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Publication Date

2006-08-01

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California PATH Research Report
UCB-ITS-PRR-2006-16

This work was performed as part of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation, and Housing Agency, Department of Transportation, and the United States Department of Transportation, Federal Highway Administration.

Final Report for Task Order 5200

August 2006

ISSN 1055-1425

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EXPERIMENTAL VEHICLE PLATFORM FOR PEDESTRIAN DETECTION

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March 31, 2006

ABSTRACT

This report documents the work conducted for PATH Task Order 5200 – the evaluation of sensor technologies for pedestrian detection. A survey of recent and available sensor products were selected and evaluated to assess their applicability for vehicle-based solutions. The performance characteristics and limitations of various products and technological approaches were investigated. Subsequently, demonstrative experimental vehicle platforms and testing facilities were developed to illustrate the concept of vehicle infrastructure integration.

KEY WORDS

Pedestrian Detection, Technology survey, Sensor Evaluation, Transit Bus Application, Vehicle Infrastructure Integration

EXECUTIVE SUMMARY

Pedestrian safety is a serious traffic issue in the urban environment. In California, more than 3,500 fatalities resulted from 75,000+ pedestrian collisions in the last five years. Pedestrian deaths are primarily an *urban* problem. Many pedestrians are killed at crosswalks, sidewalks, median strips, and traffic islands. Seventy percent of pedestrian deaths in 2002 occurred in urban areas. According to GES data, 55% of all pedestrian crashes occur at non-junctions, while 40% occur at intersections or intersection-related locations. A regional study has revealed a significant exposure to pedestrian accidents by transit agencies.

The work presented in this project represents a two-year effort taken by the research team to address pedestrian safety. With a survey of the latest technology developments and available products, a number of sensors were selected for evaluation to assess their applicability for transit bus platforms. In the course of experimental exploration, certain performance characteristics and limitations were investigated.

Recent national and state research efforts involve the use of wireless communication, combined with sensing devices, to enable the concept of vehicle-infrastructure integration (VII). The studies carried out in this project utilized an experimental platform that was built to demonstrate the feasibility of the VII approach. The success in initial testing not only validated the concept, but it was executed with a collection of commercially off-the-shelf products at reasonable costs. This is particularly meaningful because it has potential for a flexible scale of potential deployment without major infrastructure investments.

In addition to the potential VII solution, an integrated safety vehicle ideally should be supplemented with on-board sensing systems. For example, a sensor fusion approach uses multiple sensors to constitute an all-around detection system to overcome the deficiency of an individual sensing device. With the introduction of advanced computer vision, laser scanner, and infrared camera systems, a truly integrated sensing system can be expected in the foreseeable future. Furthermore, the increasing incorporation of various technologies, such as GPS, geographic mapping, inertial navigation, and dedicated short-range communication (DSRC), will provide more promising prospects for the deployment of safety solutions. Transit vehicles have the potential to be first equipped with such systems for field evaluation in an urban operating environment, which presents considerable challenges.

One critical issue that should be systematically evaluated is the human factor elements involved in the implementation of the suggested safety systems. The human-factors studies should include (1) the design of effective driver-vehicle interface (DVI), (2) experimentation with driver perception and reaction to DVI functionality, (3) field testing of the warning system through the interaction between driver and DVI, (4) establishment of performance measures to assess the effectiveness of the overall safety system. The design and evaluation of DVI remain a critical area for future studies.

1. INTRODUCTION – BACKGROUND

Pedestrian safety is a primary traffic issue in the urban environment. Even though the percentage of pedestrian accidents may not be the highest among all categories of accidents or collisions, these incidents represent a considerable hazard to the public since they often involve severe injuries or fatalities of pedestrians. Therefore, there are strong incentives to seek safety improvements based on the use of safety solutions.

This report provides a summary of work carried out under Task Order 5200, Experimental Vehicle Platform for Pedestrian Detection, in the period of February 2004 through March 2006. This report provides a summary of the literature search, sensor survey, experimental evaluation, and feasibility validation of integrated solutions. The work plan was organized to achieve the goals of the projects as follows:

(1) To further the understanding of performance constraints and limitations of commercially-off-the-shelf products, through experimental evaluation;
(2) To explore technical approaches and their requirements in implementing pedestrian safety countermeasures.

Even with the advancements of sensing technologies, the applicability of a single type of sensor for different operating conditions remains doubtful. With a variety of technical issues and complications taken into consideration, it is sensible to utilize different types of sensors in an integrated system to serve the necessary functions overall. This project aimed to establish an experimental vehicle platform, through synergistic utilization of existing equipment and vehicles from relevant Caltrans-PATH sponsored projects, to demonstrate possible technical approaches. During the execution of the project, an experimental transit bus and a passenger car were both used in conjunction with various sensing, computing, and communication devices at the PATH Richmond Field Station facility.

The project was first proposed to be carried out and tested on a transit vehicle platform, due to several characteristics associated with transit operations. For example, the relatively low equipment investment and the pre-known operational routes of buses offer desirable attributes that allow a cost-effective selection of safety countermeasures. Furthermore, for situations where transit buses operate on busy city streets, the heavy work loads of drivers make the monitoring of pedestrians even more challenging despite the fact that a great majority of bus drivers conduct their duties professionally and diligently. There is therefore a great incentive to deploy modern sensing technologies to assist drivers in identifying the presence and movements of pedestrians. However, it was also an intention of the project to make the results as applicable to other vehicle platforms as possible to maximize the usefulness of the research. For example, when a vehicle-infrastructure integrated approach was illustrated in a feasibility study, it was demonstrated with both a transit bus and a regular passenger car and was not limited to any specific vehicle type.

1.1 U.S. Situation

The national statistics regarding pedestrian crashes in the U.S. provide a sobering indication of the difficulty of addressing these crashes with infrastructure-based countermeasures. The locations in which these crashes occur are so diverse that it is hard to specify where in the infrastructure the countermeasure should be placed.

GES data, as cited by FHWA in their solicitation for ITS Technologies to Reduce Pedestrian Injuries and Fatalities [1], indicates that only 40% of pedestrian crashes occur at intersections or intersection-related locations, which would generally be the most obvious places to target for countermeasures. Of these crashes, only 45% are at signalized intersections (Table 1 of [1]), for a total of 18% of all pedestrian crashes. An additional 15% of the pedestrian crashes at intersections are at intersections controlled by stop signs (6% of the total) and another 36% (or 14.5% of the total) were uncontrolled, although many of these could have been on the uncontrolled legs at a two-way stop sign. More seriously, the data in Table 2 of [1] show that most of the pedestrians were not even in the crosswalks when they were hit. Working from the combination of Table 2 data and the percentages of pedestrian crashes defined by each of the ten scenarios defined in [1], it appears that only 11% of all pedestrian crashes occurred in crosswalks at intersections. This means that even if we were to equip all intersection crosswalks with pedestrian detection sensors to trigger warnings to drivers and/or pedestrians, we would only be addressing 11% of all pedestrian crashes.

Some of the pedestrian crashes are likely to be addressed by the new Cooperative Intersection Collision Avoidance System (CICAS) program without any pedestrian detection, particularly those associated with traffic control device violations by drivers. The data in Figure 3 of [1] indicate a modest fraction of the pedestrian crashes in three of the ten crash scenarios were associated with traffic sign or signal violations, representing a total of a little less than 3% of all pedestrian crashes. Of the pedestrian crashes occurring with vehicles turning left and right at intersections (15% of the total), about half of these involved pedestrians in the crosswalks. So, if CICAS systems included monitoring of pedestrians in crosswalks they could potentially address up to 7.5% of the pedestrian crashes.

These percentages are disconcertingly low for the level of investment that would be required to deploy such systems and cast doubt on the potential efficacy of pedestrian detection and warning systems that are based on fixed locations in the infrastructure (such as intersection crosswalks, which would seem to be the most fruitful locations). It may therefore be necessary to focus more attention on in-vehicle pedestrian detection capabilities in order to make a significant contribution to reducing pedestrian crashes. These systems can work anywhere on the road system that vehicles are traveling and where they are in proximity to pedestrians.

