is the trade-off between the drivers' acceptance and the benefit of the collision warning system, under the condition of the current system configuration and the techniques adopted. The shorter response time may be insufficient for avoiding an accident in some situations (not all situations), but it is possible for the loss of an accident to be greatly reduced because of the leading warning. Most importantly, the system becomes acceptable to the drivers. If the drivers don't accept the system because of too many nuisance alarms, even though the leading time is long enough for the driver to avoid an accident, the accident will not be avoided because the driver will not believe the alarm.

The prototype FCWS was developed to evaluate the preliminary functional requirements and technical specifications. It has been realized that the probability of a true collision is so small that suppression of false alarms or nuisance alarms becomes the biggest issue in the FCWS. Object recognition and classification, GPS map utilization, driver status monitoring may all be helpful to remove nuisance alarms in the future. Random models may be better than deterministic models in terms of describing the evolution of vehicle states. These techniques will be considered in the second phase of the FCWS.

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4 DESIGN OF THE FCWS DRIVER VEHICLE INTERFACE (DVI)

The FCWS team has taken significant effort in the design of a prototype driver-vehicle interface for a FCWS. For a comprehensive review of the issues involved in implementing a DVI for a FCWS on a transit bus see Reinach & Everson [22 & 23]. Reinach & Everson provide a detailed analysis of the transit bus operational environment and provide an extensive set of transit bus collision avoidance system DVI interface requirements. In developing the DVI for FCWS, operators and trainers from the SamTrans transit agency were approached for their input on a DVI design as the operators consulted under the Reinach & Everson projects were from dense, east coast, urban cities (Boston & Manhattan). The additional perspective of SamTrans employees was considered useful given the additional environments (suburban, semi-rural) and the different regional driving behavior (Northern California).

This phase of the project culminated in a user center designed visual DVI implemented on a SamTrans bus for a FCWS. A decision was made to build a visual DVI because this was the most commonly accepted format by day operators and since most accidents occur during daylight hours (see section 1). Previous research also suggests that a visual warning display is potentially less annoying than an auditory warning [24] and time constraints meant that it was not feasible to perform testing on different modes with one instrumented bus. However, during the process of designing the visual DVI, information was also collected on different display modalities. It is expected that this information will be used at a later date when other DVI formats will be considered. The information collected on the other display modalities is included in Appendix VIII of this report. This document initially reviews the iterative design process for development of the visual DVI. It should be noted that as with any collision warning system it is critical that the FCWS be accepted by operators [25], and that it not interfere with the primary driving task [26].

The iterative design process involved the following stages: collection of preliminary DVI recommendations, preliminary DVI design and ongoing preliminary DVI design evaluations and refinements. The design and evaluation was realized in six steps/studies which are given in chronological order below:

- SamTrans Operator and Trainer meetings to get supplemental DVI design considerations
- Synthesis of operator input and Human Factors research into preliminary DVI design
- SamTrans Operator and Trainer meetings to get preliminary DVI design feedback
- Operator and advisory committee meetings to get preliminary DVI design feedback plus a ride along on a bus with a working prototype
- Operator training and test drives with the working prototype*
- Ongoing operator review*

Each of these steps/studies will be discussed further below.
Note: * indicates a small study was run.

4.1 SAMTRANS OPERATOR AND TRAINER PRELIMINARY MEETINGS

4.1.1 Method

Interaction with operators occurred in both formal and informal meetings in June 2001. The latter were typically when a human factors researcher was present at the bus yard waiting for a operator or bus to arrive. Trainers were also consulted for input. One member of the project's Advisory Board also provided input based on his expertise as a trainer. Typical interaction involved explanation of the project and FCWS functionality followed by a request for thoughts on appropriate warning methods. When possible, comments on existing CWS warning methods were also requested.

4.1.2 Summary of Operator and Trainer Input

Most of the comments were received prior to description of existing systems. Thus, many of the comments described below can be viewed as being without bias from existing systems. The comments have been sorted into logical groupings presented in the tables below. ”D” indicates operator comments, while “T” corresponds to those from trainers. There were cases where operators’ and trainers’ comments overlapped.

Table 17 Operator comments on the current physical operating environment

Requirement from Operators/Trainers	Comment
D	Cut-ins by other operators are frequent. This is often cited for cars entering highways, *"Out of 20 cars, 19 will try to get in front of the bus."*

Table 18 Operator requirements of a FCWS

Requirement from Operators/Trainers	Comment
T	Lateral scanning is essential. Devoting a third of the operator's attention in each direction (left, center, right) is recommended.
T	For large lead vehicles (trucks), operators should back off or change lanes.
T	Forward looking behavior should emulate a *"yo-yo"* in that operators should look up the road, then back in, then back up the road, etc. The distant look-ahead phase allows more lead time for reactions.
T	Position of the rear wheel is important for turning accidents as it is a pivot point. Operators are expected to locate the rear wheel in their mirrors prior to moving the steering wheel.
T	SamTrans utilizes the Smith System for training. The main topics are: the big picture, keep eyes moving, leave yourself an out, do not get a fixed stare, and aim high (with eyes) for steering. Consistent behavior is also emphasized.
T	Trainers emphasized a general theme that proper operator behavior will lead to no forward or sideswipe accidents at all - even those for which the operator was not at fault.
D	Operators uniformly expressed the opinion that the driving public misunderstands the capabilities of a bus. *"A bus cannot stop on a dime."*

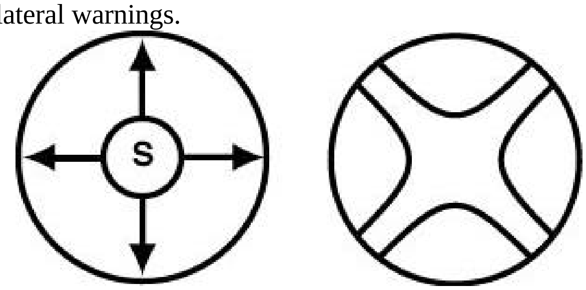
Table 19 Operators comment of when a FCWS would be most helpful

Requirement from Operators/Trainers	Comment
T	Operators cannot be expected to depend on a CWS. It is only a tool for them to use.
DT	A more sensitive system was suggested for training periods. It was felt that this would accelerate operator experience.
D	Any system that can help prevent a chargeable accident (i.e., preventable, at fault) would be popular.
D	Operators dislike passenger falls, especially fraudulent ones. Agreement was voiced with the philosophies of earlier braking rather than harder braking and that warnings should not be readily perceived by passengers. One operator described an experience when the bus made a loud sound due to a mechanical failure. After pulling over to check the bus, some passengers got out and began kneeling and praying - they thought the bus had struck something and that they had been in danger.

Table 20 Operator suggestions for design of the warning

Requirement from Operators/Trainers	Comment
DT	Two modes of display, one for day and one for night was suggested. Night operators tended to prefer sound over light while daytime operators were more interested in visual displays. The operators decided that a system with both audible and visual displays where an operator could adjust the illumination and volume would be worth considering. One trainer agreed that nighttime glare from in cab displays should be avoided.
D	Operators would like the ability to dim or shut off dash lights that they perceive as of little value or possessing high glare, but were under the impression that this was not an option for safety related systems. There was concern that the DVI for CWS systems would not permit dimming or volume control due to the inherent safety nature of the system.
DT	Initial responses often involved either a visual display on the dash and/or an audible warning.
DT	Frequent activation of graded warnings or binary alerts at low risk levels (e.g., long TTC's) were discouraged.
D	Graded warnings or a combination of a binary alert followed by a binary critical warning were considered useful.
D	Highly salient alarms are good for: 1. When a vehicle in front drops speed suddenly with respect to the bus. 2. The forward object is moving slowly and the bus approaches at a much faster speed.

Table 21 Operator comments on visual warnings

Requirement from Operators/Trainers	Comment
T	*"By the time an operator looks at the display, it is probably too late."*
T	A trainer suggested using colors other than those used by current lights if mounted in the instrument cluster. Current lights are yellow, orange, and red.
D	Downward moving tapes on the operator side A-pillar and the center windshield pillar were suggested by the experimenter after operators indicated a desire to keep the forward scene unobstructed. This idea received concern from the night operators as they felt the additional illumination would be a problem. Daytime operators did not comment in either direction.
DT	Operators proposed two similar dash-mounted displays to identify threat locations (see diagram below). For the left-hand design, the arrows would illuminate corresponding to threat locations while the "S" would indicate stationary objects and would be replaced with an "M" for moving objects. The right-hand design would simply illuminate the quadrant for which a threat was present. When the high head-down location proposed in [**22**] was described, operators were not enthusiastic over concerns about obstruction of the forward visual scene. One trainer suggested a dash mounted row or column of three lights. A similar, A-pillar mounted column display was suggested by [**22**] for lateral warnings.  **Operator Suggestions**

4.1.3 Design Paradoxes

The operator and trainer input led to the identification of three major paradoxes:

1. Operators agree with the philosophy of earlier braking rather than harder braking yet they would like as few alerts and warnings as possible.
2. Nighttime operators prefer audible warnings due to concern over glare while daytime operators tended to focus on visual warning options.
3. The warning should be salient enough to elicit an operator response but should not be readily noticeable by passengers.

All three paradoxes are present in the passenger and CVO platforms but are amplified by the potential for passenger falls, especially fraudulent ones. Interestingly, operators were aware of these paradoxes and expressed willingness to give design suggestions for compromise solutions. The following designs are a synthesis of operator suggestions and human factors principles.

4.1.4 Multimodal Displays with Operator-controlled Intensity

Operators voluntarily expressed that the best design might be a combination of audible and visual displays. Nighttime operators have indicated that it is essential that any visual display introduced into the cab have a brightness knob. The additional glare from a high mounted display may introduce problems should this feature not be present. Some have also expressed a desire to be able to fully shut off the visual display and only use other display modalities (in this case, auditory).

As for the visual display, a volume knob is also considered essential by the operators. Daytime operators and trainers indicated that the ambient sound levels within a bus can vary due to passenger load. Furthermore, daytime operators seemed to be more interested in shutting off the auditory warning in favor of the visual display.

Some form of "only one modality can be off" logic may be needed so that operators cannot totally disable the CWS DVI. This is easiest to achieve by providing a primacy switch where an operator can choose which modality he/she would prefer to shut off. This approach may be a simple, yet effective method of resolving the daytime/nighttime paradox.

4.2 PRELIMINARY VISUAL DVI

Human factors principles agree with the observation that any visual display should be mounted above the instrument cluster [22]. This is further emphasized by the assertion that experienced operators very rarely look down at their dashboard. HUDs have proven to not be suitable at this time and operators were averse to consuming any portion of the current field of view. The remaining high mount options are on the left A-pillar and the center pillar (Fig. 70). These locations are also useful in that a vertical oriented display will more naturally mimic the motion of an approaching target. The use of both pillars will allow a limited amount of spatial resolution to occur in that targets that are approaching head-on can be shown with matching column displays while cut-in targets can be shown with single columns corresponding to the direction of the threat.

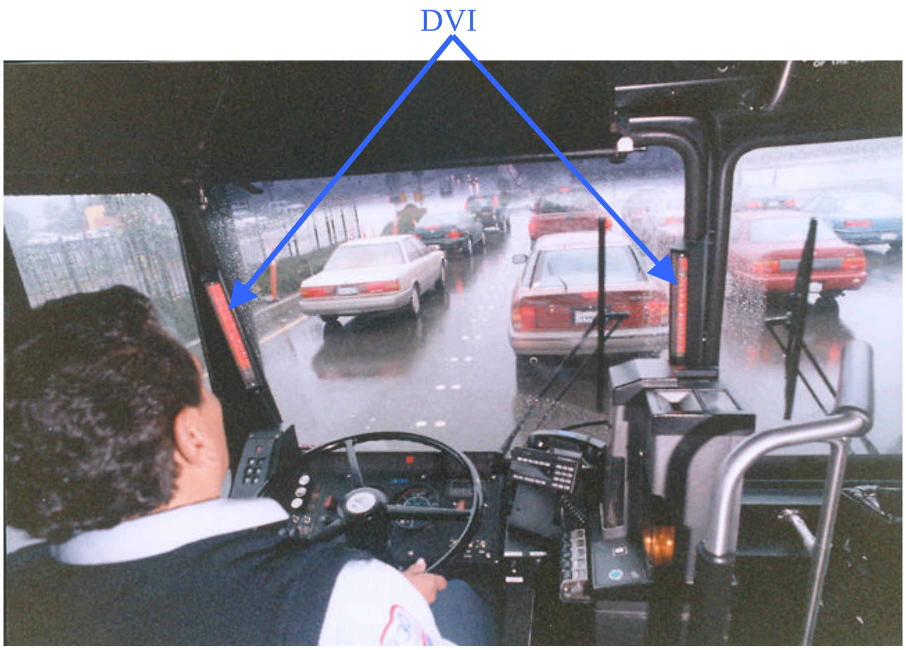


Fig. 70 Preliminary DVI design

Use of the left A-pillar leads to the logical question of interference or confusion regarding lateral warning displays. Operators and trainers both indicated that lateral warning displays should be as close to the mirror assembly as possible. Furthermore, training programs emphasize the need to locate the rear tire in the mirror prior to steering motion. As such, warnings mounted in (e.g., [27]) or on the mirror assembly are more logical than those on the A-pillars. Locating the lateral displays at the mirrors may modify the behavior of operators who do not check their mirrors prior to moving, as the warning display may increase the perceived value of looking at the mirrors.

One important design characteristic is that the columns should utilize color changes for the whole bar. Research on assistive systems for snowplows suggests that operators used the change in CWS DVI color as an important cue for following behavior [**28**].

From the information above a preliminary visual DVI design was developed. The initial preliminary DVI design consisted of seven stacked LED segments (2 LED's across per row). Each segment had the ability to light as yellow, orange, or red. The LED's used have a maximum luminance intensity of 90/60 millicandelas (mcd) and a viewing angle of 100 degrees. The use of large LED segments in this design was intentional since the columns will likely be in the operator's peripheral vision. The apparent motion of the column displays will be more salient given the large segment size. In order to limit passenger observation, a diffusion lens was placed over the LED segments.

Previous human factors research suggests that motion and size can be utilized to convey potential threat levels. In study two different illumination patterns were shown to operators and trainers. In the first illumination pattern segments of the LEDs illuminate in a downward progression as threat level increases. This pattern mimics the motion of an approaching target. This type of motion has been frequently used in passenger CWS DVIs [e.g., 22] and has been effective in the aforementioned snowplow application [28]. The second illumination pattern was the use of looming (growing to ends from the center).

In order to determine to optimum way of conveying the threat level a simulation of different patterns of illumination was developed and tested in the next study.

For the next sections small studies were designed to evaluate either different design concepts or the DVI as a whole. Each small study is broken down into the goal of the study, the method used, feedback and what DVI refinements were undertaken as a result. It should be noted here that all refinements were carefully considered as mid-course changes in design strategies and though can be onerous, the goal was to ensure through operator input a high operator acceptance of the DVI.

4.3 WARNING ILLUMINATION PATTERNS AND PRELIMINARY DVI DESIGN REVIEW STUDY

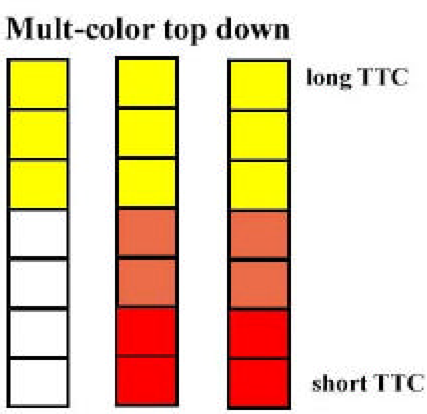
4.3.1 Goal of the study

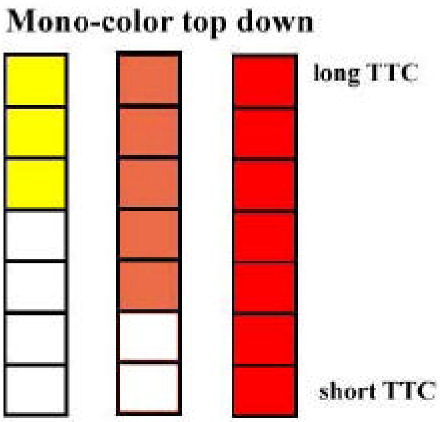
To obtain operator feedback on four different DVI warning illumination methods and on where optimal warning threshold onsets should be set.