1.2 International Context for Comparison

In this context, it is worth considering the approaches being adopted in other countries that have higher percentages of their traffic fatalities among pedestrians than the U.S. does. In Japan, where pedestrian fatalities are a significant percentage of the national total, the Ministry of Land, Infrastructure and Transport put a sizeable effort into infrastructure-based pedestrian detection and warning systems for the AHSRA demonstration that they staged in 2000. That demonstration included a fully-equipped intersection with a variety of detectors for both vehicle and pedestrian traffic, and the pedestrian detection capability was demonstrated using a mannequin mounted on top of a radio-controlled cart traversing the crosswalk. Warnings of pedestrian presence were transmitted over a wireless DSRC-like link to approaching vehicles. However, it has been difficult to find any evidence of continuing development of this capability in Japan since that time, in part because it required such a heavy investment to equip an intersection. In contrast, most of the major Japanese motor vehicle manufacturers are now offering active infrared vision systems to help drivers see pedestrians along the roadway at night, using an image of the forward driving scene projected on a small head-up display at the top of the instrument panel. A few of them (Honda, Subaru and Mitsubishi Fuso trucks) have added image processing capabilities, including the use of stereo vision systems in the latter two cases, to recognize the shapes and movements of pedestrians and to use that recognition to generate audible alerts to drivers.

The European Commission has sponsored several pedestrian safety research projects in recent years, in some cases integrated within broader ITS traffic safety projects (such as PReVENT). These have also been virtually entirely vehicle-based rather than infrastructure-based. The two current pedestrian safety projects include APALACI, which is based on vehicle-mounted combinations of radar with video and radar with laser scanner sensors, and COMPOSE, which is using a combination of a 24 GHz short-range radar with a far-infrared video camera, again mounted in vehicles. Even the intersection collision avoidance project of the European program, called INTERSAFE, is based on use of in-vehicle, rather than infrastructure, sensing (using a scanning laser in that case). In the private sector in Europe, DaimlerChrysler Research has developed several image processing approaches for recognizing pedestrians, using video cameras mounted at the front of vehicles.

We are not prepared to prejudge the relative merits of the different systems and technologies being developed overseas, but should consider future evaluations of their advantages and disadvantages in support of the development of a vehicle-based approach (or approaches) that could be applied most effectively in the U.S. To some extent, this depends on the relative importance of pedestrian safety problems in different driving environments. The vision-based systems are typically more applicable for detecting pedestrians at long range in relatively uncluttered environments, while the short-range radar systems are aimed at high-density urban stop-and-go driving environments.

With the development of vehicle-vehicle wireless communication capabilities via the new generation of DSRC, it becomes possible for one vehicle with pedestrian detection capabilities to share its information about pedestrian presence with other vehicles that may not have the complete sensor suite, multiplying system effectiveness even when the vehicle market penetration is still small.

References

[1] *Analysis of Pedestrian Crashes,* NHTSA, DOT-VNTSC-NHTSA-02-02, Volpe National Transportation Systems Center. Cambridge, Massachusetts. April 2003.

2. LITERATURE REVIEW

Pedestrians are important yet vulnerable road users, especially in urban environments. Traffic accidents involving pedestrians usually lead to serious injuries or fatalities. From an application's point of view, pedestrian detection can be used for traffic flow monitoring, intelligent pedestrian crossing or on-board vehicles for driver assistance. From the technology's point view, different sensing technologies such as piezoelectric sensor, ultrasonic sensor, microwave radar, laser scanner and computer vision can be used for pedestrian detection. In testing different systems, performance (i.e. false positives and negatives, dependability across varying conditions, durability, relative ease of maintenance, etc.) is of fundamental importance. We have carried out an extensive review of existing literature and the latest developments in related fields. The review is summarized below, primarily categorized according to technology types.

There is already a substantial body of work that has been devoted to automatically detecting pedestrians, and a much more limited amount of work on automatically counting them. The project team has built on this heritage in order to identify the most appropriate methods and technologies to test.

2.1 Application-focused evaluations

Automatic pedestrian detection capabilities have been developed for a variety of purposes. Most of these (and especially the commercially available detectors) have been related to the need to trigger warning systems at crosswalks, to provide alerts to drivers of the presence of pedestrians without depending on the pedestrians to take a deliberate action such as pushing a button. A few projects have attempted to compare alternative technologies for use in the same environment, but most of the published references have focused on individual technologies.

Beckwith and Hunter-Zaworski [2] reported on an evaluation of a variety of systems for triggering traffic signal changes in Portland, OR. They eventually chose a passive infrared (IR) detector to detect the presence of pedestrians arriving at the curbside locations in order to trigger the alert, and a 10 GHz Doppler radar to determine whether the pedestrians were still in the crosswalk before extinguishing the warning system. However, this radar system was not able to distinguish pedestrian targets from vehicle targets.

The Minnesota DOT sponsored the evaluation of a variety of commercial off-the-shelf (COTS) bicycle and pedestrian detectors as part of a broader project to evaluate traffic detection systems [3]. Their report included an extensive literature review on bicycle and pedestrian detection technologies, and they tested four such systems under low volume conditions on a bicycle and pedestrian pathway. Their tests showed that three systems were 100% successful (one video, one passive IR and one combined ultrasound and passive IR), while one system was 93% successful (active IR), however they were only presented with one target bicycle or pedestrian at a time, in a simple environment without any significant disturbances.

The University of North Carolina also tested a variety of COTS pedestrian detectors for their ability to automatically trigger walk signals [4]. They provided an excellent survey of the issues involve in automatically triggering walk signals, but with an emphasis on the responses of the pedestrians rather than on the strengths and weaknesses of the different detection technologies [5]. An analogous study in Israel was reported by Hakkert et.al. [6], again focusing on pedestrian responses but with only passing references to technical performance limitations of the two detection systems that were tested. Note that all of these evaluations have addressed the need for simple detection of pedestrian presence (Is there a pedestrian here?), but not counting how many pedestrians are present or crossing.

2.2 Piezoelectric Sensors

Piezoelectricity, or "pressure" electricity, is the property of certain materials that produce a change in electrical properties with mechanical pressure. For application to pedestrian detection, piezo-cables with piezoelectric material are usually fabricated into a "mat" [7]. When a person steps onto such a mat, an electrical signal is generated until the person leaves the mat. In [8, 9], piezoelectric detectors are used to detect the presence of a waiting pedestrian at a controlled road crossing for PUFFIN (Pedestrian User-Friendly Intelligent Crossing) and PUSSYCATS (Pedestrian Urban Safety System and Comfort at Traffic Signals).

A piezoelectric detector is a simple reliable sensor for pedestrian detection. It does not require complex signal processing. However, it does require physical contact between a pedestrian and the sensor mat. Therefore, a piezoelectric detector is usually used at a pedestrian crossing and has to be used in conjunction with other sensors such as radars or infrared sensors. The piezoelectric sensor is ideal when direct physical contact between pedestrian and sensor is assured, such as at a location where pedestrians are channeled into a crossing.

2.3 Ultrasonic Sensors

Ultrasonic detectors transmit ultrasonic waves (high frequency, outside audible frequency). When vehicles or pedestrians pass by, a portion of the transmitted sound wave is reflected back to the receiver. Based on analysis of the reflected signal, objects can be detected together with their distance and speed. There are two basic types of ultrasonic sensors depending on the waveform of the ultrasonic wave [10]. Pulse ultrasonic sensors measure the distance or presence of objects by sending a pulsed ultrasound wave and then measuring the flight time of the reflected sound echo. Continuous wave ultrasonic sensors output continuous ultrasonic waves of certain frequency and use the Doppler principle to detect a moving object and its speed.

Ultrasonic detectors can detect objects up to 30 feet. A discussion about the limitations of ultrasonic sensors follows [2, 11]. First, in order to minimize lost bounced-back ultrasound energy from a target, the preferred installation configurations are either directly facing downward (i.e. nadir incidence angle) above the targeting area or are aiming from a horizontally-mounted side-viewing position (side-fired). Second, clothing has some effects on pedestrian detection. Clothes made of natural fiber are generally more absorbent to sound waves than clothes made of synthetic fiber. Therefore, pedestrians wearing synthetic fiber (e.g. nylon) are easily detected compared with pedestrians wearing natural fiber (e.g. cotton). Finally, weather conditions change; temperature, pressure, humidity and wind will affect the performance of ultrasonic sensors. This is because the speed of sound varies according to the temperature and pressure of the medium. In [2], ultrasonic sensors placed at un-signalized crossings for pedestrian detection received more false calls during rainy weather. In [12], the effect of wind from different directions was studied for an ultrasonic sensor system.

2.4 Microwave Radar

Microwave radar works similarly to ultrasonic sensors. Instead of sound waves, electromagnetic waves are transmitted from the microwave radar antenna. Based on the analysis of bounced back signals, objects can be detected together with their distance and speed.

There are three primary types of microwave radars, based on their transmitted electromagnetic wave form (Doppler, FMCW and UWB). Doppler radar transmits a continuous wave of constant frequency. Such electromagnetic waves, when reflected from a moving object, will have a frequency shift. By analyzing the frequency shift, the speed of the object can be calculated. Doppler radar alone can only detect moving object with a speed greater than a certain threshold.

The second type of microwave radar transmits frequency-modulated or phase-modulated signals. For example, the second generation 77 GHz long-range radar sensor is based on frequency modulated continuous wave (FMCW) technology [13]. The distance to the target is determined by the time delay of the return signal [10,11].

Ultra wide band (UWB) radar is a new, emerging, technology which has great potential in ITS applications [14, 15]. The basic concept is to transmit and receive an extremely short duration burst of radio frequency (RF) energy – typically a few tens of picoseconds (trillionths of a second) to a few nanoseconds (billionths of a second) in duration. The resultant waveforms are extremely broadband, so much so that it is often difficult to determine an actual RF center frequency. The precision timing of pulses inherent to UWB radar and the successful development of advanced timer technology has enabled UWB radar to be capable of detection, ranging and motion sensing of personnel and objects with centimeter precision.

In order to offer more freedom and information, different radar technologies are often integrated together. For example, the proposed 24 GHz short-range radar (SRR) technology by the automobile industry is a combination of two functions [13]: 1) a classic Doppler radar mode providing speed information about an approaching object; 2) an UWB radar mode providing position information about objects with a resolution of approximately 10-15 cm.

Radar sensors can provide accurate object distance and speed without complex signal processing (compared with computer vision). Radar technology can operate in different environmental conditions (e.g. bad weather, poor visibility or harsh environmental impacts like ice, snow or dust coverage). If installed on the vehicle, it can be hidden behind un-shielding materials with no influence on the vehicle's appearance and thus does not disturb the vehicle design. To further differentiate detected objects, (e.g. pedestrians or other traffic participants) the power spectral density characteristics of the reflected signal can be analyzed [16]. For example, water content in the human body makes the power spectral density of the reflected signal very different from that of cars or poles. Where a single radar sensor installed on a vehicle may not be enough to cover the whole interested area, a radar network comprised of several radars with different beam designs [17] can be used to achieve large coverage area.

An early Doppler radar test of pedestrian detection was applied for detecting children boarding and alighting in the vicinity of school buses [18]. Two different radars were tested, primarily using crash dummies to represent children in standing and prone positions. These sensors detected all moving targets within their range, including not only pedestrians near the bus, but also pedestrians on adjacent sidewalks and vehicles passing adjacent to and across from the bus.

2.5 Infrared Laser Scanners

A laser scanner is a high-resolution laser range finder [18-21]. The laser scanner emits infrared laser pulses and detects the reflected pulses. The measurement principle is based on the time-of-flight method, where the distance to the target is directly proportional to the time interval between transmission and the reception of a pulse. Scanning of the measurement beam is achieved by a rotating prism and covers a viewing angle of up to 360 degrees. The original data from a laser scanner is much like vision image data in the horizontal scanning plane with accurate distance (centimeter level) and azimuth angle (from 0.25 degree to 1 degree depending on scanning frequency) information. Therefore, a procedure similar to image processing is applied. First, clustered data points are grouped into different objects by segmentation. Then the objects are classified into different categories according to their characteristics. For example, pedestrians can be classified by the characteristics of their moving legs [22]. Finally, object tracking is performed by a Kalman Filtering method [21].

In [23], a pedestrian tracking system consisting of multiple laser scanners is proposed to track pedestrians in a wide and open area. Each laser scanner is controlled by a local computer. All local computers are connected to a server computer through a LAN. The laser scanners are placed at the ground level and the moving feet of the pedestrians are extracted from the background. A human walking model-based Kalman filter is implemented to track the walking pedestrian. For application on vehicles, the vehicle model is set up to compensate for vehicle motions [19]. In order to compensate for vehicle pitch motion, a multilayer laser scanner with more than one scanning plane is designed [20]. Multiple-hypothesis classification approach is used to separate close targets' images acquired by the multilayer laser scanner in [24]. A pedestrian detection system based on a multi-layer laser scanner was built with a field-of-view of 120 degrees in front of a vehicle [25]. A region of no escape (RONE) was introduced, describing an area in front of the car where the car-to-pedestrian accident is unavoidable if the pedestrian is detected inside this area.

Excellent range accuracy and fine angular resolution make laser scanners suitable for applications in which a high-resolution image of the surroundings is required. However, since they are optical sensors, weather conditions like fog or snow will limit their detection range. The signal processing is a little more complex for laser scanner compared with ultrasonic or microwave radar, therefore a dedicated CPU may be needed.

2.6 Passive Infrared (non-imaging)

Passive infrared was suggested for near-range pedestrian detection using an array of thermopile sensors with probabilistic techniques for detection improvements [26]. A Thermopile sensor array with optimized location is designed to detect a pedestrian and estimate the pedestrian's position in [27]. The implementation of a low-cost sensor array could lower the system cost because multiple sensors can be affordably used. This increases reliability. Such a sensor array could also provide a large field-of-view compared with a single sensor, which is necessary for the near-range pedestrian detection.

To reduce the cost of infrared cameras, which were used mostly in military application before, low-cost 16-by-16 array infra-red detectors are used in groups not only to count the pedestrian number passing by, but also to capture pedestrians' moving trajectories along certain corridors in [28]. This paper describes preliminary experiments with a passive infrared pedestrian detector (IRISYS) tracking and counting pedestrians walking along an indoor corridor, under both daylight and night-time lighting conditions. The results showed some loss of counts at higher pedestrian densities, when it became more difficult for the detector to distinguish adjacent pedestrians.

2.7 Computer Vision

Vision-based pedestrian detection is a natural choice based on a human's own experience. The human visual perception system is perhaps the best example of what performance can possibly be achieved with these vision sensors. Although a video camera can obtain much richer information about the surrounding environment compared with a radar or laser scanner, the image sequences can not be used for anything directly without further interpretation. Extracting useful information from available image sequences is not a trivial task for several reasons [29, 30]:

(1) Pedestrian detection involves a complex uncontrolled outdoor environment. The illuminating conditions may change due to weather, sunrise or sunset. Pedestrians are found mostly in city traffic conditions where the background texture (e.g. nearby buildings, vehicles, poles and trees) form a highly cluttered environment.
(2) A wide range of variations exist in pedestrian appearance because of clothing, pose, occlusion, shadow, motion, size and skin color.
(3) If the camera is installed on a moving vehicle, this will increase the difficulty to differentiate between background objects and pedestrians.
(4) Image processing generally requires large computing power and pedestrian detection for an intelligent vehicle typically needs a fast response when considering the speed of the moving vehicle.

An extensive amount of work has been done on vision-based pedestrian detection. In the U.S., a couple of university research teams have been using image processing technology to detect pedestrian activity. Carnegie-Mellon University's Robotics Institute has many years of experience with image processing, and a comprehensive survey of their research includes pedestrian detection and tracking (as well as a useful reference list citing prior related work) [29].

While the CMU results were shown for low-density pedestrian activity, researchers at the University of Minnesota reported on success in detecting pedestrians in high-density environments [30]. This work reported success in tracking movements of individual pedestrians in both daylight and night-time conditions, but did not report on accuracy or estimates of pedestrian volume.

A variety of cameras or configurations have been used in vision-based pedestrian detection systems:

1. The camera could be moving (e.g. installed on a moving vehicle for driving assistance) or still (e.g. installed on a post at an intersection for surveillance purpose [33]).
2. To acquire accurate range measurement, stereo [29, 34-36] instead of monocular camera configuration may be used.
3. Infrared cameras [37, 38] are not that sensitive to illumination, as are normal cameras operating in the visible spectrum.

Various algorithms have been proposed to detect pedestrians in the image sequences acquired from video cameras. Recent research shows two main trends. Motion-based approaches take into account temporal information and try to detect the periodic features of human gait in the movement of candidate patterns. On the other hand, the shape-based approaches rely on shape features to recognize pedestrians.

Motion-based approaches use rhythmic features or motion patterns unique to human beings. In [39], the Maximum Entropy Method was applied to observe the periodic changes of image intensity caused by walking. In [40], Fourier Transformation with Hanning window was used to find periodicity in the acquired image sequences. The UK's Defense Evaluation and Research Agency counted pedestrian motions in order to estimate their exposure to risk in traffic [40]. The report on this work dates from 1997, when it needed to rely on use of custom computer hardware, and claimed 85% accuracy when sampling 35 pedestrians in 30 minutes. There were concerns about occlusion problems when going to higher pedestrian densities.

Although motion-based approaches provide an efficient way to reduce the number of false positive candidates, there are several limitations to motion-based approaches. First, motion-based schemes obviously cannot detect stationary pedestrians or pedestrians engaged in unusual movement like jumping. Second, the pedestrian's feet or legs should be visible in order to extract rhythmic features or motion patterns. Third, the recognition procedure requires a sequence of images, which delays the identification until several frames later and increases the processing time.