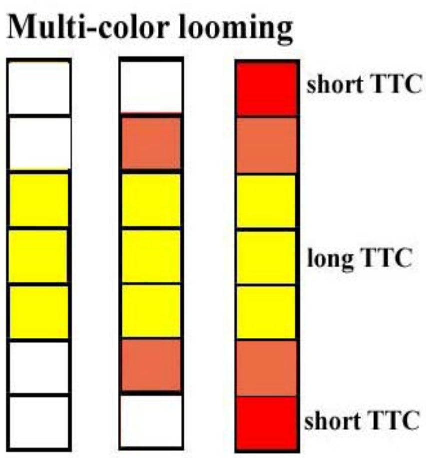
4.3.2 Method

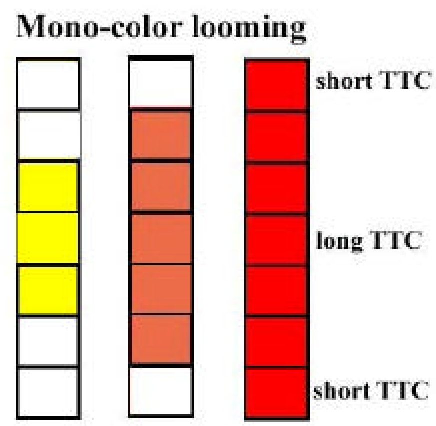
In this session PATH researchers met with operators and trainers in a meeting room at the SamTrans Maintenance Yard in October 2001. The operators and trainers were given a background of the FCWS program and shown pictures of what the DVI would look like both physically and installed on the bus. The operators were given an explanation of Time-To-Collision (TTC) and the circumstances under which the display may be of assistance to them. Operators were then shown a working simulated version that depicted a bus driving from the bus operators' perspective (Fig. 71) with four different warning illumination methods (Table 22 and 23). In addition to the different warning illumination patterns operators were shown different warning activation thresholds. The simulation was run for as long as was requested by the operators/trainers on each of the display/timing combinations.

Fig. 71 Simulated FCWS DVI

<table>
<tr><th colspan="2">Table 22 Top down illumination method</th></tr>
<tr><td>The LED's are lit downwards from the top as the TTC becomes shorter. The growing of the bars is intended to mimic that the target range is becoming shorter and shorter.</td><td>Warning Illumination Description</td></tr>
<tr><td>
</td><td>Multiple colors are displayed as TTC gets shorter. This scheme gives a good feeling of warning grades as the earlier-lit LED's stay on the original colors.
The first three segments are yellow (going from top to bottom), the next two are orange and the last two are red.</td></tr>
</table>

<table>
<tr>
<td>
</td>
<td>One color is displayed at a time. This scheme emphasizes the urgent warnings by changing the color of all the bars as TTC becomes shorter.
The first three segments are yellow (going from top to bottom), when the next two segments light up the whole bar turns to orange, when the last two segments light up the whole bar turns to red.</td>
</tr>
</table>

<table>
<tr>
<td colspan="2">Table 23 Looming illumination method</td>
</tr>
<tr>
<td>The LED's are lit from the middle to both the top and the bottom. The growing of the bars is intended to convey the sense that the visual angle of the target is becoming wider and wider.</td>
<td>Warning Illumination Description</td>
</tr>
<tr>
<td>
</td>
<td>Multiple colors are displayed as TTC gets shorter. This scheme gives a good feeling of warning grades as the earlier-lit LED's stay on the original colors.
The center three segments are yellow, the next two segments (one either side of the yellow) are orange and the remaining two segments are red.</td>
</tr>
</table>



One color is displayed at a time. This scheme emphasizes the urgent warnings by changing the color of all the bars when TTC becomes shorter.
When TTC is long the center three segments are yellow, as TTC gets shorter if five segments are on the color is orange, if seven segments are on the color is red.

4.3.3 Feedback

Feedback from the operators indicated that the operators unanimously preferred the top down mono-color illumination method, as this was the least distracting/annoying and the easiest to interpret. There was some concern over the yellow color with some operators reporting that they found it irritating and were interested in the possibility of canceling this color out. Some operators also reported that they did not associate the color yellow with a threat or a warning. One operator wanted only red to be used. The operators reported that the three colors made the display too visually busy at a time when their attention was needed outside of the bus.

The operators were reluctant to comment on the warning activation thresholds as they felt that this really needed to be tested by driving with a real system.

4.3.4 Outcome – DVI Refinements

A decision was made to use the top-down mono-color warning illumination pattern. It was decided that a decision on canceling out one of the colors and determining optimum parameters for warning activation would wait until the prototype system was tested on a bus.

4.4 ADVISORY COMMITTEE MEETING

4.4.1 Goal of the Meeting

To gather feedback from the advisory committee members on the FCWS project progress.

4.4.2 Method

In December, 2001 PATH hosted a FCWS program review meeting for operators, trainers and members of the advisory committee. At this meeting attendees were given talks on the following subject areas: IVI program status, program overview, and review of technical development, algorithm development, prototype data collection system hardware, DVI design considerations, DVI development, data analysis, data analysis tools, integration project plan and given a demonstration. The demonstration was conducted on a bus driving on both local and freeway streets in the Richmond (California) vicinity with a working prototype system on the bus.

After the demonstration feedback was collected from the meeting attendees on the program in general as well as the DVI development. Only the DVI development feedback will be discussed here.

4.4.3 Feedback

Feedback from this meeting was that:

- The location of the display was deemed to be "perfect".
- That the current DVI is too large. Operators would like to see the display reduced in both height and width "to about the size of Christmas tree lights" was a common comment.
- Optimal sensitivity level(s) for when warning activation should be further refined.
- That the radar or lidar sensor needed to work when the bus is stopped (if possible).
- That three colors in the display required too much visual attention and that removal of the yellow color should be further investigated.
- Night operators expressed concern at the amount of potential glare from the DVI. The night operators reiterated their request for an audible DVI.

4.4.4 Outcome – DVI refinements

A decision was made to reduce the size of the DVI for the DVI to be installed in the second bus and then to compare longer term operator evaluations of the two different size DVIs. The DVI for the second bus was reduced by approximately two thirds in length and consists of a single row of seven stacked LED segments. In addition the yellow color was removed from the DVI.

4.5 TEST-DRIVE STUDY

4.5.1 Goal of the Study

To obtain test-drive operator feedback from the working prototype DVI.

4.5.2 Method

Six operators (one female and five males) were introduced to the system in February 2002. Five operators attended two 1.45 hour sessions. One operator attended only the first session as he was unavailable for the second. The operators' bus driving experience ranged from 2.5 to 27 years with a mean of 14.1 years experience. One operator indicated that they drove predominantly on day shifts, one on night and the other four operators were extra board so drove both day and night shifts as required.

The test drive sessions occurred over a four-day period with the second session occurring after a one day break. The test drive sessions were conducted in two blocks, the first block began at 10 am and the second began around 4:30 pm finishing around 9 pm (we encountered some system problems on the first day so the schedule ran on later into the evening). The intention was to give drivers exposure to the system in both daylight and lowlight conditions. All sessions began in the SamTrans maintenance yard.

4.5.2.1 Session one

Each operator was first given an overview explanation of the FCWS, this included how objects were detected, conditions that the system worked well in and not well in and what the different display illumination methods meant. The operators were then given a system walk-through; they adjusted the display brightness and had their questions regarding the system answered. The operators were then asked to drive the bus in the SamTrans Maintenance Yard and approach stationary objects so that they could see the system working, after which any further questions were answered. The operators were then asked to drive on a local route that they were familiar with (their normal route, if they had one). All of the routes included both local streets and freeway driving. Operators were asked to drive the way that they normally would, including pulling into bus stops where it was practical and safe to do so. Operators did not pull into bus stops where there were buses entering and exiting or where there was groups of people waiting for a bus as we did not want to frustrate and/or confuse SamTrans patrons.

A range of different warning thresholds were tried over the approximately 1.5 hours of driving time.

At the end of each session the operators were asked questions about the system. Responses to the questions can be seen in the table in section 4.5.3.

4.5.2.2 Session two

In the second session operators were encouraged to test the system in any way that they were interested in order for them to see how the system performed. This session took approximately 1.45 hours and again was conducted on both local streets and on the freeway. Areas that operators were interested to test the system on included a section around San Francisco International Airport that was under construction, as they wanted to see how it performed with the construction equipment, concrete pillars and overhead roads, down narrow windy streets and to a hospital exit that had a large dip at the bottom.

At the end of both sessions operators were asked for their feedback on the visual DVI. Answers from both sessions are combined below.

Table 24 Operator Feedback of FCWS System

Question to operators	Number of operators	Response	Comments
Did the system function the way that you thought it would?	6	"Yes"	"It gave alarms close to the distance I would stop at"
Please describe any instances where you felt you should have received a warning but didn't?	1	"Cars cutting in"	"It doesn't always pick up cars cutting in soon enough"
Can you describe any instances where you received a warning but felt that you shouldn't?	1	"Picking up reflective road signs"	"Is a problem particularly in construction areas"
	1	"Picks up parked cars in narrow windy residential streets"	"Picks up too many parked cars on this (particular) street "
	1	"Off ramp guard rails – where the off ramp has a curve, it picks up the outside curve"	"This is dangerous at night as the light impedes vision when need to be able to see the outside curve"
	1	"Sometimes if on freeway and change lane to the left lane it picks up the car in front on right hand side as you go past"	"This directs your attention away from looking over your left shoulder to see if the lane you are moving into is clear" "This is distracting"
Did you like the system?	5	"Yes"	"cool concept" "help drivers to reduce some accidents" "get their attention"
	1	"Overall impression – concept (is) good – but need audible/vibration/blue light"	
Did you find the system easy to	6	"Yes"	

use?			
Would you like to drive with the system the way it currently is?	5	"Yes"	"False alarm level seems – ok"
	1	"No"	"I do not want a visual display" "To many false alarms"
How long do you think an operator would need to become comfortable with the system	1	"No time"	
	1	"1 hour"	
	1	"1 time driving"	
	1	"A couple of hours"	
	1	"A couple of days"	
	1	"Unsure"	
When did the system provide you with the most assistance? (note: some operators indicated more than one response)	1	"Construction areas"	
	1	"Cut in's on the freeway"	
	2	"With pedestrians"	
	1	"In heavy traffic"	
	1	"When operator is inattentive"	
	1	"When turning slowly"	
If you could change/add one feature what would it be?	6	"Creeping after bus has stopped"	
	1	"Give sound/vibration warnings"	
	1	"Would like speech "slow down" "your to close""	
	1	"To always pick up kids in the gutter"	

4.5.3 General Comments

It was generally felt that the FCWS could assist operators in avoiding forward collisions. Operators indicated that passengers in some seats could observe the display and that some negative comments had been made by passengers. One operator felt that there was too much glare from the DVI, the other five operators felt that there was not too much glare. Two drivers noted that there is less glare from the DVI than from many of the other systems on the bus.

In evaluating the DVI it is apparent that the following two main factors affect the operator's acceptance of the DVI: the false alarm rate of the system and the degree to which individual operators are either affected by glare or would prefer not to have a visual display.

While the operators felt that it took a short time to become used to the system (responses ranged from zero time to a couple of days) they did recommend that operators needed to be trained with the system prior to use. The operators did not report any difficulty understanding the top down mono color illumination method.

Operators' comments varied when asked about the different ranges of warning activation thresholds that they experienced. Some drivers could not tell the difference between the different thresholds, so had no comments (probably due to the short nature of their exposure). Two drivers said that they wanted the maximum amount of warning time possible, while two operators said they wanted the minimum number of warnings.

In these drive-alongs it was observed that all of the operators changed on occasion their driving behavior to perform a thorough test of the system. This included speeding up and slowing down behind traffic to test where the alarms were activated.

It was observed by the researchers that there was a wide range of driving styles amongst the six operators (some operators were more aggressive than others). The different driving styles resulted in the operators receiving differing numbers of warnings. This taken with the above differences in operator preferences for alarm warning onset thresholds seems to suggest that operators should have the ability to change the sensitivity of a FCWS. It was also observed that when operators could explain why a false alarm occurred (e.g., the system picked up a fence) they were more satisfied than when they could not tell what an alarm was for.

4.5.4 Outcome – DVI refinements

The decision that future iterations should include alternative display modalities was further confirmed. It was also further confirmed that operators should be allowed the ability to fully shut off one mode. Alternative diffuser covers for the display will be further investigated to see if glare from the DVI can be further reduced. A decision was made to allow the operators to adjust the sensitivity level of when warnings come on and to monitor what their preferences are.

4.6 ONGOING OPERATOR REVIEW

4.6.1 Goal of the Study

To obtain operator feedback after operators have some "in service" experience with the prototype FCWS and the DVI.

4.6.2 Method

Due to changes in bus assignment two new operators were assigned to the bus in March, 2002. As none of the operators who were available to meet from the previous test drive study had been driving the bus in normal service we were unable to do a follow-up assessment of their opinions at this time. The two operators were meet by a researcher on the bus with the prototype system after they had been driving with the system for approximately two weeks. Both operators are very experienced, one with 18.5 and the other with 20 years. Both operators had driven with the system for a little over two weeks. The operators were both driving bus 600, which has the original larger DVI. One operator had been given only a brief description of the system prior to driving, the other had not been given any training prior to using the system for the two week period. While this situation was not ideal it did allow us to get a better understanding of what would happen if deployment occurred without training. In this session the operators were given an explanation of the FCWS asked questions and completed a questionnaire. In addition a limited amount of driving was done in the SamTrans maintenance yard to try out some different diffuser covers in attempt to reduce the glare from the DVI.

4.6.3 Feedback

It should be noted that as this feedback is only from two operators it should be considered preliminary at best, the intention is to gather further feedback both from these two operators and additional operators as time goes forward.

Operators generally felt that they would need a few months of driving before they could fully evaluate the system for issues such as annoyance. One operator reported "tuning out" the "orange warnings" when they went off "too often". The operator was not able to define what period of time was too often.

One operator felt that it would take 2-3 weeks to become comfortable with the system. One driver reported that the system had been helpful in busy downtown traffic (at 6pm) and that it had helped make some driving decisions. **Neither operator reported any situations where the system was distracting or led them to make an inappropriate maneuver or error in judgment.** Both operators were interviewed together and filled out the surveys separately. One operator wanted sound and the other operator did not. Both operators had driven the system in day and night conditions. One operator did report that passengers had asked "what's with the lights", but said that avoiding passenger comments about anything new is near impossible.

Both operators said that they did not have a problem with glare from the DVI. The operators also agreed that out of the alternative diffuser covers tried they preferred the original one.

Operators were asked to rate the DVI on the scale as is shown below:

Table 25 Operator ratings sheet of the visual DVI

Question	Mean Rating	Rating Scale Used
How easy is the system to use overall?	5	(not easy) 1 2 3 4 5 (very easy)
How much do you like the system overall?	4.5	(not at all) 1 2 3 4 5 (a lot)
How well do you think the warnings conveyed a sense of urgency?	4.5	(not at all) 1 2 3 4 5 (a lot)
If you had more time with the system, would you like it more?	5	(no) 1 2 3 4 5 (yes)
Do you think that they system is beneficial in terms of increasing your safety?	5	(not at all) 1 2 3 4 5 (extremely)
How annoying was the system?	1	(not at all) 1 2 3 4 5 (extremely)
How distracting was the system?	1	(not at all) 1 2 3 4 5 (extremely)

4.6.4 Outcome – DVI Refinements

A decision was made not to change the diffuser covers at present, but to investigate other ways to decrease the brightness of the display.

Arrangements were made to develop a laminated "cheat sheet" that would explain the FCWS that could be left on the bus. Arrangements are being put in place to provide training to a larger number of SamTrans operators.

4.7 FUTURE WORK

4.7.1 Operator Acceptance

Ongoing research will be conducted on long term operator acceptance of the current visual DVI interface, this will involve further meetings and drive-alongs. Research will be conducted to further refine optimal levels of false positive alarms. Visual lab studies are planned to determine optimum timings for the sequencing of colors used in the display. Operator feedback will also be collected to compare the larger DVI on the first bus and the smaller DVI on the second bus. Efforts will also be made to further reduce the level of glare and the amount of passenger observation from the visual DVI.

4.7.2 Operator Driving Performance

Analysis of operator driving performance data will be performed to determine if the FCWS changes operators driving in any way. Where possible driver performance data will be compared prior to the introduction of the FCWS and after the introduction of the FCWS. Comparisons will also be conducted between performance with the larger DVI on the first bus and the smaller DVI on the second bus to see if they elicit any different driving behaviors.

4.7.3 Multimodal Displays

Alternative display modalities will be further investigated in future research this will include determining the benefit of implementing redundancy coding with some form of "only one modality can be off" logic. This approach appears to be a simple, yet effective method of resolving the daytime/nighttime paradox.

4.7.4 False Alarms / Display Annoyance

A false alarm is a warning issued when there is no threat to the subject bus at all. A nuisance alarm is a warning given in the case that a collision is correctly forecasted, but the bus operator does not consider it to be a true potential threat for the bus [29 & 30]. Both false and nuisance alarms are incorrect warnings (false positives). While this assessment was intended to address the DVI it is difficult to parse out what operators find annoying about the display from annoyance at the false and nuisance alarm rate. Put another way, even the best display will quickly become annoying if a majority of the alarms are false or thought not to be required by the operator.

In addition to the false positive rate of the system [31] suggests that the false alarm rate (false positives) of other devices in the system must also be considered. This has important implications and should be revisited when the FCWS is combined with other collision avoidance systems.