Shape-based methods allow recognition of both moving and stationary pedestrians. The primary difficulty associated with this approach is how to accommodate the wide range of variations in pedestrian appearances due to pose, various articulations of body parts, lighting, clothing, occlusion, etc. The key issues here are: first, find a concise yet sufficient human shape feature representation that could achieve high inter-class variability with low intra-class variability. Second, maintain a balance between accuracy of detection and processing time.

In [42], an over-complete dictionary of Harr wavelets is used as representation of human shape characteristics. A support vector machine trained with characteristics extracted from example human images is used as a classifier. In order to detect a partially occluded pedestrian, the same system is modified to detect components of the human body (e.g. head, torso or limbs) first, then the detected body parts are assembled together [43]. The proposed system has to search the whole image at multi-scale for pedestrian characteristics. This brute force search increases the computation cost substantially.

To achieve real-time processing, trade-offs have to be made between accuracy of classification and processing time. Two-step processing approaches are used to relieve such computational burden in [29, 34, 35, 37, 44, 45]. Usually a coarse segmentation step is carried out first to separate the foreground and the interest region from the background. The fine analysis of the separated foreground objects is then followed to check for the presence of pedestrians. In [34], the distance measurement from stereo vision is used for the segmentation step. A neural network trained by example pedestrian images is used to classify segmented foreground objects. The stereo vision system developed for the ARGO vehicle is introduced in [35]. The vertical symmetry of a pedestrian is used in the segmentation step. Then pedestrian candidates are filtered by head shape, distance, size and aspect ratio. In [44, 46], the Chamfer system developed by DaimlerChrysler is introduced. The segmentation step is performed by matching distance-transformed images with different pedestrian shape templates. To reduce the processing time, the templates are organized in a certain hierarchy. A Radial Basis Function-based fine analysis is then implemented to reduce the false positive rate. The information produced in this way is then passed on to the tracker module, which reconstructs an interpretation of the pedestrian positions in the scene by using a Kalman filtering method [47].

Although the shape-based method is more general, the major drawbacks associated with the shape method are: 1) high false positive rate due to variation of human shape and changing lighting conditions, and 2) heavy computation burden when performing feature matching. Different approaches are proposed to resolve these drawbacks. In [30], the single-frame shape match is combined with motion analysis to reduce false positive rates. A specialized system-on-a-chip [48, 49] hardware solution is used to increase processing speed. In [50], knowledge about certain sites and situations (e.g. traffic signal, pedestrian crossing, etc.) are used as *a priori* information to optimize the vision-processing algorithm.

Computer vision-based systems have been suggested based on a variety of technical approaches. One method is based on the use of a convolutional neural network (CNN) classifier [51]. This method achieves high accuracy by automatically optimizing the feature representation to the detection task and regularizing the neural network. The false positive rate (FPR) of the proposed CNN classifier is less than 1/5-th of the FPR of a support vector machine (SVM) classifier using Haar-wavelet features when the detection rate is 90%. The computational demand of the CNN classifier is, however, more than an order of magnitude lower than that of the SVM, irrespective of the type of features used. Another approach [52] presents a method for pedestrian detection with stereo vision and graph comparison. Images are segmented by the N-Cut method and applied on a single image, and the disparity is computed from a pair of images. This segmentation enables capturing only shapes of potential obstacles by eliminating the background. Another method [53] proposed a pedestrian feature representation approach based on Spare

Gabor Filters (SGF) which would learn from examples. In the phase of pedestrian detection, it used a support vector machine to detect the pedestrian.

Compared with cameras operating in the visible spectrum, infrared (IR) cameras [37, 38] are not that sensitive to changes in lighting condition. The advantage of a passive infrared sensor is its ability to detect pedestrians without illuminating the environment. Such an environment-friendly feature brings in no regulations and licensing issues compared with other sensor technologies like radar. Pedestrians are bright and sufficiently contrasted with respect to the background in IR images. Other objects which actively radiate heat show similar imaging behavior. However, people can be recognized thanks to their distinct shape and aspect ratio [54].

Honda has developed an intelligent night vision system which is available on the new Honda Legend in Japan [55]. Two long wave infrared cameras are installed in the front bumper. The target distance is acquired by the stereo infrared vision from two cameras. Pedestrians can be identified by shape recognition and their movements are tracked through vector analysis. The system will provide the driver visual and audio cautions when it detects pedestrians in or approaching the vehicle's path.

For longer-range pedestrian recognition with infrared camera images [56], the technical approach was based on the localization and distance estimation of warm areas in the scene. The algorithm groups areas with similar position and considers only results with specific size and aspect ratio. A micro-bolometer technology sensor, sensitive between 7 and 14 micrometers in the long wave infrared band, with a spatial, temporal and spectral resolution of 164 x 129 px @ 25 Hz, 14 bit was used [57] to provide a recognition scheme. Three detection algorithms were simultaneously evaluated and fused afterwards.

Researchers at INRETS in France reported success in counting the number of passengers passing through specific locations in transit stations, using a "linear camera" optical method [58]. They used an IR camera and active illumination source on the ceiling, looking down at reflective lines on the ground, and then counted the number of pedestrians passing by, including estimates of their speed. They claimed accuracy of 99% in counting pedestrians passing through a 3 m wide passageway, but noted some loss of accuracy at higher densities when pedestrians were so close together that their image "blobs" merged together.

A different application of automatic pedestrian detection is to analyze the flows of travelers in crowded terminals. Reference [59] described a study in France that identified the patterns of pedestrian motion by automatically processing images from video cameras mounted in subway corridors. In this case, the goal was to identify abnormal patterns of motion rather than to count the volume of pedestrian traffic. Related work was reported from a study in the Netherlands [60], where the experiments were conducted in a large room, with a camera mounted directly overhead at a height of 10 m. The authors of this study were concerned about how to extend their capabilities to accommodate highly variable lighting conditions in outdoor settings.

2.8 Sensor Fusion

After reviewing different sensor technologies, a natural idea is to combine different technologies together so that one technology‘s advantage can be used to compensate another’s limitation. In [61, 62], computer vision together with microwave radar are used for pedestrian detection from a moving vehicle. The radar information is used to generate a potential target list and vision is used to do the fine searching. In [63], the combination of dynamic passive infrared detection and active ultrasonic ranging in a single detector gives highly reliable presence information in the intelligent pedestrian crossing application. In [44], the next generation vehicle surround sensing system could use a combination of different sensors. Ultrasonic sensors could be used for very short-range sensing when parking or reversing. A 24 GHz Short-range Radar (SRR) could be used to cover the vehicle perimeter up to 20 meters. A 77 GHz Long-range radar or LIDAR would be used for long-range sensing up to 120 meters. Computer vision would be used for fine sensing around medium-range (0-80 meters), with an infrared camera for night driving.

The sensor-fusion approach was suggested in [16, 64, 65], which utilizes multiple sensors (e.g. radar and laser scanner [18-20]) together with computer vision to reduce false positive rates.

Although sensor fusion could improve system performance by employing different sensor technologies, this will increase system complexity significantly and brings in reliability problems. Also, sensor fusion is not just stacking different sensors together. It needs more “smart” processing of different sensor data so that we could have a deeper understanding of surrounding information. For example, radar and vision systems are integrated together in [66] to provide target information for a stop-and-go Adaptive Cruise Control (ACC) system in an urban environment. The system design assumes that each subsystem could detect and classify a target independently. Target matching is then performed to link targets detected by radar and vision system. During that process, “ghost” targets from the radar and occluded targets from the vision system are identified to make the whole system more robust.

A multi-sensor system was developed [67] consisting of a far infrared camera, a laser-scanning device and ego-motion sensors. Arranging a set of Kalman filters in parallel, a multi-sensor/multi-target tracking system was created based on the shapes and motions of pedestrians.

Some of the most ambitious efforts to date at detecting pedestrians have been in Japan, whose Ministry of Land, Infrastructure and Transport is researching the possibility of using remote sensors to detect pedestrian positions in crosswalks. They have tested multiple sensors to cover a 12 x 15 m crosswalk area, including laser scanners (accurate, but slow) and both visual and IR imaging sensors (only accurate to within +/- 5 m, but faster) [68, 69]. Their results showed how the different types of sensors complemented each other for identifying the location of a single pedestrian, but have not addressed the counting of multiple pedestrians. Another project by Japan’s National Policy Agency combined IR scanners and image processing for pedestrian detection at a crosswalk, identifying the need to improve the accuracy of the image processing detector [70].