In discussing the acceptable number of false positives a majority of operators felt that they would need to drive with the system for at least a couple of months to be able to determine how annoying the system would be. Previous research has not provided guidelines for determining acceptable rates [26]. A study to determine acceptable levels of false positive when people are driving their own passenger cars by [32] suggests that individuals show a wide range of annoyance sensitivity. Lerner [32] also suggests that annoyance of false positives rates may change over time. In the same study Lerner et al [32] found that a 4 per hour tone and a one per hour voice false alarm was significantly more annoying than a 1 per hour, 1 per 4 hours or a 1 per 8 hours tone. However, it is unclear how this finding could be applied in the transit bus FCWS environment given the different nature of the vehicle, driver, task and environment.

A number of the operators commented that they felt that their driving patterns would probably change over time with the system so that the number of annoying alarms would probably decrease with time as they "kept better distances from traffic in front". Such a change in driving patterns when collision warning systems have been implemented was found in commercial trucks [33] and in a separate field review [34] of collision warning systems for heavy trucks it was revealed that out of 171 drivers 80 percent reported changing their way of driving. Observation of the operators while testing the system suggested that they quickly learnt points at which they would receive a warning and then changed their driving to keep from getting an alarm. This was particularly true on the freeway, possibly because fewer false positives occurred on the freeway than on local streets. Given the different driving styles and the differing requests for levels of warning time we suggest that operators be given the ability to change the sensitivity threshold of when alarms are activated. This is consistent with previous researcher's recommendations for CWS [31]. This issue will be further investigated in the next phase of this project.

Another factor that became apparent was that false positives were more tolerable if the operators could determine what their cause was. For example, when the system picked up a fence post this appeared to be more tolerable than when the operators could not determine what the system was detecting. It would be interesting to know how this affects long-term use of the system. It would be useful to know if operators adapt by tuning out all alarms or if they ignore alarms that occur in situations that produce the largest numbers of false alarms. This does suggest the need for all operators to be trained on the system so that they can fully understand what situations are likely to cause false alarms.

It was also confirmed at this point that operators were less concerned about the level of false positives if they occurred in the orange warning condition, as the number of false positives increased in the red warning condition operators were more frustrated. One operator reported that they "tuned out" the orange warnings. This is also consistent with previous human factors recommendations that providing a graded warning decreases the tradeoff between giving as few false positives as possible with providing the maximum time for the operator to react [31].

5 CONCLUSIONS

At this point it appears that operator acceptance of the visual DVI and the FCWS as a whole is very high. Operators have indicated that they feel that the system could potentially increase their safety.

It is clear going forward that there is a need to determine what effect (if any) the DVI and the FCWS have on longer term operator performance. It will be particularly of interest to know how the operators use the system, preliminary feedback suggests that there is some tuning out of the orange "advisory" alerts. It will be necessary to determine what long term effect this will have on the viability of the system. Feedback from operators emphasizes that for operator acceptance the following three elements are important:

- Need to reduce/minimize the false positive rate,
- Need to provide the option of alternative display modalities and that operators must have the ability to switch modalities
- Need to allow the operator to adjust the sensitivity of alarm activation thresholds
- Need to provide training to operators prior to their using the system

These studies (though somewhat preliminary) suggest that the iterative design process meet its objective of developing a DVI that supports the operator primary driving task and has a high user acceptance rating.

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Section Three

Development of Preliminary Specifications

5 DEVELOPMENT OF PRELIMINARY SPECIFICATIONS

A number of parties have studied the basis of frontal collision warning/avoidance systems. Eaton VORAD™ developed and commercialized the EVT- series automotive collision warning systems. DELCO and GM, through the Defense Advanced Research Project Agency (DARPA) under the administration of National Highway Traffic Safety Administration (NHTSA), have been working on the Automotive Collision Avoidance Systems (ACAS). DENSO and IBEO developed laser scanners for collision warning/avoidance applications. NHTSA also sponsored a number of projects under the ITS Crash Avoidance Research Program to develop the requirements, specifications and relevant techniques for read-end collision warning/avoidance systems. Publications [35–39] and reports (refs of Burgett [35]) discuss collision warning system requirements.

Although the specifications for collision warning radars can be found in the literature, they may not be suitable for transit bus applications due to the different application environments, host vehicles and driver populations. Each of these elements is considered in further detail below.

(A) Application environment differences

Most of the commercial collision warning systems and sensors were primarily developed for highway applications. Transit buses usually run at lower speed in urban streets for public transportation services. The movement of buses is typically stop-and-go. The traffic environment in urban streets is more complex than that of freeways and highways. Along bus routes, more objects, such as trees, poles, traffic signs, parked cars, pedestrians, bicycles, motorcycles, and other vehicles, may be encountered. The stationary objects in urban streets, e.g. the parked cars, cannot be simply discarded, because it is possible that the bus is on a collision course with them.

(B) Host vehicle differences

Most of the commercial collision warning systems and sensors were designed for passenger cars and freight trucks. Transit buses are designed with lower maneuverability in comparison with cars and trucks to ensure reliability and safety. The acceleration/deceleration, steering sensitivity and capability are restricted to prevent on-board passenger injuries. It takes more time to maneuver a bus to avoid a crash.

(C) Driver differences

The bus operators are professional drivers. They are well trained. Their reaction to a critical situation may be more efficient than usual individual passenger car drivers. But their workload is relatively high during driving. The drivers need to: operate the bus, collect fares, respond to passenger requests and dispatching commands, keep up with the schedule, pull the bus in and out the bus stops and take care of passengers. If not designed appropriately, a collision warning system on the bus can distract the driver and increase their workload. Driver acceptance should be emphasized in transit applications.

The following sections provide supporting documentation on the performance specifications. It should be noted that this document is based on the developers' knowledge and understanding about FCWS at this time. As the project continues into the next phase, additional specification items may be added.

5.1 DEVELOPMENT OF TECHNICAL SPECIFICATIONS

5.1.1 Subject Vehicle-Status-Sensing Capability

For a collision warning system mounted on a transit bus, the subject vehicle is the bus, in other words, the bus is the platform for the collision warning system. Motion of the subject vehicle obviously will influence the performance of the collision warning system. The motion of the subject vehicle can be characterized by longitudinal and lateral kinematical states. The longitudinal states can be represented by speed and acceleration. The lateral states can be described by lateral speed, yaw rate, or front wheel angle. Given the wheelbase of the bus, if the longitudinal speed (one of the longitudinal states) is known, these three quantities are equivalent to each other. We choose front wheel angle to represent the lateral states.

(A) Speed

The maximum bus speed is restricted. The Gillig bus design specification has a maximum speed of 64mph (28.5m/s). In the data that PATH collected, the maximum recorded bus speed is 31.5m/s (70.8mph), this occurred when the bus was moving on a downhill highway. The maximum bus speed that the system can measure is specified to be at least **33.3m/s** (75mph), this should ensure that the FCWS will cover all maximum possible bus speeds.

When a bus is stopped the bus speed is zero. The minimum bus speed that the system can measure is specified to be no greater than 0.5m/s (1mph). The reason that the minimum speed is not specified as zero but 0.5m/s is that when the bus speed is below this minimum value but greater than zero, the bus is creeping. If the creeping continues, a creeping warning should be issued, regardless of whether there is an obstacle in a collision course with the bus. It is optimal though not a requirement that the FCWS functions if a creeping warning is issued. The EVT-300 Eaton VORAD™ collision warning system has host vehicle speed coverage of 0.5-120 mph (0.8-190 km/hr, or 0.2~52.8m/s).

(B) Acceleration

The accelerating performance of the bus is restricted. The Gillig bus takes at least 2.05sec to speed up to 10mph from rest, 6.33sec to 20mph, 12.87sec to 30mph, 23.0sec to 40mph, 38.2sec to 50mph, 60.37sec to 60mph; the peak deceleration (slowing down) of Gillig bus is 23.8ft/sec^2 (7.25m/s^2), average deceleration usually is between 6.4-9ft/sec^2 (1.95-2.74m/s^2) (J. Moon of Gillig). Average acceleration of Gillig bus in the first two seconds is 2.17m/s^2. In the data that PATH collected, the maximum bus acceleration recorded is 0.523g (1g=9.8m/s^2); the maximum bus deceleration is 0.692g. The maximum acceleration/deceleration that the system can measure is specified be at least **0.55g/-0.75g** (negative for deceleration). The minimum bus acceleration/deceleration that the system can measure should be no greater than ±0.05g. It is better if all possible accelerations /decelerations are covered.

(C) Wheel angle

In the data that PATH collected, the maximum front wheel angle recorded is 45.5 degrees to the right, 50 degrees to the left. The maximum front wheel angle that the system can measure is specified to be at least 50 degrees for both right and left.

Note that a real FCWS doesn't necessarily have to measure these states to fulfill the warning function. However, the system must be functioning when the bus states are within these specified ranges.

5.1.2 Object-Sensing Capability

5.1.2.1 Spatial coverage and resolution

As is shown in the specifications the spatial coverage of transit FCWS is illustrated in Fig. 72. The coverage proposed herein is the minimum system requirement for object detection. The system may cover larger areas.

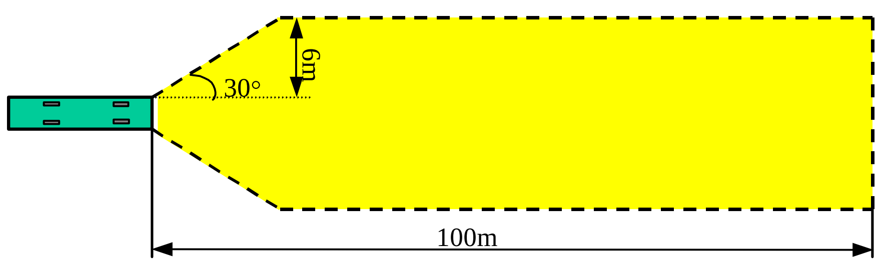

Fig. 72 Spatial coverage illustration

Based on the Stopping Distance Algorithm (SDA) and Closing Rate Algorithm (CRA), Kenue [39] conducted Monte-Carlo simulation to assess how the maximum range and azimuth angle selection affects the accident detection rate of a FCWS. The decelerations of both the lead vehicle and the host vehicle, and total delay time, including the driver reaction, sensor processing, and brake reaction time were taken into account in the simulation. The conclusion is that "further increasing the range beyond 300 feet does not increase the potential accident warning rate and that multi-beam sensors have a higher probability of accident warning as the number of beams increase." (p 497). Where micro-wave sensors are used multiple beams cover adjacent lanes. The recommended azimuth angle coverage at 250-275 feet is 8-9 degrees, as this can cover adjacent lanes on a curved road.

The EVT-300 Eaton VORAD™ collision warning system has a range coverage of 0.9-110 meters (typical); azimuth angle coverage of 12 degrees (6 degrees to both the right and the left). The Denso laser scanner covers up to 160m with 10 degrees to both the right and the left (20 degrees in total). [38] suggests that multiple beam micro-wave sensors should have a range coverage of 100-150 meters with +/-1m resolution, and 10-14 degrees azimuth Field Of View (FOV).

We specify the maximum range as 100 meters. This can be calculated from the extreme situation given bus speed 28 m/s, deceleration 5m/s^2, facing a static object, driver's typical reaction time .75s. The distance that is needed to stop the bus is 28*28/5/2+28*0.75=28*3.55=99.4 meters. This calculation shows 100m maximum range shall cover most of the potential accidents.

We specify the azimuth coverage as 30 degrees with a coverage range of 12 meters at the maximum angle. The wider angle is for early detecting cut-in vehicles. Review of the accident data and field data suggests that cut-ins happens more often in front of a bus and that passenger car drivers usually pass a bus rather than follow it. The 30 degree coverage assures that the system can detect the front half of a passenger can in the next lane when the car's back is in line with the bus front bumper. It should be noted that the 30 degrees is not necessarily the nominal azimuth angle coverage of a specific sensor, because the range requirement at the maximum angle, that is 6*2=12 meters, is much shorter than that for the forward direction. For a microwave radar, the nominal azimuth FOV is usually defined as the 3dB beam width. The lateral coverage is specified as 6 meters to cover one and half lanes.

5.1.2.2 Timing and update rate

(A) Delay

See 5.3.1.2 (A) for delay specifications explanation.

(B) Update Rate

The sensor data update rate is specified to be at least 10 Hz. This update rate is required because the tracking algorithm shall associate consecutive measurements to refine the object state estimations. This update rate assures that the association area will not exceed 3 meters, which is approximately half the size of a passenger car.

5.1.3 Warning system

5.1.3.1 Power supply

(A) Voltage

The power supply should be compatible with the bus battery, i.e. 12V or 24V DC as this provides the most convenient power supply interface. High voltage is prohibited on transit buses because of safety considerations.

(B) Power consumption

The Gillig buses can provide 300+ watts power capacity for extra electronic equipments. The total warning system power consumption should be no greater than 100W to reserve some capacity for other systems, such as side- and rear- collision warning systems. The Eaton VORAD™ EVT-300 power requirement is 20W.

5.1.3.2 Processing capability

(A) Delay

The processing delay from system input to output should be no longer than 0.5 s (this includes the maximum 0.3s sensor delay). The sensor delay is needed to collect data to estimate speed from position measurements or acceleration from velocity measurements. The extra 0.2s system delay is needed to assess the situation. Longer delay may help to improve the accuracy of estimation and assessment; however it is unacceptable because the human driver will realize the system delay. Too much system delay will negatively affect the system performance as warnings may either be displayed too late for the operator to respond to them or they may arrive after the operator is responding to the potential threat which will either distract the operator (which could have hazardous consequences) and/or decrease operator trust in the system. Any decrement in operator trust may lead the operator to ignore the system. Previous research on the development of a lane change, merging and backing collision avoidance system [46] found that drivers did not notice a delay of .5 seconds.

(B) Update rate

The system processing batch rate should be at least 2 Hz. More frequent update of warning information may improve the timeliness of the warning, but warnings that are shorter than half a second will be annoying. Once a warning is detected, the signal sent to the DVI is suggested to keep on for about half a second.

5.2 DEVELOPMENT OF PERFORMANCE SPECIFICATIONS

5.2.1 Object Presence Detection Performance

The object presence detection performance is a matter of output Signal-to-Noise Ratio (SNR), i.e. how well the system can suppress noise and clutters. It is convenient to use probability of detection (P_d, true object detection) and probability of false alarm (P_{fa}, false object detection) to describe detector performance. The relationship between SNR and (P_d, P_{fa}) can be found in the *Radar Handbook* [40]. False alarm time is defined as the average time between false alarms. False alarm time is a more practically useful concept, which is equivalent to P_{fa}.

Colgin [41] reported a mathematic model for simulating FMCW radar performance at 76.5GHz working frequency. The model calculates radar performance in distributed background clutter, along with atmospheric attenuation, due to air, rain, snow or fog. Multi-path effect and target fluctuations are taken into account. The model was calibrated assuming that a $1m^2$ non-fluctuating target at 100m produces a SNR of 24.1dB at the peak of the beam and the peak of an FFT filter. The report shows the Signal-to-Clutter plus Noise Ratios (SCR) in: ground only clutter, ground plus rain clutter, ground plus snow clutter and ground plus fog clutter, at 24.1dB, 21.2dB, 22.8dB are 24.0dB respectively. The *Radar Handbook* reports that for non-fluctuating targets, this level of SNR can bring P_d to almost 100% and lower than 10^{-12} P_{fa}, for the Swerling case 1 fluctuating targets, this level of SNR can bring to 90% P_d and 10^{-6}~10^{-12} P_{fa}.

We specified the average P_d and P_{fa} in all possible atmospheric conditions, with 99% P_d allowing one false alarm in every two hours. Atmospheric condition is a critical factor that affects the detector performance. In rainy, foggy or snowy days, P_d may be a little bit lower than the specification, or false alarm time may be slightly shorter than the specification. The specification is based on the assumption that there are 10% of rainy days, 10% of foggy days, 10% of snowy days and 70% of clear days. To avoid confusion the terms true object detection and false object detection are used in the specification.

5.2.2 Collision Detection Performance

A false alarm is a warning issued when there is no threat to the subject bus at all. A nuisance alarm is a warning given in the case that a collision is correctly forecasted, but the bus operator does not consider it to be a true potential threat for the bus (see Burgett's interpretation [30] and [31]). Both false and nuisance alarms are incorrect warnings (false positives).

Traffic safety facts show that nationally 1.8 million rear-end crashes happen annually, while the same drivers brake perhaps 10 trillion times to prevent a crash [35]. This indicates that the probability of a real crash is very low, approximately 10^{-7}. The probability of a false object detection is very low as well, see the previous section for false object detection probability. It is therefore evident that most of the warnings will be nuisance alarms.

Prior Human Factors research reports that drivers try to match their response rates to the reliability of the warnings ([44] and refs). It will be distracting and disturbing to the driver if warnings are issued too frequently, as most of the warnings are nuisance alarms which bring little information to the driver. But if the system never emits a warning, the driver may be startled by first warning and not respond appropriately [45]. This implies that the appropriate warning rate must be within a range, and the warning rate is driver-dependent.