2.9 Testing and Verification

The pedestrian detection system is a critical part of a pedestrian protection system with its accurate, reliable and robust performance. Currently, pedestrian detection systems are often tested and evaluated in real world traffic. Although this could provide accurate results, it is not safe and is also time/resource-consuming. A simulation evaluation tool could be a better choice before real world testing and evaluation. In [71], the pedestrian accident data is first analyzed to find its statistical distribution characteristics. The pedestrian model is set up according to the available pedestrian accident statistics. A simulation tool for the pedestrian detection system could be considered with a new pedestrian model.

2.10 Pedestrian Detection System Applications and Requirements

An automatic pedestrian detection system could be applied to serve a variety of different purposes. It is not realistic to expect a single set of performance requirements to satisfy all application needs, but rather the end-use applications will have a strong influence on the performance requirements. The following five classes of applications are suggested, in order of increasing severity of requirements:

A. Counting pedestrians for off-line analysis (data collection)
B. Actuating or holding a pedestrian crossing signal
C. Actuating an infrastructure-based hazard alert system (such as IDS/CICAS)
D. Actuating a vehicle-based pedestrian collision warning system
E. Actuating a vehicle-based pedestrian collision avoidance system

Application A has no safety implications, so the consequences of poor performance are limited, and it is not time critical. Application B has limited safety implications and time criticality, but applications C to E are increasingly safety-critical and time-critical.

Some of these applications have implicit requirements for the detection field of view, based on the locations where they are expected to be used. Actuating a pedestrian crossing signal requires detecting pedestrians in the vicinity of the curb at the end of a crosswalk, in a zone that should be at least the width of the crosswalk. Holding a pedestrian crossing signal requires detecting pedestrians who are in the crosswalk, ideally along its entire length. Actuating an infrastructure-based hazard alert system generally requires detecting pedestrians anywhere in the crosswalk or entering the crosswalk from the vicinity of the curb at either end. Actuating a vehicle-based pedestrian warning system involves a very extensive and challenging field of view – typically covering a significant distance in front of the vehicle, over a zone considerably wider than the vehicle width, or in the special case of detecting passengers boarding or alighting from a bus, covering a zone most of the length of the bus and several feet to its side. The last category, actuating a collision avoidance system, is the most demanding and challenging application. In the following discussions, category (E) is excluded because it is still in the research stage and sees limited opportunities for applications.

The other categories of requirements (other than field of view) that should be considered for evaluating pedestrian detection systems are:

(1) Frequency of missed detections (or the ratio of false negatives to true positives): This is the most safety-critical concern, since failure to detect a pedestrian could lead to an undetected hazardous condition.
(2) Ratio of false positives to true positives: This provides an indication of nuisance alerts, and the likelihood that a system could be disregarded because people do not find it trustworthy.
(3) Ability to detect stationary, or moving, pedestrians, or both: This determines the flexibility of the system for use under a wider range of conditions.
(4) Ability to detect presence of pedestrians, number of pedestrians, or presence and speeds of movement of pedestrians: This determines how complete a description of the pedestrian environment the system can provide.
(5) Ability to detect pedestrians in adverse weather conditions (rain, snow, fog, dust…) and adverse lighting conditions (dawn, dusk, nighttime, in shadows or backlighting): In order to support systems to improve pedestrian safety, it is preferable for a detector to be able to work under the very conditions when people (especially drivers) have the most difficulty detecting pedestrians.
(6) Latency (delay time to detection): In the most urgent safety-critical situations, the latency could affect the feasibility of issuing a timely alert.
(7) Sensitivity (ability to detect the smallest pedestrians, down to the size of small ambulatory children): This determines how widely applicable the system could be, particularly since the smallest children are generally also the most difficult for people to detect and track.

Initial thoughts about mapping the performance requirements into the four application classes are summarized in the table below. The requirements for a particular application can be better defined once its operating environment and targeted scenarios are evaluated in further details.

Table 2.1 Performance Requirements of Pedestrian Detection Applictions

Requirement	A	B	C	D
1. Missed detections	5%	2%	1%	1%
2. False positives	5%	5%	2%	2%
3. Stationary, moving pedestrians	Both	Stationary/Both	Both	Both
4. Presence, number, speed	Number	Presence, number	Presence, speed	Presence, speed
5. Adverse weather, lighting	Depends on applic.	All but most extreme cases	All but most extreme cases	All but most extreme cases
6. Latency	N/A	5 s	1 s	0.5 s
7. Sensitivity	Toddler	Toddler	Toddler	Toddler

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3. SENSOR SURVEY AND EVALUAITON

In this study, an extensive survey of products was conducted following the literature review described in the previous section. Available and prospective products are then experimentally evaluated. The testing of sensors was carried out with PATH experimental, including real-size transit bus and regular passenger vehicles.

3.1 Summary of Field Test Data from FCWS Bus

To design a pedestrian detection system for transit bus applications that is suitable for future field deployment, it is important to understand the interactions between pedestrians and transit buses in the real traffic conditions. As part of our efforts in Task Order 5200, we relied on data from the field experiments that have been carried out under the Frontal Collision Warning Systems (FCWS) project, which was sponsored by the Federal Transit Administration (FTA) and Caltrans and is synergistic with the objectives of TO 5200. This experimental bus is equipped with computerized data acquisition systems and a variety of sensing devices, and the data represent real-world traffic conditions encountered when the buses were operated by regular drivers on normal Samtrans (San Mateo County Transit Authority) daily routes.

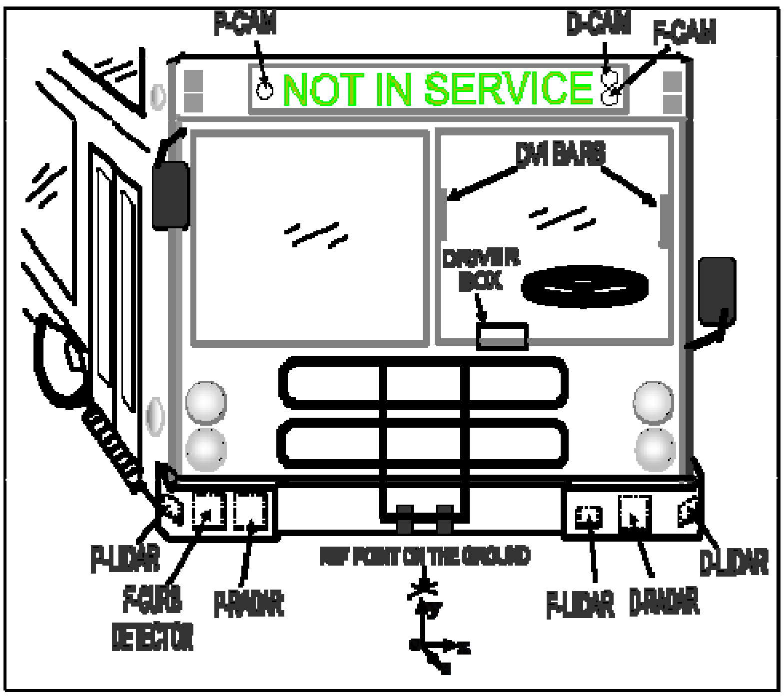

Fig. 3.1 Samtrans bus configuration

3.1.1 Sensor Configuration on FCWS Experimental Bus

Fig. 3.1 shows the configuration of an instrumented Samtrans bus. Three video cameras are installed near the front display panel, oriented towards the front, right front and left front directions ahead of the bus. Two Eaton VORAD radars and three LIDARS are installed on the bus bumper. Targets detected by the LIDARs and radars are recorded by the on-board computer, and video streams from the video cameras are also recorded for verification purposes.

A data visualization tool was also developed by the FCWS project. Fig. 3.2 shows a snapshot of the data visualization software tool. Three video streams from three cameras are displayed at the top of the window. Targets identified by radars are labeled with crosshair markers, and targets identified by LIDARs are labeled with square markers on the video images. Although data from three LIDARs are available, the data visualization tool only shows data from the F-LIDAR (center one) in Fig. 3.2. The status of the bus operation (e.g. steering wheel angle, bus speed, brake pressure and bus acceleration) are displayed in the right lower corner of the window.

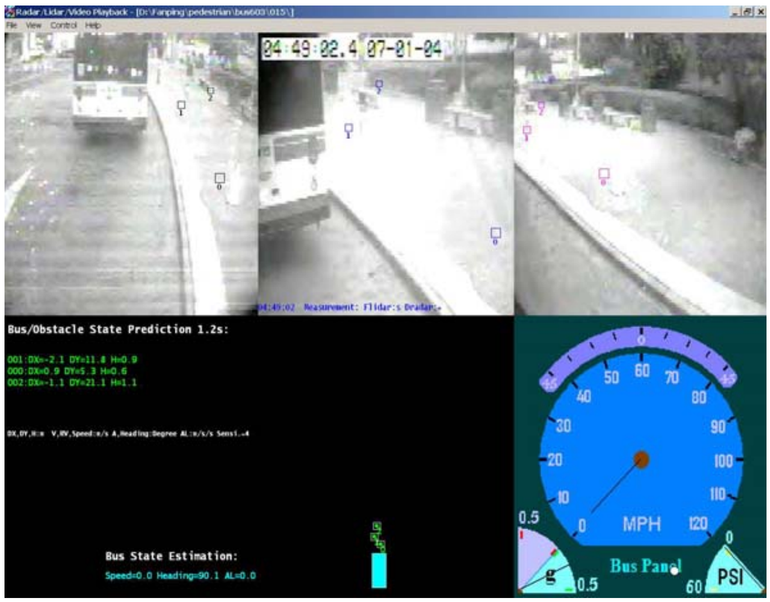

Fig. 3.2 Data Visualization Software snapshot

The reasons for using the field data and the associated software tool for the review are several -fold:

(1) The data contain the target detection information provided by the LIDAR and RADAR installed on the bus, both of which are candidate technologies that we have explored earlier in the project.
(2) The data further supplement the sensor data with video images, which can help us distinguish legitimate pedestrian targets from other targets.
(3) The video data cover the regular bus operation routes in suburban and urban environments, which allows us to evaluate specific scenarios of pedestrian-bus interactions.

3.1.2 Noticeable and Most Commonly-Seen Scenarios involving Pedestrians

There is a considerable amount of field data available for review. Since our main interest is to study the typical scenarios during bus operations, we started by selecting a full day of operational data to review and screen for situations when pedestrians appeared in the vicinity or the path of the bus. In this section, we highlight a few particular scenarios of interest observed in the data.

Fig. 3.3 Pedestrians walking across the intersection in front of a stopped bus

Fig. 3.4 Pedestrians walking across the intersection in front of a moving bus

We reviewed data collected on July 1, 2004, when the bus started its operation at 4 am and stopped at 4 pm. The scenario most frequently encountered is shown in Fig. 3.3. Pedestrians walk through cross walks at an intersection. The bus is either stopped in front of the crosswalk as shown in Fig. 3.3 or approaching the crosswalk as shown in Fig. 3.4.

Fig. 3.5 Pedestrians waiting at platform on the sidewalk

Fig. 3.6 Pedestrians walk around a big station with several buses

Pedestrians are also typically present on the platform waiting for buses. Fig. 3.5 shows pedestrians waiting for buses at a platform on the sidewalk. Fig. 3.6 shows the scenario at a big bus station where several buses are stopped or moving nearby. In this particular situation in Figure 3.6, pedestrians are moving around the instrumented bus to rush to another bus.

Fig. 3.7 Pedestrians walk on the sidewalk

Fig. 3.8 Pedestrian walks with bicycle in front of bus

Other scenarios that are frequently seen include pedestrians walking on the sidewalk as the bus passes by, as shown in Figure 3.7, and pedestrians walking his/her bicycle near a bus as shown in Figure 3.8.

3.1.3 Detection Issues in Real-World Traffic

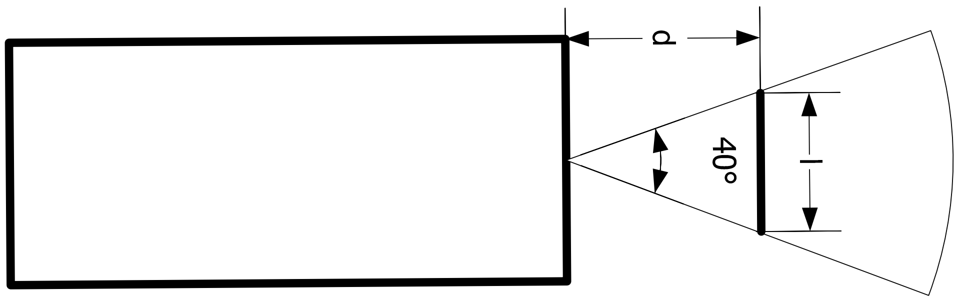

Fig. 3.9 Sensor Field of View

As frequently seen in the real-world data, pedestrians generally appear within a close distance to the bus and they may move in various directions. This significant characteristic of pedestrian traffic encountered by transit buses presents serious challenges for those sensors intended for long-range detection. The sensor package (radar and LIDAR) installed on the Samtrans data collecting bus has superb capabilities for detecting and tracking targets at long range. Their performance specifications are the same as or similar to those that we have explained and illustrated in our earlier report for the Eaton VORAD Doppler radar evaluation.

However, one common nature of these long range sensors is that they are designed for a relatively narrow field of view. Furthermore, there may be other design limitations. For example, the minimum detection distance for the Eaton VORAD EVT300 radar is about 5 m and its detection sensitivity drops significantly for objects moving perpendicularly to the orientation of the radar antenna. Unfortunately, these are the typical cases for pedestrian detection that are required by transit bus operations. Therefore, the radar performance for pedestrian detection is very poor in the data we reviewed. The laser scanner from IBEO that we evaluated earlier is designed to have a 360-degree all-around capability, and does not have the same limitations on field of view as those on the Samtrans bus.

LIDAR has a much better pedestrian detection performance than radar, based on the field data. Nevertheless, one particular problem associated with the LIDAR for pedestrian detection is the limited field of view due to their directional nature. Keep in mind that these sensors are designed for other applications, such as detecting and tracking targets in highway driving. If they are used for short-range applications, then the coverage area is quite limited. As shown in Fig. 3.9, the LIDAR installed on the Samtrans bus has a view angle of 40 degrees to the front of the bus. If a pedestrian walks about 1.5 m (*d* in Fig. 3.9) in front of the bus, the pedestrian will be exposed to the LIDAR detection for about 1 m in his/her path (*l* in Fig. 3.9). In other words, if the pedestrian has a walking speed about 1 m/s (2.2 mph), the LIDAR has only about 1 sec to establish its target identification and tracking. Then the pedestrian will disappear from the LIDAR beam. Multiple LIDARs or other sensors can be combined to provide a wider coverage area, however, the cost of the complete system must be reasonable to be considered for field deployment. Therefore, to implement sensing systems for near-range pedestrian detection around the perimeter of a transit bus, developments should consider (1) the installation of sensor units at strategic locations around the bus that are most safety critical, and (2) constructing multiple sensor units that consist of low-cost arrays in large numbers.

3.1.4 Summary

The review of field data collected from regular transit bus operations has proven to be valuable for the evaluation of design issues for pedestrian detection. We have utilized the real-world data and the visualization and playback software tool for data review from another transit project (FCWS), which is synergistic and applicable to the objectives of this project. It will be useful to consider the option of conducting further review of field data. Furthermore, if field operational testing (FOT) is to be conducted for any candidate technologies for pedestrian detection, data should also be collected and reviewed to verify the effectiveness of the selected system.

In daytime operations such as the data set that was reviewed, it was found that there were very rare events that the driver needed assistance for pedestrian identification at long ranges. It appeared that more hazardous situations for bus drivers occurred when pedestrians were within about 10 meters. The other aspect to be considered for pedestrian detection is that pedestrians often walked in a direction perpendicular to or at a large angle relative to the heading direction of the bus. In other words, it is more meaningful to provide driver assistance when pedestrians are in crossing maneuvers. In this case, the most critical detection range may be as little as 5 meters. Coincidentally, this is also the range for blind spots or limited field of view within the drivers' vision. In these conditions, the drivers are also likely to have a greater workload as they pay attention to their stopping and pulling out maneuvers right before and after passenger boarding and alighting.

It should be noted, however, that a longer range of detection will be strongly desirable. This is evident since the night time conditions will not allow the driver to have as long a visibility range as is available in daytime. Highlights of the Honda night-time infrared system, at the following link, indicate strongly that there will be more stringent requirements for night-time operations. See http://world.honda.com/HDTV/IntelligentNightVision/200408/

3.2 Categorization of Evaluation Criteria

Following the considerations given in the technical approach section (Section 2.0), we have decided to tackle the pedestrian detection problem in three separate manners. This is a slight departure from the original outline in the proposal because the third option of vehicle-infrastructure cooperation is adopted.

(1) Near-range or close proximity detection

This is most relevant when the bus is stationary or near-stop at bus stops or intersections. Under these conditions, there tends to be a higher level of pedestrian traffic while the driver's attention is more likely to be distracted. The requirements of this application place more emphasis on short-range presence of pedestrians.

(2) Pedestrian movements at longer ranges

This applies to the operating condition when the vehicle is in a cruising state. The requirements focus on relative motions and long-distance detection of targets in a mostly forward direction.