In the development work for this project operators felt that they would need to drive with the system for at least a couple of months to be able to determine appropriate levels of nuisance alarms. Previous research has not provided guidelines for determining acceptable rates [47]. A study to determine acceptable levels of false positive when people are driving their own passenger cars by Lerner et al [47] suggests that individuals show a wide range of annoyance sensitivity. Lerner et al also suggests that annoyance of false positives rates may change over time. In the same study [47] found that a 4 per hour tone and a one per hour voice false alarm was significantly more annoying than a 1 per hour, 1 per 4 hours or a 1 per 8 hours tone. However, it is unclear how this finding could be applied in the transit bus FCWS environment given the different nature of the vehicle, task, driver and environment. In the absence of any specific guidelines we suggest setting a preliminary warning rate range of within 1 to 4 warnings per hour. This rate will be updated as further studies are conducted in this area.

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6 Transit Bus Frontal Collision-Warning Systems: Preliminary Performance Specifications

6.1 INTERFACE REQUIREMENTS

This performance specification represents the research conducted under the Transit Bus Frontal Collision Warning System project sponsored by the Federal Transit Administration (FTA) in 1999. The goal of this project is to develop performance specifications for transit bus frontal collision warning systems (FCWS).

This work was undertaken in conjunction with the FTA by California PATH of UC Berkeley, in partnership with San Mateo County Transit District (SamTrans) in California, California State Department of Transportation (Caltrans) and bus manufacturer Gillig Corporation (Gillig).

PATH began this project by conducting the following tasks:

1. A literature review to determine the impact of frontal collisions on the transportation industry and to determine if any similar systems are currently deployed
2. A review of transit bus accident statistics in the San Francisco Bay Area (California)
3. Development of a kinematical model showing movements of the bus and surrounding vehicles prior to a collision
4. The development and implementation of a data collection system including sensors, cameras, and data recording devices on a SamTrans bus
5. Ongoing industry discussion with San Francisco Bay Area transit agency advisory committee members
6. Ongoing Bus Operator meetings with SamTrans employees

In conjunction with the above tasks, PATH developed a prototype FCWS on a Gillig manufactured SamTrans owned bus to verify the specifications for the FCWS (see the final project report for further details). It is important to note that as these specifications are based in part on information collected from the PATH developed prototype used by SamTrans employees on regular normal services in the SamTrans service area, it has not been validated in any other area, on any other bus, or with operators outside of SamTrans employment.

Some items in this document are expressed in terms of sensing capabilities, these are not requirements for specific sensors, they should be considered as the working condition requirements for a FCWS. Other items (for example, the collision detection and driver vehicle interface characteristics) are given as design considerations rather than specifications due to the complex nature of the issues involved and the fact that there may not be one best way to specify for future developers or that the issue requires further verification in a longer term study with a working system. It is envisaged that in these cases the function of the system should be recommended and that developers should meet those functional requirements.

This document represents the developers' current understanding of FCWS requirements. It might not be a complete set of requirements for FCWS. As the development efforts continue, additional specification items may be added.

6.1.1 Definitions

6.1.1.1 System functions

The functional goals of the FCWS are to address imminent potential crashes, by providing a warning to the operator in unsafe situations and to provide environmental guidance for smoother maneuvering. The primary goal of the frontal collision warning system is to predict imminent potential crashes, or collisions with objects. To achieve these goals the collision warning system must have the sensing capability to gather information from both the subject vehicle and the surrounding environment (subject and object sensing). The system then must fulfill the following five basic signal and data processing functions: object detection, object status estimation, collision detection, collision severity assessment, and generation of warning signals.

(a) Subject and object sensing

A FCWS may need to: assess the bus status, detect operator actions, obtain environment information, and measure object status. Sensors will be used to provide the necessary inputs to the system. The system sensing capability can be divided into two categories: subject vehicle status and object status sensing.

(b) Subject vehicle status sensing

Subject vehicle status sensing refers to the acquisition of information on operator operations and the current kinematical states of the bus. Examples of subject vehicle status sensors are: speedometers, accelerometers, brake pressure sensors, steering angle sensors, and GPS receivers.

(c) Object status sensing

Object sensing refers to the acquisition of information from the environment (for example, road curvature), the presence of other objects (for example, vehicles and pedestrians) and the current kinematical states of the objects. Examples of sensors for object status sensing are microwave radars, laser radars, imaging sensors and ultrasonic sensors.

6.1.1.2 Signal and data processing

(a) Object detection

The function of object detection is to tell if there is an object within the monitoring coverage of the collision warning system.

(b) Object status estimation

The function of object status estimation is to determine the kinematical states of an object; these states may include such information as spatial position, velocity and acceleration of an object.

(c) Collision detection

The function of collision detection is to determine if the bus and an object will collide in a certain period of time.

(d) Collision severity assessment

The function of collision severity assessment is to determine the potential severity of a collision by assessing such factors as the probability of a collision, time to the potential collision and the likely damage of a collision.

(e) Generation of warning signal

This function generates the warning signals that are displayed to the operator.

Note: Some radars and lidars may already implement functions (a) and (b) as preprocessing functions.

6.1.2 Driver-Vehicle Interface (DVI)

The DVI reports the outputs of the FCWS to the operator for appropriate corrective action. These signals are presented via displays whose modalities may include any of the following: visual, auditory, tactile (vibration), and/or haptic (force). Displays may use a combination of binary and graded warnings.

(a) Binary warnings

Binary warnings are those which are either on or off. They may include a ramp-up in amplitude or other characteristics; however, these ramp-ups are independent of the scenario (e.g., the volume increases quickly over 0.5 seconds every time the alarm sounds).

(b) Graded warnings

Graded warnings indicate multiple levels of warning and may be continuous or discrete in nature. The level of warning is tied to the measure of warning necessity.

6.2 TECHNICAL SPECIFICATIONS

6.2.1 Transit Bus Status Sensing Capability

The following items specify the sensing capability requirements. The transit bus interface should include signals for speed, steering angle, and provide system power. All system interfaces should be non-invasive to prevent interference with transit bus operation. The FCWS should be functioning in the following given conditions.

6.2.1.1 Speed

The maximum bus speed that the system can measure should be at least 33.3m/s (75mph). The minimum bus speed that the system can measure should be no greater than 0.5m/s (1mph). It is more preferable if all possible speeds are covered. The scalar speed sb of the bus should be known to within 5 %.

6.2.1.2 Acceleration

The maximum subject vehicle acceleration/deceleration that the system can measure should be at least 0.55g/-0.75g (1g = 9.8m/s^2, negative for deceleration). The minimum bus acceleration that the system can measure should be no greater than ±0.05g. It is more preferable if all possible accelerations/decelerations are covered.

6.2.1.3 Wheel angle

The maximum front wheel angle that the system can measure should be at least 50 degrees to both right and left. It is more preferable if all possible front wheel angles are covered. The Yaw-rate $\dot{q}_b$ of the bus should be known to within +/- 1 deg/sec.

6.2.2 Object-Sensing Capability

6.2.2.1 Spatial coverage and resolution

Spatial coverage is illustrated in Fig. 73. The coverage proposed herein is the minimum system requirement for object detection. The system may cover larger areas.

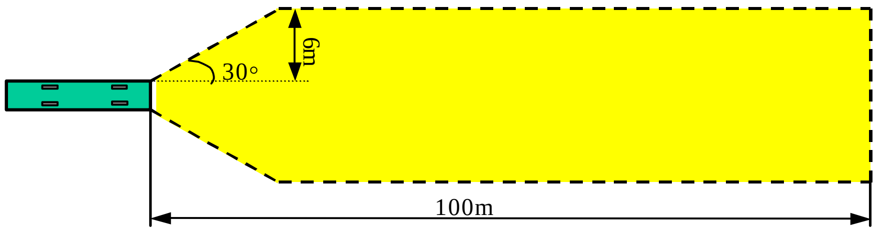


Fig. 73 Spatial coverage illustration

6.2.2.2 Range

The farthest detectable range in the same lane should be at least 100m (330ft). The closest detectable range in same lane should be no greater than 3m (10ft). The resolution should be finer than 1m (3.3ft).

6.2.2.3 Range-rate

The maximum detectable range-rate should be at least 20m/s (45mph, separating). The minimum detectable range-rate should be no greater than -44m/s (–100mph, approaching). It is more preferable if all possible range-rates are covered.

6.2.2.4 Azimuth or lateral position

The maximum detectable side-looking angle from the front bus corners should be at least 30 degrees. The maximum lateral position should be at least 6m (20ft).

6.2.2.5 Elevation field of view

The field of view in the forward looking direction is 4DEG.

6.2.2.6 Timing and update rate

(a) Delay

The sensing delay from sensor input to output should be shorter than 0.1 s.

(b) Update rate

The sensor data update rate should be at least 10 Hz.

6.2.2.7 Sensor alignment requirements

(a) Spatial alignment

Most sensors for object sensing measure the environment in their own coordinate frames. These measurements need be transformed to a common system coordinate frame which is fixed with the subject bus. Calibration may be needed to determine the spatial relationship between the sensor coordinate frames and the common system coordinate frame. It should be easy to do field calibration of these systems.

(b) Temporal alignment

Sensors and computers may have their own timing clocks which are running independently. Different sensors may have different delays or update rates. From the system point of view, sensor measurements should be aligned in time to ensure that the data collected simultaneously from all sensors is describing the same scenario at the same instant.

(c) Metrological alignment

All measurements should be converted into the same metrological system.

6.2.2.8 Sensor protrusion

All sensors shall not protrude more than 6 inches outside the envelope unless a sufficient guard is put into place.

6.2.2.9 Sensor cleaning

All sensors shall be operational with only one daily cleaning. The cleaning procedure should be provided in the systems operational procedure.

6.2.3 FCWS Power Requirements

6.2.3.1 Power supply

(a) Voltage

The power supply should be compatible with the bus battery, i.e. 12V or 24V DC.

(b) Power consumption

The total FCWS power consumption should be no greater than 350W.

6.2.4 FCWS Processing Capability

6.2.4.1 Latency

The processing delay from system input to output should be no longer than 0.3 seconds (this includes the maximum 0.1 second sensor delay). The FCWS shall compensate for this computational latency in the probability calculations and generate the safety level at the correct time

6.2.4.1 Update rate

The system processing batch rate should be at least 2 Hz.

6.3 PERFORMANCE SPECIFICATIONS

6.3.1 Object Presence Detection Performance

6.3.1.1 Probability of true object detection

The probability of true detection of a passenger-car-like object should be greater than 99.9%.

6.3.1.2 False object detection time

False object detection is defined as a target detected without any substantial object presence. The mean time between two consecutive false object detections should be at least 2 hours. It should be noted that a false object detection does not necessarily lead to a false collision detection, because a warning is issued only if the system determines that the falsely detected object is on a collision course with the bus.

6.3.2 Collision Detection Performance

A false alarm is a warning issued when there is no threat to the subject bus at all. A nuisance alarm is a warning given in the case that a collision is correctly forecasted, but the bus operator does not consider it to be a true potential threat for the bus. Both false and nuisance alarms are incorrect warnings (false positives). Given that by definition what constitutes a nuisance alarms is determined by operators it can be expected that nuisance alarm rates will be driver-dependent. Previous human factors research suggests the need to balance the total number of alarms with the number of false alarms.

6.3.2.1 False positive rate

Previous human factors research suggests that too many false alarms will result in a loss of operator confidence and trust in a system. This loss of confidence and trust can lead operators to either ignore the system or spend valuable time verifying each alarm; both of these options will decrease the effectiveness of the system. The FCWS shall generate less than 5% False Positives.

6.3.2.2 Total number of alarms

If the total number of false and nuisance alarms is kept to a minimum and given that the probability of a real crash is very low, it is likely operators will not receive any alarms for long periods of time. In this case when an operator does receive an alarm the alarm may produce a startled response resulting in a longer response time which will decrease the effectiveness of the FCWS. It has been suggested that some false and nuisance alarms will minimize this effect.

This implies that the appropriate warning rate must be within a range, and the warning rate is driver-dependent, i.e. the optimal warning rate for different drivers may be different. The acceptable warning rate issue is still under investigation in the field of human factor. See 0 for considerations of correct warning performance.

6.3.3 Warning Algorithm Performance

6.3.3.1 Safety levels for FCWS

The FCWS shall generate the appropriate safety level as defined below based on object type, probability of collision, and time to collision, as given by the following charts

Alert — Potential obstacles exist and may pose a collision hazard.
Warn — Collision is imminent without evasive action.

6.3.3.2 Warning thresholds

Whatever safety measures are used, warning thresholds which are to be compared with the safety measures should be able to match with drivers' normal operational performance. Diversity of driver performance should be taken into account, thus multiple sensitivity levels may be needed to provide sensitivity options for drivers.

6.3.3.3 Warning algorithm hysteresis

The FCWS shall provide hysteresis in generating safety levels to prevent toggling of the DVI Inputs. Safety levels will be output for a minimum of 0.5 seconds unless overridden by a higher safety level.

6.4 SUGGESTED DESIGN CONSIDERATIONS

6.4.1 Correct Warning Performance

6.4.1.1 Correct warning probability

Under the condition in section 5.2.2, the total detection probability of correct warnings should be as high as possible, and the warning should be displayed to the operator as early as possible, so to minimize any potential damage.

6.4.1.2 Odds of a correct warning

A correct warning occurs when the situation (including the operator) requires a warning. The specification of odds of a correct warning shall be determined in the field test. The odds of a correct warning should be as high as possible. We will investigate this issue further in phase two of this project.

6.4.2 Operator behavior performance

6.4.2.1 Response time

It will be necessary for a transit bus FCWS to induce a response no slower than under normal conditions. Even small savings in response time can be considered beneficial as they will impact on the probability of a crash. In the event of a crash, small improvements in response time will reduce the severity as the speed of the bus will likely be lower.

6.4.2.2 Braking behavior

Due to the risk of passenger falls the system should promote earlier braking rather than harder braking.

6.4.2.3 Swerving behavior

Due to the size and mass of transit buses it is preferred that the system does not induce excessive, swerving behavior. Swerves that are executed with complete situational awareness are not as risky, but in surprise conditions the operator may not be fully aware of objects to the side of the bus.

6.4.2.4

Passenger considerations

A major concern of transit agencies is passenger falls. The system displays (visual, audible, etc.) should not be readily observable by the passengers. This will reduce the risk of fraudulent passenger fall claims and causing unnecessary surprise or concern from passengers.

7 Summary

Analysis of accident data collected from selected Bay Area and California transit agencies indicates that frontal collisions constitute 20-30% in statistics and 30-40% of cost of all transit related accidents. These collisions typically result in property damage, service interruptions and personal injuries while contributing to an increase in traffic congestion. This projects accident analysis, feedback from transit agency representatives from the Bay Area Transit Advisory Committee, and driver feedback indicate that an effective collision warning system could help to reduce the likelihood of accidents and facilitate smooth driving.

Previous collision warning and collision avoidance systems have focused exclusively on highway applications for trucks and light-duty passenger cars. No previous work was found on frontal collision warning systems for transit buses. The research for this project suggests that there are two fundamental differences between a transit collision warning system need and that of a highway truck or light-duty passenger car system. The first is the operating environment, an urban and suburban operating environment is dramatically different from those targeted in previous studies. The different environment presents a considerable challenge with respect to the presence of a much larger number of objects needing to be screened for hazards and due to the more complicated traffic patterns. Secondly as transit bus drivers are professional drivers they may have different needs from and sensitivities to a collision warning system. In the process of the developing requirement specifications, both of these issues were addressed.

The primary goal of this project was to develop the performance requirement specifications for the frontal collision warning system for transit buses. To accomplish this goal, the FCWS team has applied System Engineering Process (SEP) in the requirement analysis process. To support the primary goal, research was conducted in the areas of data collection and analysis. In addition the team maintained a driver needs focus in all phases of the study and verification of requirements through field-testing. Each of these activities are further described below.

Accident Data Analysis: In order to define the operational environment and the bus operation scenarios, thorough data collection and analysis was conducted. In addition to reviewing national accident statistics, accident records collected by SamTrans and 34 additional transit agencies were analyzed. The accident data analysis revealed that bus frontal collisions mostly occur at low velocity on suburban corridors, local streets and near bus stops, traffic lights, or intersections. Many incidents involved the bus making contact with a neighboring vehicle at the front corners at relatively low speeds. In addition to frontal collisions, passenger falls resulting from emergency braking also contribute to an increased potential for passenger injuries and liability.

Field Data Collection and Analysis was an essential element of this project. The accident data provides a knowledge base for determining the type and frequency of frontal collision accidents. However, because transit accident data are heavily dependent on the recollection of the involved operator, most data may not accurately describe the cause and the time sequence of accidents. In order to further understand the environment that a CWS will operate in, data acquisition systems were developed and instrumented on three SamTrans buses. The data acquisition system collected several types of data, including sensor data such as detecting the presence and relative motion of obstacles in front of the bus, vehicle status (i.e., velocity, acceleration and steering angle), and video data. A data analysis tool was developed to overlay the sensory data onto the video data to enable us to see what sensors detect. A second tool is being developed for automating the data analysis process.