(3) Infrastructure sensors combined with vehicle on-board driver alert

This is based on the vehicle-infrastructure integration approach described in Section 2. Essentially an infrastructure sensor is used to detect the presence or movement of pedestrians. The sensor can be implemented based on a variety of technological choices such as microwave, infrared or computer vision. In the meantime, a wireless communication link is provided to transmit an alert signal under appropriate conditions to an on-board receiver, which then in turn activates the warning system on the bus. This operating concept is particularly meaningful for transit bus operations for the following reasons:

- Transit buses run on fixed and pre-known routes. Therefore, the high-risk locations can be pre-determined and selectively equipped with such systems.
- Transit buses are relatively high-price vehicles, therefore the addition of wireless transceivers will add minimal costs to the overall vehicles.
- Infrastructure-based sensors can be selectively deployed at strategic locations and can be tailored to meet the needs or constraints of specific locations without the issue of performance deterioration or variations caused by vehicle motions and individual platforms.
- There is increasing interest to adopt wireless communication devices on the national roadway infrastructure, such as the national VII program, http://www.its.dot.gov/initiatives/in9/vii.htm. The application for transit safety can be an early deployment candidate for VII.

3.3 Sensor Survey and Comparison

Based on the three identified technical approaches, we then set out to survey available commercial products and down-select the appropriate candidates for further experimentation. However, in addition to the technical performance specifications, we also place a high priority on the costs of equipment and implementation because it is an important criterion for deployment. Simply put, we are looking for reasonably-priced devices that can be adopted and modified to fit the needs of any one of the three concepts of operations, even if they do not necessarily represent the most sophisticated or accurate sensors that have been developed.

For example, a number of video systems have been developed either in the research stage or into the commercial stage for object recognition, including pedestrian identification. One particular product that has advertised such capabilities is highlighted at http://www.mobileye.com. However, the vendor mostly deals with automotive OEMs and the price of a development kit for specific applications will be well over $50,000, which is not realistic for deployment unless in the long run, the technology becomes cheaply available and can be utilized on a large number of vehicles. Several other video detection systems are available commercially, but they are mostly designed for indoor use or particular lighting conditions and are subject to performance deterioration if placed in outdoor and all-weather operating conditions. For this reason, we also excluded a few other candidates

Another example is a popular laser scanner, IBEO, which has been demonstrated to be able to capture rich sets of information in its field of view. It is also highly priced. However, since another PATH project already is in possession of an IBEO sensor, we are including it in the experimental evaluation at no purchase cost.

Yet another example is a newly available infrared imaging system offered by Honda on some its advanced model vehicles in Japan. Even though this is a very promising technology, currently it is not available for research evaluation and we will not be able to acquire it for experimental evaluation.

One of the candidate technologies identified early in the project is capacitance sensors, which have been commercialized for automotive applications. Elyses America produces a sensing system based on electric field variations due to the presence of human bodies, for application to occupant sensing to disable airbags if the occupants are seated in an improper location.

The following table offers a comparison of various technologies that are potential candidates for implementing a pedestrian detection solution.

Technology Type	**Technical Summary**	**Pros**	**Notes**
Capacitance	• Range: low. • Output: analogue or digital (set-point). • Sensing elements: charged and sense electrodes	• Non-contact • Detection of metallic or non-metallic objects. • Ability to detect targets non-invasively.	• Range too low for application.
Electric Field	• Electrodes generate an electric field to detect disturbance in the field caused by objects. • Range: low • Output: analogue or digital (set-point) • Sensing elements: charged and sense electrodes.	• Non contact • Possible to infer the chemical composition of materials by using the combination of capacitive and electric field sensing.	• Range too low for application.
Radar	• Radio Detection and Ranging for long range target detection. • Using microwave wavelengths in the range from sub-1 cm to 1 m, frequency range of about 300 MHz to 80 GHz and various polarizations. • Detection and imaging of targets uses combinations of echo and Doppler shift. Range: long. • Sensing elements: directional sending and receiving microwave frequency antenna.	• Ability to determine speed and direction using Doppler shift analysis on received data.	• Radar absorbent materials deaden response. • Subject to clutter in operating environment. • Doppler radar unable to detect stationary targets.
Ultrasonic	• A piezo transducer generates	• Vibration of	• The speed of

(Active)	ultrasonic waves (short wavelength, high frequency normally outside the audible frequency) which are reflected by suitable target objects (echo). • The reflection is received by a piezo transducer and time of flight is calculated to determine range to object. • Can be used internally if coupled to a surface where internal reflection will occur at changes in material consistency. (medical ultrasound) • Range: up to 20 m • Sensing elements: transmitting piezo transducer, receiving transducer (often same transducer when not transmitting).	piezo transducer has self cleaning effect. • Longer range capability normally than capacitive or inductive techniques. • Can do background suppression. (Able to tune out range >X).	sound varies according to temperature and pressure of the medium, changes or gradients affect accuracy and may require compensation. • Freezing can affect transducers esp. if ice forms.
Optical IR	• Active: Generates infra red wavelength light to detect reflections or levels of reflection, or the inverse, from target areas or objects. • Passive: responds to changes in received Infra red light. • Range: low to medium • Sensing elements: IR emitter and receiver diodes & lenses. May also include polarization filters and/or discrete reflectors for reflective beam breaking detection modes. • Basic function making or breaking IR light beams, detection of target scatter.	• Immunity from ambient light interference. • Ability to measure temperature with suitable IR sensors.	• Limited immunity to ambient light interference.
Laser Scanner; Laser Radar (Lidar)	• Active laser pulses to detect reflections from target areas or objects. • Sensing elements: laser emitter and receiver diodes & lenses.	• Rich contents • Diversity in applications for object detection and tracking	

Computer Vision	• Images captured by camera • Image processing to provide information of objects within images • Color or mono	• Rich contents • Diversity in applications for object detection and tracking	• Limited immunity to lighting conditions and shading

Notes:

1. See http://www.sensatech.com/solutions/comparison_of_techniques.html for a summary of proximity detection techniques.
2. For relevant pedestrian detection, see literature review in Chapter 2.

3.4 Sensor Selection for Evaluation

Based on the literature review and product survey, we found several types of sensor technologies that have been suggested or deployed for various applications, including

- Capacitance sensing
- Electric field sensing
- Computer vision
- Infrared
- Laser scanner
- Radar
- Ultrasonic

After initial evaluation and information exchange with potential vendors, it was determined that capacitance and electric field sensing have very limited range and high sensitivity, which would not be appropriate for the applications defined in this project. Computer vision with image processing is a very promising technology and there have been commercial developments for other roadway or vehicle based safety applications, such as sign or lane recognition. However, for pedestrian detection, there is limited availability of products that can be acquired for evaluation. This is an active research and development field and therefore should be closely monitored.

In addition, in July 2004 we learned of a Canadian project, titled "Evaluation of advanced pedestrian detection systems (APDSs) for school buses." See the following link for more detailed descriptions: http://www.tc.gc.ca/tdc/projects/road/d/8244.htm. The project utilized Eaton-Vorad radar as the bus-mounted sensor in its evaluation. Since the PATH experimental bus already is equipped with an Eaton-Vorad radar, we decided that we should identify and test this radar as a candidate technology.

For the other categories of technology, we conducted a comparative search and evaluation and decided to purchase for this project the following products for further testing:

- Infrared People Counter (IRISYS), http://www.irisys.co.uk/products/index.htm
- Microwave Pedestrian Detector (MS SEDCO), http://www.mssedco.com/traffic-pedestrian.html
- Ultrasonic Proximity Switch (SENIX), http://www.senix.com/model_ultra-100_ultrasonic_proximity_switch.htm

We also arranged through collaboration with our colleagues working on other projects to utilize the following sensors to conduct a series of preliminary testing:

- an IBEO laser scanner, http://www.ibeo-as.de/html/applications/applications.html, and
- an EVT-300 Doppler radar (http://www.roadranger.com/products/vorad/vorad.htm) on the PATH experimental bus

The properties, attributes, and performance specifications for the products to be tested are given below.