The team was not expecting to acquire actual collisions during the course of this project, However, the abundant data collected on these buses provides us with an accurate description of the relative movement of the buses, the surrounding vehicles and potential crash scenarios. In the absence of collisions, hazardous conditions that potentially can lead to accidents have been identified and driver reactions to these hazardous conditions have been analyzed. The in-depth understanding of bus operating environment and hazardous conditions helped to establish scenarios under which accidents may occur and provide a foundation for the determination of sensor performance, and system specifications. Currently there are over 200 gigabytes of video and sensory data stored on a Redundant Array of Inexpensive Disks (RAID). Additional data is being collected and data will continuously be analyzed in the Phase Two project.

A Prototype Frontal Collision Warning System was also developed. The hardware platform was based on the data collection system hardware in order to evaluate the preliminary functional requirements and technical specifications. A preliminary collision-warning algorithm was specifically designed for bus operation in an urban environment. Significant efforts were devoted to deal with problem areas revealed through the data collection process using the playback tool and the collected data. The current warning algorithm, which was evolved through different stages of the project, has much better performance in dealing with most of false positive patterns.
It has been realized that the probability of a true collision is so small that suppression of false alarms or nuisance alarms is the central point for developing a FCWS, particularly for operation in urban environment. The project team recognized that several signal processing and sensor fusion techniques such as object recognition and classification, GPS map utilization, driver status monitoring may all be helpful for reducing nuisance alarms in the future. Random models may be better than deterministic models in terms of describing the evolution of vehicle states. These techniques will be considered in the second phase of the FCWS.

The **Driver Vehicle Interface (DVI)** is a critical element for effective communicating the warning information to the driver. Through iterative studies of the driver needs and desires, a prototype visual DVI was developed. So far, field tests have shown that operator acceptance of the visual DVI and the FCWS as a whole is very high. Operators have indicated that they feel that the system could potentially increase their safety. The project team has determined that there is a need to determine what effect (if any) the DVI and the FCWS have on longer-term operator performance. It is particularly of interest to know how the operators use the system. Preliminary feedback suggests that there is some “tuning out” of the amber “advisory” alerts. It is necessary to determine what long-term effect this will have on the viability of the system. Feedback from operators emphasizes that the acceptance of the system relies on the reduction/minimization of the false-positive rate, options for alternative display modalities, ability to adjust the sensitivity of the alarm activation thresholds, and training to operators prior to their using of the system.

The DVI study under this project (though somewhat preliminary) suggests that the iterative design process meet its objective of developing a DVI that supports the operator primary driving task and has a high user acceptance rating. The FCWS team will continuously use this approach to ensure that the collision warning system can indeed help to reduce both the frequency and severity of collisions. Topics that need further examination include warning thresholds for both advanced cues and critical warnings, alternative modalities, and the impact of transit specific driving tasks.

As the final product of this project, the **preliminary performance requirement specifications** for transit FCWS are developed.

Based on the research separately conducted on advanced technologies for frontal and side collisions, starting late 2002, Caltrans, CMU, PennDOT, PAT, Samtrans and UC PATH, in partnership with FTA have committed to conduct further development on an integration of the advanced side collision warning and frontal collision warning systems into a unified whole with one transit operator interface. This work will lead to a unified collision warning system specification of Integrated Collision Warning System (ICWS) and two prototypes for limited operational testing. The goals identified by the ICWS team are to (1) develop a Functional ICWS, (2) create a system acceptable to operators (drivers & operations), (3) demonstrate a potential for reduction in the severity and frequency of collisions and (4) prove technical feasibility through field test of prototype system(s). Under the ICWS project, the FCWS are being improved and as part of the ICWS performance requirements, the FCWS performance requirement specifications will be finalized. The ICWS project is scheduled to be complete by mid 2005.

Section Eight

Appendix

Appendix I: List of 32-CalTIP Members

1. AMODOR Regional Transit System
2. City of Arcata & Mad River Transit System
3. City of Auburn
4. City of Azusa
5. Butte County
6. Central Contra Costa Transit Authority
7. Culver City
8. City of Dixon
9. El Dorado County Transit Authority
10. City of Folsom
11. Golden Empire Transit District
12. Humboldt Transit Authority
13. City of Lincoln
14. Livermore Amador Valley Transit Authority
15. City of Lodi
16. Mendocino Transit Authority
17. Monterey-Salinas Transit
18. Morongo Basin Transit Authority
19. Napa County Transportation Planning Agency
20. Nevada County
21. Placer County Transit
22. Riverside Transit Agency
23. San Luis Obispo Regional Transit Authority
24. Santa Cruz Metropolitan Transit District
25. Siskiyou County
26. South Coast Area Transit
27. South County Area Transit
28. City of Vacaville
29. City of Vallejo Transit
30. Western Contra Costa Transit Authority
31. City of Whittier
32. Yolo County Transportation District

Appendix II: Sample JGAA Cost Report

```
   Div        ALL                  Select Period:          As of:        Activity
Period:         Printed: 09/11/2002 Page:    1
                              07/01/1994 - 09/11/2002  09/11/2002          -
                                    Selected by:          Claims With Incurred
from:                         Examiner ID: ALL
                                   DATE  OF  LOSS           -$999,999,999  thru
$9999999999         Leg/Oth: YES      Recovs:  NO
Proc Off: ALL         ALL CLAIMS IN CLAIM NUMBER ORDER FOR CALENDAR YEARS 1994-2002
Info-Only: YES    Late-Rpt: YES

Maint-Only: YES   *HistSumm: N/A
=============================================================================
=======================================================
Claim   Sts   Carrier      Loss   Reported  Entry   Denied    Closed   Reopen
Paid in     --------TOTALS AS OF: 09/11/2002-------
  No          No         Date     Date     Date    Date      Date     Date   Pay
Period      Paid       Reserve     Incurred
=============================================================================
=======================================================

0053740  C            01/09/00 01/14/00 01/18/00        01/31/01
       Loss: 63   ON BRD-STOPPING   Desc: ABRUPT STOP PAX FELL

                Claimant: XXXXXXXXXXXXXXXXXX                        Bod Inj:
0.00       400.00        0.00      400.00
                                                      Totals:            0.00
400.00        0.00       400.00

                          ---CLAIM  SUMMARY---                          Totals:
0.00       400.00        0.00      400.00
                                                                ------------
------------- ------------ ------------

NET:      400.00


0053750  C            01/13/00 01/17/00 02/01/00        03/15/00
       Loss: 8    TRN LFT-OTH LFT   Desc: UNSAFE LANE CHANGE VEHICLE COLLI

                Claimant: XXXXXXXXXXXXX                    Totals:        0.00
0.00        0.00        0.00

                          ---CLAIM  SUMMARY---                          Totals:
0.00         0.00        0.00        0.00
                                                                ------------
------------- ------------ ------------

NET:       0.00
```

Appendix III: Loss Code Description

<u>Property damage (code 1~49)</u>

1 Intersection: Bus straight ahead - other vehicle from left
2 Intersection: Bus straight ahead - other vehicle from right
3 Intersection: Bus turning right - other vehicle from ahead
4 Intersection: Bus turning right - other vehicle from left
5 Intersection: Bus straight ahead - other vehicle from opposite direction turns left
6 Intersection: Bus turning right - other vehicle from rear
7 Intersection: Bus turning left - other vehicle from ahead
8 Intersection: Bus turning left - other vehicle from left
9 Intersection: Bus turning left - other vehicle from right
10 Intersection: Bus turning left - other vehicle from rear
11 Intersection: Other vehicle turns right in front of bus
12 Intersection: All other intersection collisions
13 Head-on - vehicles from opposite directions
14 Sideswipe - bus passing other vehicle
15 Sideswipe - other vehicle from opposite direction
16 Sideswipe - other vehicle passing bus
17 Cutting in - by other vehicle
18 Other vehicle pulling from curb hit bus
19 Collision with standing vehicle (includes opened doors, parked auto)
22 All other accidents between intersections
23 Rear end - bus hit vehicle
24 Rear end - other vehicle hit bus
25 Loading zone: Bus pulling into zone involved with standing vehicle
26 Loading zone: Bus pulling from zone involved with standing vehicle
27 Loading zone: Bus pulling from zone involved with moving vehicle
28 Loading zone: Other vehicle involved with bus standing in zone
29 Loading zone: Bus pulling into zone involved with moving vehicle
30 Miscellaneous: All other collisions with other vehicles, bikes.
31 Scrapes at corners. Intersection sideswipes (includes right turn squeeze)
32 Sideswipes between intersections other than opposite direction
33 Opposite way sideswipes between intersections
34 Collisions between company passenger vehicles: end to end - in loading zones
35 Collisions between company passenger vehicles: end to end other than loading zones
36 Collision between company passenger vehicles: on company property, yards, terminal company parking
37 All other collisions between company passenger vehicles.
38 Collision with stationary object while bus backing.
39 Pedestrians - Intersection/crosswalks
40 Pedestrians - loading zones
41 Pedestrians - hit by overhang (bus turning)
42 Pedestrians - Between intersections
43 Pedestrians - all others
44 Miscellaneous collision: alleges - location - division or department unknown
45 Collisions with (fixed) stationary objects
46 Collision due to bus mechanical failure.
47 Collision due to bus leaving road
48 Collision not classified
49 Bus backing collision with moving vehicle.

<u>Passenger injury (code 50~118)</u>

50 Falls boarding
51 Miscellaneous boarding
52 Struck by front door - boarding
53 Falls alighting - front door
54 Handi Lift

55 Falls alighting - rear door
56 Falls alighting - rear door (push type)
57 Fall alighting not otherwise classified
58 Struck by front door - alighting
59 Struck by rear door - alighting
60 Struck by rear door - alighting (push type)
61 Struck by door not otherwise classified
62 On board: bus starting
63 On board: bus stopping
64 On board: bus turning
65 On board: bus running straight
66 On board: caught/struck by doors
67 On board: injuries from arms, head, etc. out of window
68 On board: accidents not otherwise classified
70 Property damage caused by defective equipment
71 Injuries caused by defective equipment
72 Disturbances, ejectments fainting, sickness, fits, deaths on vehicles, etc.
73 Injuries or prop damage caused by other passengers or other person except bus motion
74 Falls - approaching to board or after alighting
75 Clothing soiled off bus (splashed water, etc.)
76 Thrown missiles (injuries/damage)
77 Thrown missiles (no injuries/damage)
78 Incidents not otherwise classified
79 Observation or witness reports (operator's vehicle not involved)
80 Non-operating vehicle accidents (supervisor cars, co. trucks, vehicles operated by mechanics, vandalism)
81 Other alleged
82 Other alleged
88 Bicycle
90 Employee accidents
99 Public accidents on company property - not defined
100 Striking and injuring or killing animal
101 Wheelchair: Falls boarding
102 Wheelchair: Door hit
103 Wheelchair: Miscellaneous boarding
104 Wheelchair: Lift stand
105 Wheelchair: Lift WC PAX
106 Wheelchair: Fall alighting
107 Wheelchair: Fall alighting
108 Wheelchair: Fall alighting
109 Wheelchair: PAX start
110 Wheelchair: PAX stop
111 Wheelchair: PAX curve (turning)
112 Wheelchair: PAX straight
113 Wheelchair: PAX door
114 Wheelchair: PAX window
115 Wheelchair: On board
116 Wheelchair: Tie down
117 Wheelchair: Tie down
118 Wheelchair: Lift

Violation (code 119, 120)
119 Civil right
120 ADA violation

Appendix IV: Accident Data as Shown in Bar Charts

For Table 26 and 27 the percentages shown in black are actual cost data, and those in blue are generated by the statistics from Agency IV and V.

Table 26 Claim and cost distributions for collision accidents with cost less then 10K

Agency	Total claim	Total cost	Percent of claims				Percent of costs			
			F	S	R	N	F	S	R	N
I	324	$665,044	29.0	55.2	11.1	4.6	36.1	49.5	11.1	3.4
			26.0	***48.7***	***13.7***	***11.6***	***35.1***	***44.4***	***10.7***	***9.8***
II	1,10 9	$1,108,053	13.3	40.8	6.3	39.5	18.5	36.6	4.0	40.9
			19.5	***54.4***	***13.8***	***12.4***	***27.5***	***50.8***	***9.9***	***11.8***
III	346	$263,970	16.2	46.2	24.3	13.3	20.7	51.1	15.9	12.3
			18.7	***44.7***	***23.9***	***12.7***	***25.3***	***45.3***	***16.8***	***12.6***
IV	243	$343,870	27.6	35.4	25.5	11.5	34.4	32.4	22.7	10.5
			24.0	***37.6***	***26.0***	***12.4***	***30.9***	***36.9***	***22.0***	***10.2***

Table 27 Claim and cost distributions for all collision accidents

Agency	Total claim	Total cost	Percent of claims				Percent of costs			
			F	S	R	N	F	S	R	N
I	353	$2,904,763	31.7	52.4	10.2	5.7	70.6	22.4	2.5	4.4
			29.0	***46.4***	***12.6***	***12.1***	***70.4***	***21.3***	***2.4***	***5.9***
II	1,146	$6,319,107	14.7	40.2	6.2	38.9	20.5	45.0	0.9	33.6
			20.6	***53.3***	***13.4***	***12.7***	***22.1***	***47.5***	***1.9***	***28.5***
III	358	$997,982	17.3	45.3	23.7	13.7	22.4	17.5	5.7	54.5
			19.7	***43.8***	***23.4***	***13.1***	***23.6***	***15.9***	***5.9***	***54.6***
IV	261	$1,032,796	29.9	34.1	24.9	11.1	61.4	19.6	14.3	4.7
			26.6	***36.1***	***25.4***	***12.0***	***60.2***	***21.1***	***14.0***	***4.6***

Table 28 Transit agencies: General collision accident costs by initial point of impact

Agency	Total claim	Total costs	Percent of claims				Percent of costs			
			F	S	R	N	F	S	R	N
I	348	$1,186,535	31.0	52.9	10.3	5.7	45.2	37.8	6.2	10.7
II	1,137	$1,826,183	14.4	40.4	6.2	39.0	31.2	31.8	3.0	34.0
III	357	$543,490	17.4	45.4	23.8	13.4	41.1	32.1	10.4	16.4
IV	260	$796,180	29.6	34.2	25.0	11.2	49.9	25.5	18.5	6.1
V	1,731	$3,098,536	25.2	48.1	16.2	10.6	18.4	18.8	1.8	20.0
CalTIP(30)	1,391	$3,339,754	22.5	43.4	19.0	15.1	38.2	29.4	8.5	24.0
All (35)	5,224	$10,790,680	22.2	44.6	15.3	17.9	40.2	33.4	8.2	18.1

Table 29 Transit agencies: General collision accident costs by collision object

Collision object	Total claims	Total costs	Percent of claims				Percent of costs			
			F	S	R	N	F	S	R	N
Vehicle	4,762	$9,313,621	22.6	46.0	16.2	15.2	41.3	34.6	9.2	14.9
Pedestrian	184	$1,027,244	26.3	17.5	1.6	54.6	37.2	21.4	0.2	41.2
Stationary object	278	$449,815	12.4	38.8	9.5	39.2	24.7	35.7	6.7	32.9
Total	5,224	$10,790,680	22.2	44.6	15.3	17.9	40.2	33.4	8.2	18.1

Table 30 Transit agencies: General vehicle collision costs by accident scenario

Accident scenario	Total claims	Total costs	Percent of claims				Percent of costs			
			F	S	R	N	F	S	R	N
S1	668	$1,697,209	31.5	49.0	5.1	14.4	40.2	43.1	4.9	11.9
S2	461	$2,174,890	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
S3	486	$432,289	0.0	0.0	100.0	0.0	0.0	0.0	100.0	0.0
S4	852	$1,243,354	12.0	55.8	5.8	26.5	22.7	52.0	4.5	20.8
S5	752	$935,215	0.0	100.0	0.0	0.0	0.0	100.0	0.0	0.0
S6	230	$340,937	25.2	49.3	4.5	20.9	31.5	50.4	6.2	11.9
S7	432	$407,126	19.6	48.4	22.8	9.1	13.8	44.8	23.8	17.5
S8	382	$873,890	12.6	42.1	12.9	32.3	28.2	34.8	5.3	31.7
S9	499	$1,208,711	22.0	31.0	9.0	38.1	18.9	28.3	9.8	43.0
Total	4,762	$9,313,621	22.6	46.0	16.2	15.2	41.3	34.6	9.2	14.9

Table 31 Transit agencies: Passenger injuries by bus movements

Bus movement	Claim	Cost	Percent of claims	Percent of costs
Boarding	499	$1,013,907	11.6	7.5
Alighting	770	$1,816,013	18.0	13.4
Starting	168	$567,644	3.9	4.2
Stopping	849	$3,820,606	19.8	28.1
Turning	115	$387,192	2.7	2.9
Going straight	136	$521,322	3.2	3.8
Moving (others)	561	$2,259,218	13.1	16.6
Others	1,187	$3,199,336	27.7	23.6
Total	4,285	$13,585,239		

Appendix V: Development of Data Acquisition System (DAS)

Calibration of DAS

The location and direction of some sensors will influence the system performance. Before running the bus out to collect data, the sensors and the entire system must be calibrated. The calibration process involves the following three tasks: 1) measure the location and direction of the sensors, 2) correct the location and direction of some sensors, and 3) examine the system alignment.

This section describes the calibration process of the first DAS on the first bus and gives the results. The 1st section gives the measurements of location and sensor direction. The 2nd section describes the laser radar calibration procedure and results. The 3rd section describes the calibration approaches for cameras. Calibration of system alignment is given in the 4th section. Calibration of other sensors is given in the 5th section. The DAS design was changed after the first DAS was calibrated. However, the calibration process and the techniques presented in this document were conducted to calibrate all the systems. For convenience, the following abbreviations are used.

Table 32 DAS calibration abbreviations

Sensor Name	*Abbreviation*
passenger side corner camera	P-CAM
front-looking camera	F-CAM
driver side corner camera	D-CAM
passenger side upper ultra-sensor	UP-SONAR
passenger side lower ultra-sensor	LP-SONAR
passenger side radar	P-RADAR
laser radar	LIDAR
front-looking ultra-sensor	F-SONAR
driver side radar	D-RADAR
driver side upper ultra-sensor	UD-SONAR
driver side lower ultra-sensor	LD-SONAR
Interior-looking camera	I-CAM
rear-looking camera	R-CAM
rear radar	R-RADAR
global positioning system	GPS

Sensor position

Coordinate systems

To locate the sensors, two reference frames were built on the bus. One is the Front Coordinate System (FCS) and the other is the Rear Coordinate System (RCS). Locations of front sensors, including P-CAM, F-CAM, D-CAM, UP-SONAR, LP-SONAR, P-RADAR, LIDAR, F-SONAR, D-RADAR, UD-SONAR, LD-SONAR and I-CAM, are measured in the FCS. Locations of rear sensors, including R-CAM, R-RADAR and GPS are measured in the RCS. The reference points of the coordinates and the positions of the sensors are illustrated in the following figures. The positive x-axis is horizontally to the left, the positive y-axis is vertically upward, and the positive z-axis is horizontally to forward. The basic dimensions of the bus are: length = **12200** mm, width = **2750** mm.

Front Sensors

The reference point of the FCS and the locations of the front sensors are illustrated in Fig. 74.

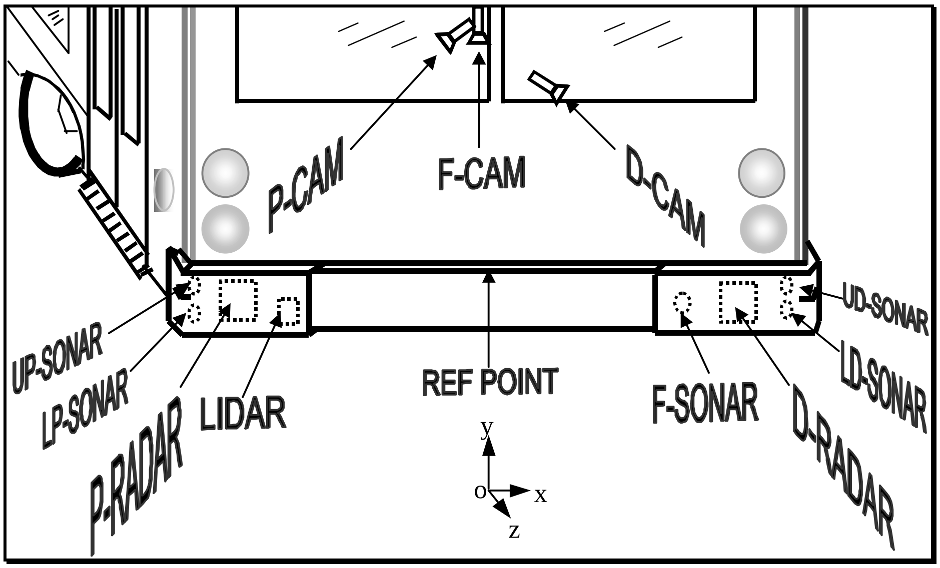


Fig. 74 FCS and front sensors

The reference point is on the front center of the bus. The height of the reference point from the ground is **585**mm. The coordinates of the front sensors are listed in the following table.

Table 33 Front sensor locations

1. Sensors	2. x (mm)	3. y (mm)	4. z (mm)	5. Angle (Deg)
6. LIDAR	7. -836	8. -195	9. 78	10. [1]N.A.
11. P-RADAR	12. -1050	13. -132	14. 70	15. N.A.
16. UP-SONAR	17. -1201	18. -97	19. 64	20. [2]-36
21. LP-SONAR	22. -1201	23. -176	24. 64	25. [2]-26
26. D-RADAR	27. 985	28. -135	29. 67	30. N.A.
31. UD-SONAR	32. 1190	33. -95	34. 64	35. [2]35
36. LD-SONAR	37. 1190	38. -175	39. 64	40. [2]26
41. F-SONAR	42. 790	43. -161	44. 61	45. N.A.
46. D-CAM	47. 396	48. 991	49. -80	50. [3]14
51. F-CAM	52. -69	53. 1653	54. -61	55. [3]13
56. P-CAM	57. -109	58. 1563	59. -95	60. [3]25
61. I-CAM	62. -409	63. 2186	64. -365	65. N.A.

66. 1: N.A. = Not available;
67. 2: These are azimuth angles;
68. 3: These are tilting angles.

Rear Sensors

The reference point of the RCS and the locations of the rear sensors are illustrated in Fig. 75.

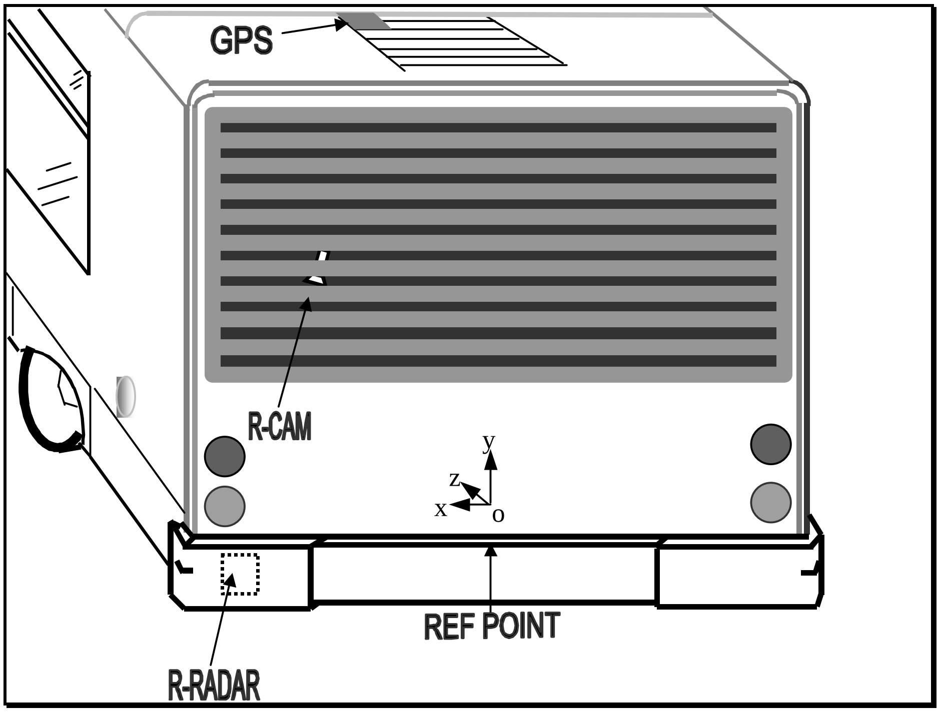


Fig. 75 RCS and rear sensors

The reference point is on the rear center of the bus. The height of the reference point to the ground is **790**mm. The coordinates of the rear sensors are listed in the following table.

Table 34 Rear sensor locations

69. Sensors	70. x (mm)	71. y (mm)	72. z (mm)	73. Angle (Deg)
74. R-RADAR	75. 950	76. -154	77. -39	78. [1]N.A.
79. GPS	80. 590	81. 2220	82. 800	83. N.A.
84. R-CAM	85. 500	86. 1500	87. 140	88. [2]16

89. 1: N.A. = Not available;
90. 2: Tilting angle.

LIDAR calibration

Optical axis orientation

The LIDAR beam is scanning in 2D by rotating a hexagon mirror. The equivalent detection scope is 16 degrees in horizontal and 4.4 degrees in the vertical direction. The equivalent optical axis is defined to originate from the LIDAR lens extending to the center of the detection scope, i.e. eight degrees to both the left and the right margins and 2.2 degrees to both the top and the bottom margins. There are two adjustable screws on the front face of the LIDAR, which can be rotated to adjust the optical axis in 2D (both horizontal and vertical directions). As the LIDAR has been mounted on the passenger side on the 1st bus, to calibrate the LIDAR, we must first adjust the optical axis to an appropriate direction [1].

The LIDAR optical axis is set horizontally to the point on the bus's longitudinal center line, 50 meters away from the bus front reference point, and vertically 2.2 degrees up with respect to the horizontal plane. The geometric relationship is illustrated in Fig. 76.

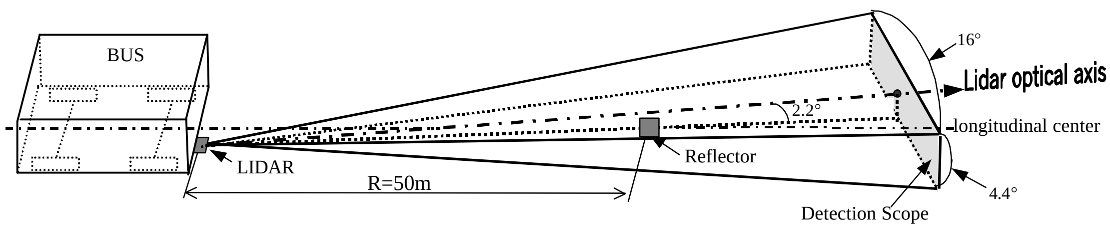


Fig. 76 LIDAR calibration geometry

LIDAR calibration procedure

91. LIDAR calibration was done by the following procedure.

1. Measure LIDAR lens vertical position (height to ground) **H =** ***0.425*** (m).
2. Measure **R= 50m** from bus front reference point along the longitudinal direction.
3. Set the reflector at ***R=50m*** with vertical position = **H**.
4. Adjust both the lower and the higher screws simultaneously, make reported "lateral position" = 0. Change lateral position to check the adjustment.

Table 35 LIDAR lateral position test

Actual lateral position	Expected report number	LIDAR report (5th col)
6m Left	-60 *.1m	*-61*
3m Left	-30 *.1m	*-30*
3m Right	30 *.1m	*30*
6m Right	60 *.1m	*61*

5. Adjust the lower screw, make reported "Vertical Position" changing from smaller to larger numbers thru 12.
6. Adjust the lower screw to " – direction" 0.3-0.5 rev, make sure that the LIDAR keeps detecting the reflector.
7. Change distance to check the adjustment:

Table 36 LIDAR range test

Actual distance	Expected report number		LIDAR report (1st-2nd col)	
40m	31*1.28m	32*.01m	*31* *1.28m	*98* *.01m
30m	23*1.28m	56*.01m	*24* *1.28m	*14* *.01m
20m	15*1.28m	80*.01m	*16* *1.28m	*48* *.01m
10m	7*1.28m	104*.01m	*8* *1.28m	*46* *.01m

8. Put the reflector at ***R=10m***, with vertical position changing, check the adjustment:

Table 37 LIDAR vertical position test

Actual vertical position	Expected report number	LIDAR report (9th col)
H+0.76m	2	*2*
H+0.57m	3-4	*4*
H+0.38m	6-7	*5*
H+0.19m	9-10	*6*
H+0m	12	*8*

Camera calibration

Rough adjustment

Three different options of focal length are available: 3mm, 4mm, and 7.5mm. Lenses with different focal length were fitted on the camera heads. Comparing the field of view and selecting the one list that best matches the area of interest around the bus, the optimal fitted focal length was chosen for each camera, as in the following table.

Table 38 Focal length of cameras

Camera	Focal length
D-CAM	4mm
F-CAM	7.5mm
P-CAM	4mm
I-CAM	4mm
R-CAM	7.5mm

Image plane rotation and optical axis direction of each camera was roughly adjusted by monitoring the video output. The factors of interest while adjusting are: range coverage, azimuthal direction of interest, and consistency between adjacent cameras. The tilting angle of each camera was measured with a level and an angle measure.

Intrinsic and extrinsic parameters calculation

Control points

To calibrate the cameras, 20 control points arranged in 4 lines with 5 points in each line were made on a vertically standing black screen. The adjacent lines are 50 centimeters apart. The distance between adjacent points in each line is also 50 centimeters. The screen was put in front of each camera with the points facing the camera. A picture was taken and stored in the computer. The screen was then moved 25 centimeters (for F-CAM and R-CAM) or 20 centimeters (for D-CAM and P-CAM) closer to the camera. This process was repeated until five pictures were taken for each camera. Every time a picture was taken, the position of the screen in the bus coordinate system was marked on the ground and measured later to calculate the control point coordinates.

The pictures were opened in Microsoft Photo Editor™ to read the image coordinates of the control points. We get the coordinates of the control points in the bus coordinate system and their corresponding image coordinates in the picture. Each control point and its image are called a calibration pair. By substituting the coordinates of the calibration pairs in the camera model described below, two equations for each pair were obtained. We can solve the unknown camera parameters from the equations for all pairs in the sense of Least Square Error (LSE).

Camera model

Let $P=(X,Y,Z)^T$ represent the coordinates of a point in the bus coordinate system (FCS or RCS), $P_C=(X_C,Y_C,Z_C)^T$ represent the coordinates of the point in the camera coordinate system, (x_U,y_U) and (x_D,y_D) represent the undistorted and distorted image coordinates of the point respectively, and (i,j) represent the coordinate read in Microsoft Photo Editor™, i.e. the pixel location with respect to the top-left corner in the image, viz. the computer image coordinate. The relationship between the bus coordinate system and the camera coordinate system is given by [2]:

$$P_C = RP + T \quad (1)$$

where $R=\{r_{ij}\}$ is a 3×3 ortho-normal rotation matrix defining the camera orientation and $T=(t_1,t_2,t_3)^T$ is a translation vector defining the camera position. The camera coordinate system is transformed to the undistorted image coordinate (2D) system according to the pin-hole model:

$$\begin{cases} x_U = f\dfrac{X_C}{Z_C} \\ y_U = f\dfrac{Y_C}{Z_C} \end{cases} \quad (2)$$

where f is the focal length. The distortion of image coordinates can be modeled by [4]:

$$\begin{cases} d_x = 2p_1x_Uy_U + p_2\left(r^2+2x_U^2\right)+k_1x_Ur^2 \\ d_y = p_1\left(r^2+2y_U^2\right)+2p_2x_Uy_U + k_1y_Ur^2 \end{cases} \quad (3)$$

where $r^2=x_U^2+y_U^2$, p_1,p_2 are coefficients of tangential distortion, and k_1 is the coefficient of radial distortion. The distorted image coordinates are then obtained:

$$\begin{cases} x_D = x_U + d_x \\ y_D = y_U + d_y \end{cases} \quad (4.1)$$

or

$$\begin{cases} x_D = x_U + 2p_1x_Uy_U + p_2\left(r^2+2x_U^2\right)+k_1x_Ur^2 \\ y_D = y_U + p_1\left(r^2+2y_U^2\right)+2p_2x_Uy_U + k_1y_Ur^2 \end{cases} \quad (4.2)$$

The relationship between the distorted image coordinates and the computer image coordinates is given by:

$$\begin{cases} x_D = w_x (i - i_0) \\ y_D = w_y (j - j_0) \end{cases} \quad (5)$$

where w_x, w_y are the distance between the adjacent imaging sensor elements in rows and columns, respectively, (i_0, j_0) represents the computer image coordinate of the principal point of the image coordinate system.

The model itself is a nonlinear one. The unknown parameters can be categorized into intrinsic and extrinsic, or linear and non-linear parameters, as follows:

Table 39 Parameter table

	Linear	Nonlinear
Intrinsic	$f, w_x, w_y, (i_0, j_0)$	k_1, p_1, p_2
Extrinsic	$R = \{r_{ij}\}_{i,j=1,2,3}, T = (t_1, t_2, t_3)^T$	

Calibration procedure

It is hard to solve all the parameters simultaneously from the complete nonlinear camera model. However, if the nonlinear distortion can be neglected, the model becomes linear. Once the linear parameters are known, the nonlinear parameters can be solved from linear equations (3). These properties of the camera model help us to simplify the calibration procedure into the following steps [3]:

Step 1: Assume no distortion, calculate linear model parameters

Step 2: Calculate distortion using the linear parameters estimated in Step 1

Step 3: Calculate nonlinear parameters using the distortion and linear parameters estimated in Step 2

Step 4: Calculate distortion using the linear and nonlinear parameters estimated in Step 2 and 3

Step 5: Subtract the distortion estimated in Step 4 from the image coordinates, loop to Step 1 or terminate

The procedure is terminated when it is convergent. As noise exists in the calibration pair coordinates, the distortion used in Step 5 was multiplied with a positive fraction to confirm convergence. The positive fraction used in our calculation is 0.999.

Calibration results

Control point images

Control point image coordinates estimated with linear-only and nonlinear-plus models together with the actual image coordinates read in Photo Editor™ are illustrated in the following plots, where the 'o' signs represent the actual images read in Photo Editor™, the '+' signs represent the images estimated only with linear model, and the ‘x’ signs represent the images estimated with linear plus nonlinear model.

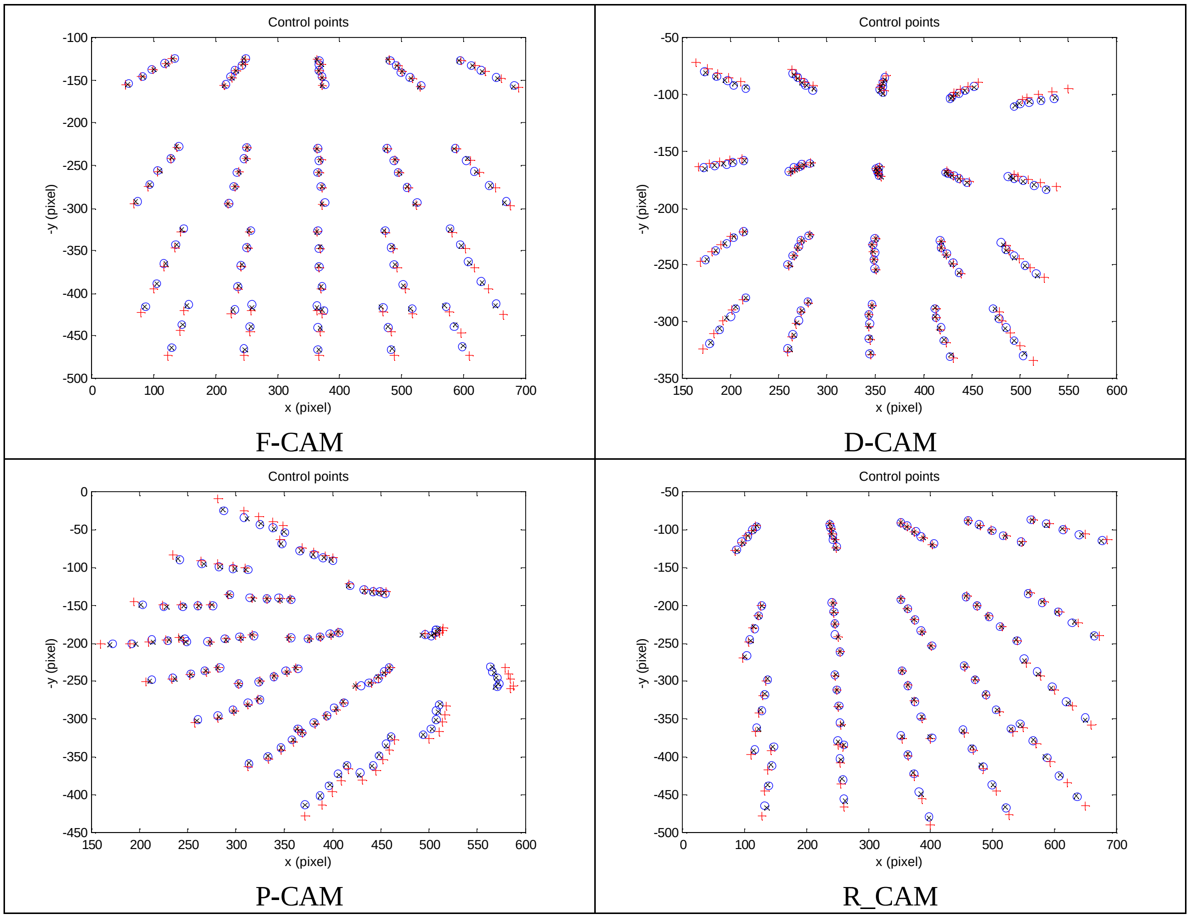
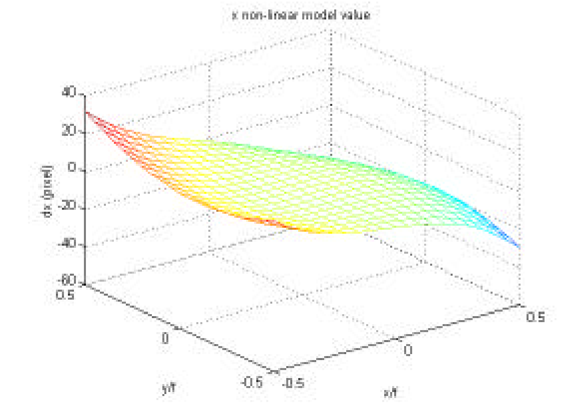


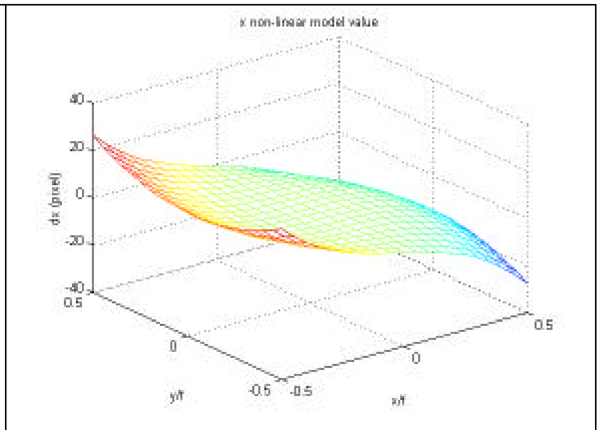
Fig. 77 Control point images

Distortion

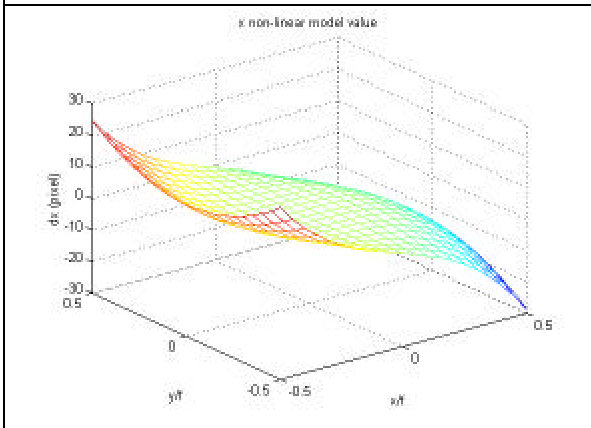
Distortion is calculated and plotted in the following plots.



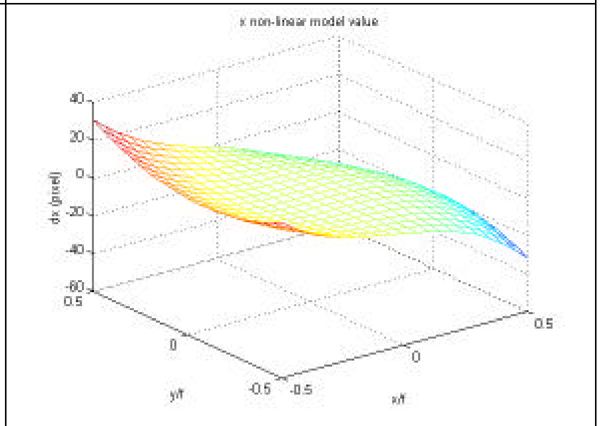
δx of F-CAM



δx of D-CAM

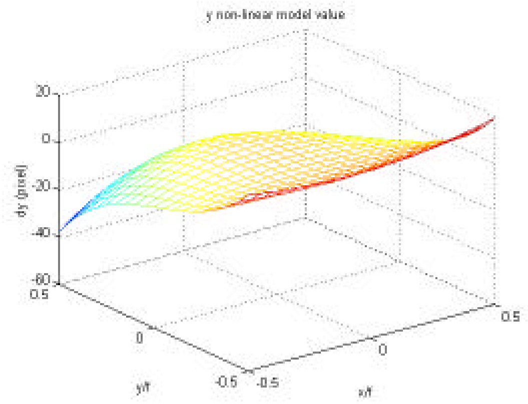


δx of P-CAM

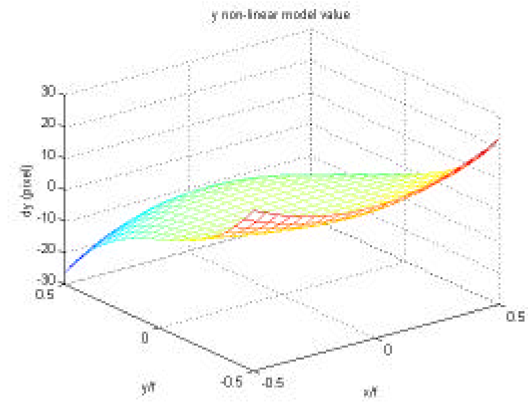


δx of R-CAM

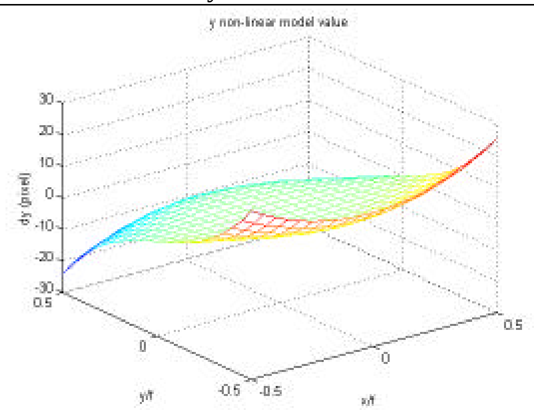
Fig. 78 a d**x of four cameras**



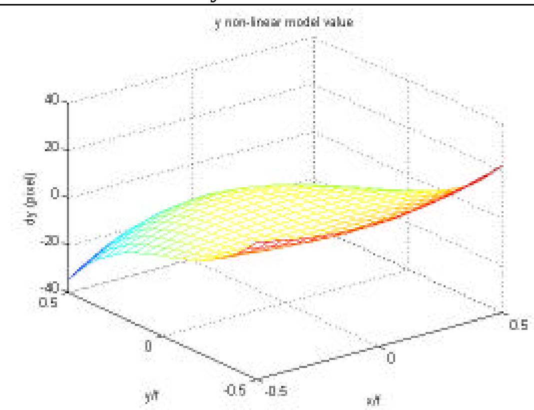
δy of F-CAM



δy of D-CAM



δy of P-CAM



δy of R-CAM

Fig. 79 d**y of four cameras**

Intrinsic and extrinsic parameters

The intrinsic and extrinsic parameters for different cameras were calibrated and are listed in the following table.

Table 40 Intrinsic and extrinsic parameters

Parameters	F-CAM	D-CAM	P-CAM	R-CAM
R^T	R_1 R_2 R_3 -1.0000 -0.0042 -0.0035 -0.0011 -0.9743 -0.2252 -0.0038 -0.2252 0.9743	R_1 R_2 R_3 -0.7018 -0.1878 0.6877 0.0535 -0.9763 -0.2092 0.7103 -0.1080 0.6952	R_1 R_2 R_3 -0.7390 -0.3102 -0.5965 0.6001 -0.7109 -0.3714 -0.3063 -0.6312 0.7115	R_1 R_2 R_3 0.9921 -0.0326 0.1207 -0.0037 -0.9678 -0.2518 0.1257 0.2496 -0.9602
T^T (m)	-0.0658 1.6280 0.5324	0.3428 1.0512 0.0723	-1.1015 1.0498 0.5364	-0.5286 1.4410 0.4298
(i0,j0)	359.79, 222.63	348.61, 226.08	366.81, 216.45	361.05, 206.93
$(f/w_x, f/w_y)^1$	860.83, 790.62	461.00, 419.96	438.66, 403.40	841.70, 771.48
(p1,p2,k1)/f	-0.0146 -0.0056 -0.1434	-0.0064 -0.0044 -0.2342	-0.0006 -0.0048 -0.2447	-0.0108 -0.0055 -0.1486

1. *The imaging element size parameter w_x, w_y can not be determined in the calibration procedure. These parameters can be found in camera manufacturer's specifications. The cameras mounted on bus No.1 are from ELMO. The camera head model is MH42H. The effective image area is 6.54mmx4.89mm. Effective image pixels are 768 x 494. By simple calculation, the size parameters are:*

Derived parameter verification

Some parameters can be derived from the calibrated parameters. Location of the cameras can be derived by [5]:

$$\begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} = R^T T .$$

Focus length of the cameras can be calculated by simply multiplying f/w_x with w_x or multiplying f/w_y with w_y. Angles of the cameras can be calculated from the rotation matrix R:

Tilting angle = $-\arcsin(r_{32})$;

Azimuth angle = $-\arctan(r_{31}/r_{33})$

Image rotation = $\arctan(r_{12})$

These derived parameters are listed in the following table.

Table 41 Derived parameters

	F-CAM		D-CAM		P-CAM		R-CAM	
	Measured	Calculated	Measured	Calculated	Measured	Calculated	Measured	Calculated
Location X (mm)	-69	-57	396	388	-109	-168	500	523
Location Y (mm)	1653	1706	991	1023	1563	1607	1500	1501
Location Z (mm)	-61	-152	-80	-180	-95	-56	140	111
Focus fx (mm)	7.5	7.32	4.0	3.92	4.0	3.73	7.5	7.15
Focus fy (mm)	7.5	7.83	4.0	4.16	4.0	3.99	7.5	7.64
Tilting Ang (Deg)	13	13.01	14	12.1	25	21.8	16	14.6
Azimuth Ang (Deg)	N.A.	0.20	N.A.	-44.7	N.A.	40.0	N.A.	7.2
Image Rotation Ang (Deg)	N.A.	-0.06	N.A.	3.06	N.A.	31.0	N.A.	-0.21

System alignment

The purpose of system alignment is to determine the inter-relationship of multiple sensors in the system. Three sensors, LIDAR, P-RADAR and D-RADAR, are considered. Thirteen locations were marked on the ground in front of the bus. A microwave reflector and a laser reflector were used as targets for the sensors. A person moving from location to location in the order of the numbers illustrated in Fig. 82 held both reflectors. When the person moved to one location, he stayed there for about six seconds, with the microwave reflector swinging forth and back to simulate a moving target. Data was collected in the on-bus computer. This is plotted in Fig. 80 thru Fig. 83.

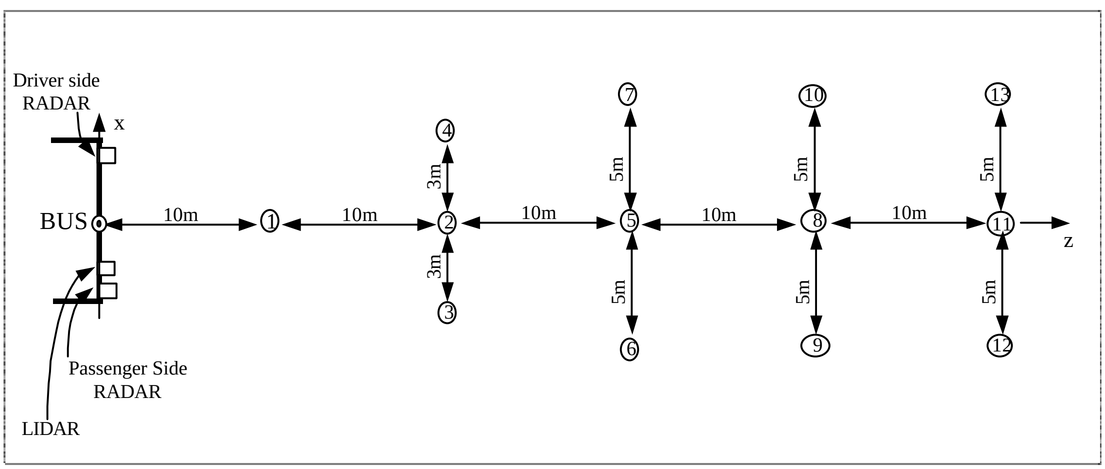


Fig. 80 Object locations for system alignment

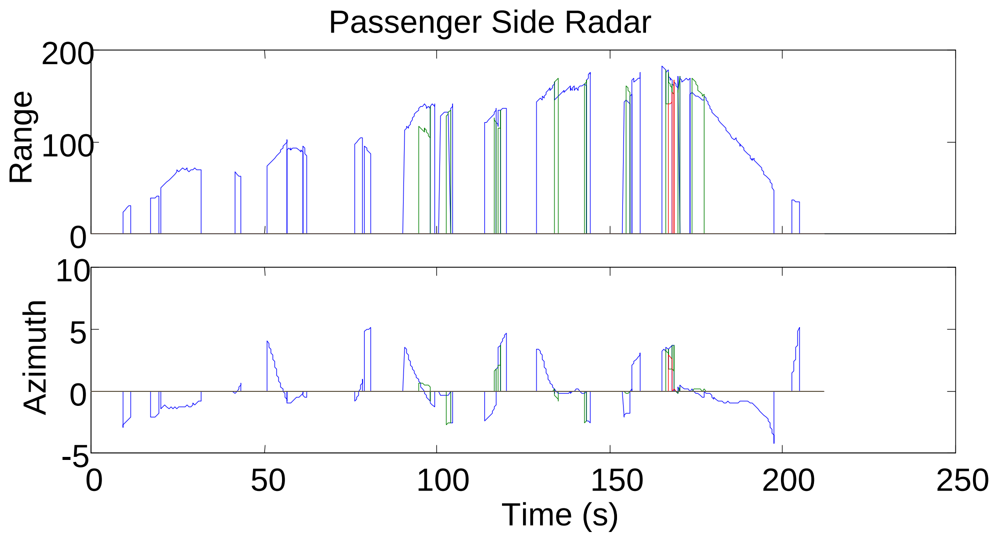


Fig. 81 PRADAR data for system alignment

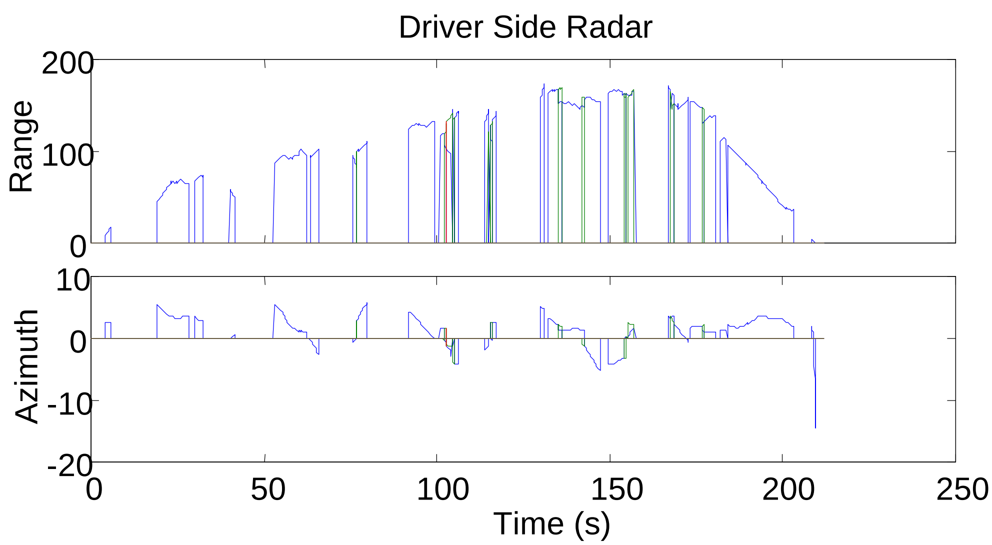


Fig. 82 DRADAR data for system alignment

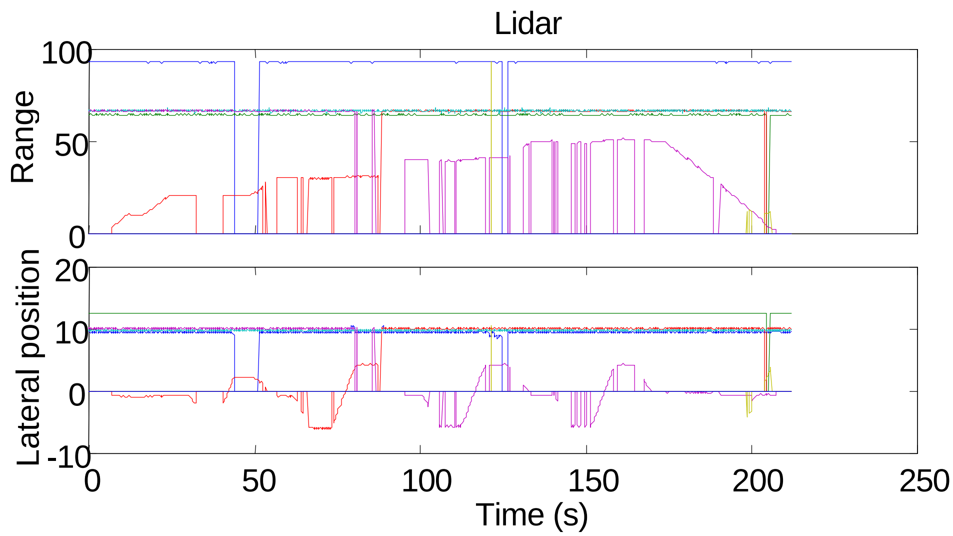


Fig. 83 LIDAR data for system alignment

The target parameters on the marked locations were extracted from the data and transformed to the bus coordinate system (FCS). Deviations are then calculated with the assumption that the marked locations are precise. The deviations are listed in Table 42 and plotted in Fig. 84. The average deviation of both distance and lateral position is less than 1m. This indicates the sensors are aligned well.

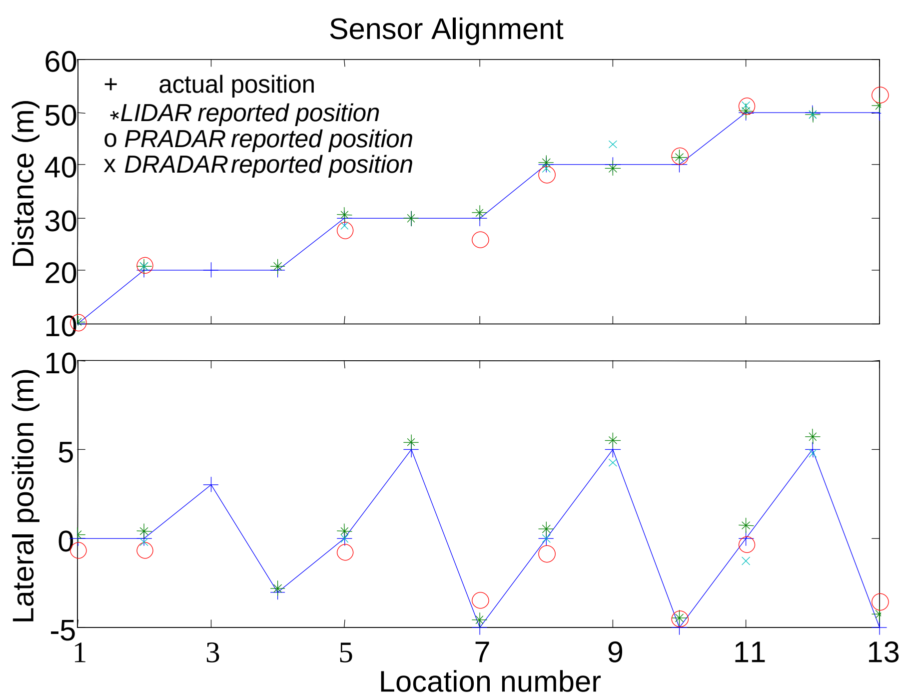


Fig. 84 Object locations reported by sensors

Table 42 Object locations reported by sensors

Locat. #	LIDAR				Passenger Side Radar				Driver Side Radar			
	Report		System (m)		Report		System (m)		Report		System (m)	
	R(H/L)[1]	L[2]	Ds[5]	Ls[5]	R[3]	α[4]	Ds[5]	Ls[5]	R[3]	α[4]	Ds[5]	Ls[5]
1	8/00	-9	**10.32**	**0.23**	340	-19	**10.43**	**-0.66**	Missed			
2	16/29	-9	**20.85**	**0.40**	690	-11	**21.10**	**-0.59**	680	30	**20.76**	**-0.26**
3	Missed				Missed				Missed			
4	16/30	23	**20.86**	**-2.80**	Missed				Missed			
5	24/00	-8	**30.80**	**0.46**	910	-5	**27.81**	**-0.77**	930	18	**28.4**	**-0.04**
6	23/33	-58	**29.85**	**5.46**	Missed				Missed			
7	24/29	42	**31.09**	**-4.54**	860	45	**26.17**	**-3.41**	Missed			
8	31/88	-7	**40.56**	**0.53**	1253	-3	**38.26**	**-0.82**	1290	12	**39.38**	**0.04**
9	30/90	-57	**39.38**	**5.53**	Missed				1442	-37	**43.90**	**4.23**
10	32/40	43	**41.44**	**-4.47**	1375	41	**41.84**	**-4.48**	Missed			
11	39/30	-7	**50.22**	**0.7**	1680	-7	**51.27**	**-0.33**	1680	22	**51.23**	**-1.27**
12	38/80	-57	**49.44**	**5.7**	Missed				1628	-38	**49.55**	**4.75**
13	40/20	43	**51.4**	**-4.3**	1752	27	**53.39**	**-3.53**	Missed			
Deviation Range		-	**-0.62** **1.44**	**0.23** **0.7**	-	-	**-3.83** **3.39**	**-0.77** **1.59**	-	-	**-1.60** **3.90**	**-1.27** **0.04**
Average Deviation		-	**0.52**	**0.49**	-	-	**-0.09**	**0.05**	-	-	**0.54**	**-0.43**

1. *Range. 'H/L' are two bytes of Lidar report. The LSB of H-byte is 1.28m and that of L-byte is 0.01m.*
2. *Lateral position.*
3. *Radar range is an integer, multiples of 0.1ft.*
4. *Azimuth angle. Radar azimuth angle is an integer, multiples of 0.002rad.*
5. *Distance and lateral position in bus coordinate system.*

Host vehicle parameter

Offset

The following host vehicle (bus) parameters are biased in the collected data: steering angle, acceleration, brake pressure and wheel speed. The biased values were measured when the bus was stationary and are listed in the following Table.

Table 43 Host vehicle parameter biased values

Parameter	Biased Value
Steering Angle	7.36
X Acceleration	2.40
Y Acceleration	2.45
Z Acceleration	2.45
Brake Pressure	1.02
Wheel Speed	0.038574

Sensitivity

Steering angle sensor

The bus hand-wheel was turned counterclockwise as far as it would go, held for five seconds, then turned clockwise step by step. For each step the hand-wheel was rotated 120 degrees and held for five seconds (the last turn was less than 120 degrees). The steering angle sensor outputs when the hand-wheel was held are listed below:

```
8.715820 (anticlockwise end)
8.525391
8.374023
8.198242
8.012695
7.822266
7.631836
7.441406
7.255859
7.070312
6.894531
6.723633
6.562500
6.406250
6.254883
6.201172 (after the last turn)
```

Average sensitivity factor is 1.5 mV/degree. Average angle-to-voltage ratio is 687.6148 degrees/V. The Steering ratio is 20.42:1 (for every degree of road wheel change requires 20.42 degrees of handwheel input). The wheel base is 279 inches.

Accelerometer

The accelerometer sensitivity is given by Summit Instruments™ as (unit: mV/g):

Table 44 Accelerometer sensitivity

	To X Acceleration	To Y Acceleration
X Sensitivity	1302.31	8.76
Y Sensitivity	-13.07	1299.00
Z Sensitivity	-3.25	2.97

The accelerometer was not calibrated on the bus.

Brake pressure

The brake pressure transducer output is proportional to the pressure. The sensitivity factor is 50mV/psi. The pressure range is 0-100psi. The corresponding output range is 1-6V.

Data storage

This project has generated large amounts of data. Currently there are over 200 gigabytes of video and sensor data. The data was initially stored on one computer with three large hard drives but soon the data storage reached its maximum capacity. A new storage solution was therefore developed. This new storage method is built using a RAID. It currently has 800 gigabytes of storage capacity which will allow this project to collect full data from three buses for one year. The RAID can be expanded to 1.5 terabytes if necessary. Later in the project we expect to perform more selective data collection which will reduce the rate of data collection. This will be done by only collecting data when the warning algorithm has given an alert. The new storage system is connected through the internet to allow users obtain data online. The RAID-based storage system has proven to be the most convenient and economical solution to our data storage needs.

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Appendix VI: Suggestions on Other Display Modalities

Table 45 Audible warnings feedback from operators and trainers

Requirement from Operators/Trainers	Requirement
T	Suggested an earbud since it would provide a private audio warning, but recognized that operators would probably not be too keen on wearing them.
T	Sound was perceived to be a more effective option than vision as a knowledgeable operator would not have to look at anything to detect the warning.
T	Operators are trained to look down when an audible alarm trips as they often signal a mechanical problem. Instrument panel lights are used to identify the problem.
D	Ambient sound levels within a bus can vary due to passenger load.
D	Operators find some existing warnings very annoying, especially when repeated false alarms occur. One example frequently cited was the rear door buzzer.
D	Speakers placed behind the operator's head (e.g., one on each side for directional information) were uniformly rejected. This location was perceived to be too startling. Music was identified as the only acceptable audio source from this location
D	One operator proposed a dash-mounted display similar to an on-board radar screen for airplanes.
D	Head-Up Displays (HUDs) were voluntarily suggested. Operators were aware that the cost would likely be too great. For a detailed discussion of additional problems with HUDs in transit buses see [**22**].
D	Dash lights already flicker often during normal driving (e.g., when braking, retarder activation, etc.).
D	Operators with night runs indicated that there is already too much illumination in the cab and were not enthusiastic about additional light sources. The ability to dim the illumination level or even shut off visual warnings was requested. Redundant warnings in other modalities (e.g., audible) were recommended for night driving.
DT	Experienced operators often downplayed the value of dash-mounted visual warnings as they rarely look at their instrument cluster.
D	Audible warnings that change pitch as the danger increases were suggested.
D	Chimes or other subtle, pleasant sounds were suggested as ways to provide alerts (prior to full-blown warnings).
D	Ramping up the volume or pitch was suggested as a way to not startle the operator.
D	Concern over having passengers mimic the sound of any warning

Table 46 Tactile warnings feedback from operators and trainers

Requirement from	Requirement

Operators/Trainers	
DT	Seat vibrations were roundly described as not worthwhile. One operator commented, *"After 8 hours I don't have any idea what's going on down there."*

Table 47 Vehicle control feedback from operators and trainers

Requirement from Operators/Trainers	Requirement
D	Operators voluntarily suggested longitudinal control actions by the bus. The existing interlock was subsequently mentioned as a potential method. The interlock activates whenever the rear door is opened by applying brake pressure to the two rear wheels. This prevents the bus from rolling away while passengers are loading. In the past, the interlock would be triggered if the rear door was opened while the bus was in motion. Maintenance has prevented the rear door from opening while in motion due to concerns over brake wear. Experienced operators described the braking action as being smooth enough to prevent falls, yet fast enough to bring the bus to rest.

2. Audible component design

One of the more interesting operator suggestions was to use a non-traditional auditory sound for the alert level (in this case a chime or a clock tick). This level would be the point at which the system indicates that there might be a target that could lead to a critical threat. The use of a chime or some other semi-pleasant notification earcon for this threshold is important, as this event will be somewhat frequent. A comparable warning would be the soft thunderclap or "clink" sound used by supermarkets to warn patrons in the produce section of an upcoming water spray. The sound is unique enough for patrons and employees to detect, yet is not obtrusive enough to annoy those present.

For cases of true critical events (i.e., chances are high that a crash will occur) a more salient and obtrusive earcon was recommended. Furthermore, the warning should not be binary in nature. The volume should ramp up as the threat level increases. In reality, the inclusion of a volume knob will allow operators to have either earlier or later perception, as the early ramping phase will be highly affected by the knob setting.

Speaker positioning will be important, as it will be necessary to provide a clear sound to the operator without being readily detectable to the passengers. Obviously the trainer suggestion of ear buds would be the easiest solution but the driving population would not accept these. Speakers behind the operator's head are another logical solution, but again, this was not popular with the operators. The remaining options are in front of the operator as side mounted locations will be directed towards passengers in the front seats and the sounds will not have good spatial mapping to the forward threat [1]. Final speaker placement will likely be done during the DVI installation process as the geometry of the cab is complex.

References

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Appendix VII: FCWS Survey Questions

Forward Collision Warning System (FCWS) Evaluation Survey Questions
SamTrans February 2002

We would like to ask you some questions regarding your opinion of the FCWS. 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?

Probing Questions – used as required:
Did the system function the way that you thought it would?
  Please describe any instances where you felt that you should have received a warning but didn't?
  Please describe any instances where you received a warning and felt that you shouldn't have?
Do you like the system?
Did you find the system easy to use?
How long do you think you would need to become comfortable with the system?
When did the system provide you with the most assistance?
Would you like to drive with the system the way it currently is?
If you could change/add one feature what would it be?
Questions/comments

Appendix VIII: FCWS Evaluation Questionnaire

Forward Collision Warning System (FCWS) Evaluation Questionnaire
SamTrans April 2002

We would like to ask you some questions regarding your opinion of the FCWS. 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 FCWS on?__________

Did you receive any training prior to using the FCWS?____________

General Assessment:

1. Please describe the system and how it works the way that you would to another operator 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)