Product	**Technology Category**	**Detection Range (m)**	**Accuracy**	**Target Tracking range (m)/ Field of view**	**Application for Transit Bus**
IBEO laser scanner	Lidar	0 - 250	+- 5 cm	0 – 50/ 270 degrees	Long range; bus moving
EVT-300 radar	Doppler radar	5 -140	5%/+- 1 m	5 – 140/ 12 degrees	Long range; bus moving
IRIS people counter	Infrared	2 - 5	On-off	N/A/ 60 degrees	Short range; bus stop
MS SEDCO SmartWalk 1800	Doppler radar	2 - 15	On-off	N/A/ 45-60 degrees	Short range; bus stop
SENIX Ultra-100	Ultrasonic	0.15 - 3	On-off	N/A	Short range; bus stop

3.5 Summary

The background needs for improving pedestrian safety with an emphasis on the operation of transit buses were explained in Section 3.1. In Section 3.2, we suggested three separate approaches to tackle the task of pedestrian detection: proximity sensing, long-range detection, and vehicle-infrastructure integration. The approaches in turn demand different performance requirements of the selected technologies. An extensive literature review was conducted to provide an up-to-date understanding of the latest technologies for pedestrian detection, which was summarized in Section 3.3. Based on our suggested technical approaches, we then conducted a product survey to select candidates that are reasonably priced and commercially available for evaluation. The results were described in Section 3.4. The remaining phase of this project will be focused on the testing of the selected components and the implementation of detection methods.

4. INDIVIDUAL SENSOR TESTING

Based on the product survey in the last section, a few selective sensors were acquired and implemented for experimental evaluation. This Chapter contains the descriptions of the sensor testing that was carried out in the course of this project.

4.1 Laser scanner

4.1.1 System configuration and installation

The Laser scanner was loaned by the Integrated Collision Warning Systems (ICWS) project. It is manufactured by IBEO Automobile Sensor GmbH in Germany. The system is composed of a laser scanning head, an industrial PC (IPC) and a user computer (Fig. 4.1). The laser scanner head emits eye-safe infrared laser pulses and detects the reflected pulses. The measurement principle is based on the time-of-flight method, in which the distance to the target is directly proportional to the time interval between transmission and reception of a pulse. Scanning of the measurement beam is achieved by a rotating prism, covering a viewing angle of up to 360 degree. The raw scan data is sent to the IPC via ARC net, where an object detection and tracking algorithm is running. The results are a set of object data with each object's size, position and velocity. The object data are sent to the host computer via a standard CAN bus. To facilitate user visualization, a CAN/USB converter is added so that the user computer can receive object data through a standard USB port.

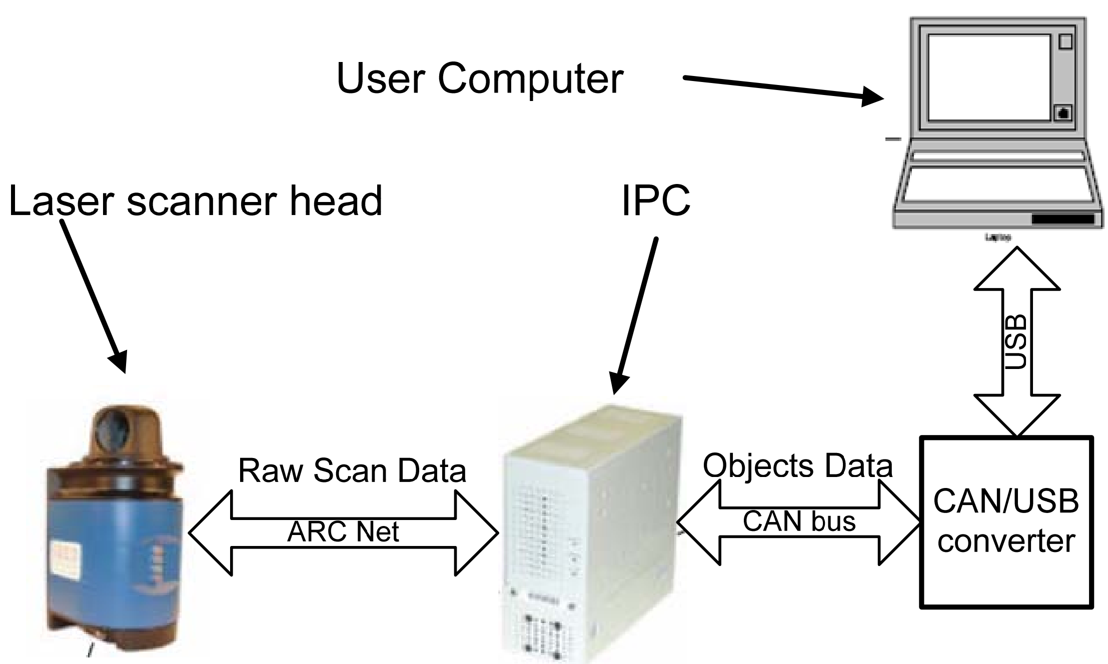

Fig. 4.1 IBEO Laser Scanner System Configuration

As shown in Fig. 4.2 and Fig. 4.3, the laser scanning head was mounted on the front bumper of a Buick LeSabre for testing and the IPC was put into the back seat.

4.1.2 Calibration

Fig. 4.2 IBEO Laser Scanner head installation

Fig. 4.3 IBEO IPC in the back seat

Fig. 4.4 Special IBEO laser pointer with red laser

Calibration is performed by fitting a specially designed laser pointer (Fig. 4.4) on the laser scanner head and following procedures in [1, 2].

4.1.3 Testing Scenarios

A set of tests were performed in the PATH vehicle tent under stationary conditions. Fig. 4.5 shows one of the test scenarios and results. In Fig. 4.5, the upper half shows the picture of the scenario taken by a camera placed on the scanner head and the lower half shows the object data received from the laser scanner. The large blue cross represents the laser scanner position and the crosshairs define a 2 meter grid. The contours of the objects on the horizontal scanning plane and their positions are shown in the object data. One thing that needs to be pointed out is that the Ford Taurus and snow blower on the left are so close together that they were recognized as one object by the laser scanner.

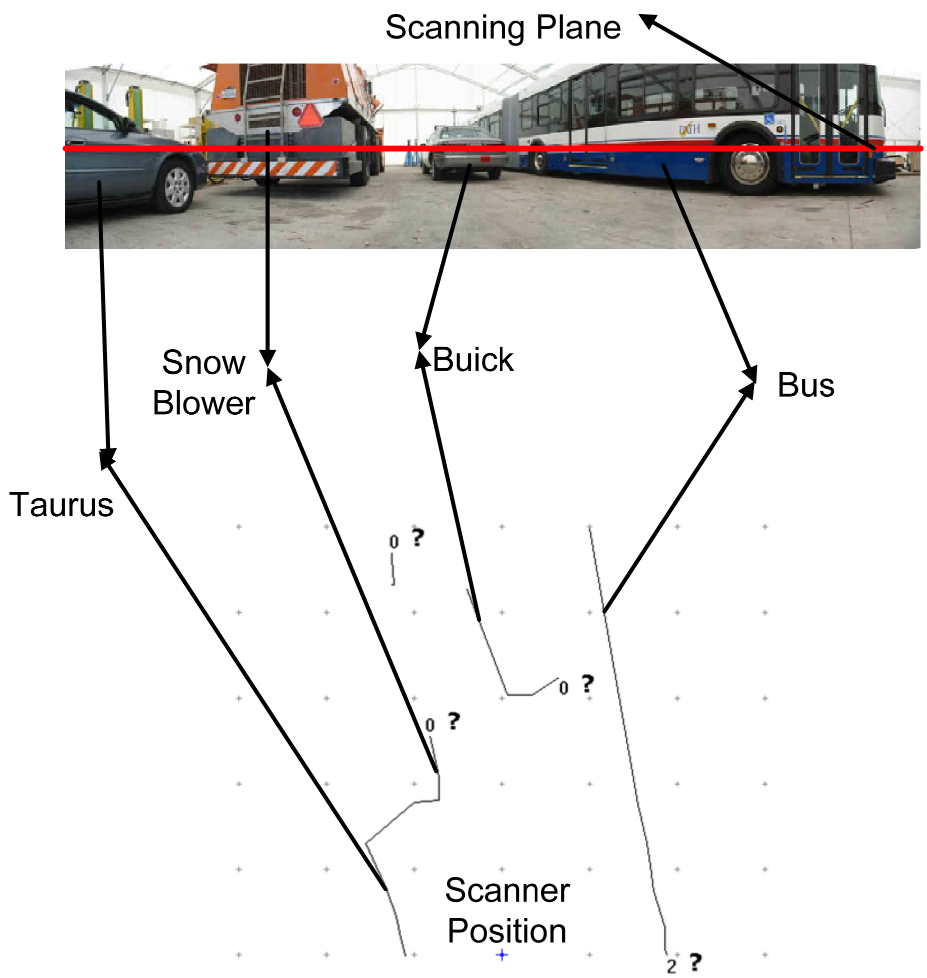

Fig. 4.5 IBEO Laser Scanner Test Scenario

Fig. 4.6 shows a pedestrian walking in front of the laser scanner. The laser scanner identified the object as a pedestrian based on its size and velocity.

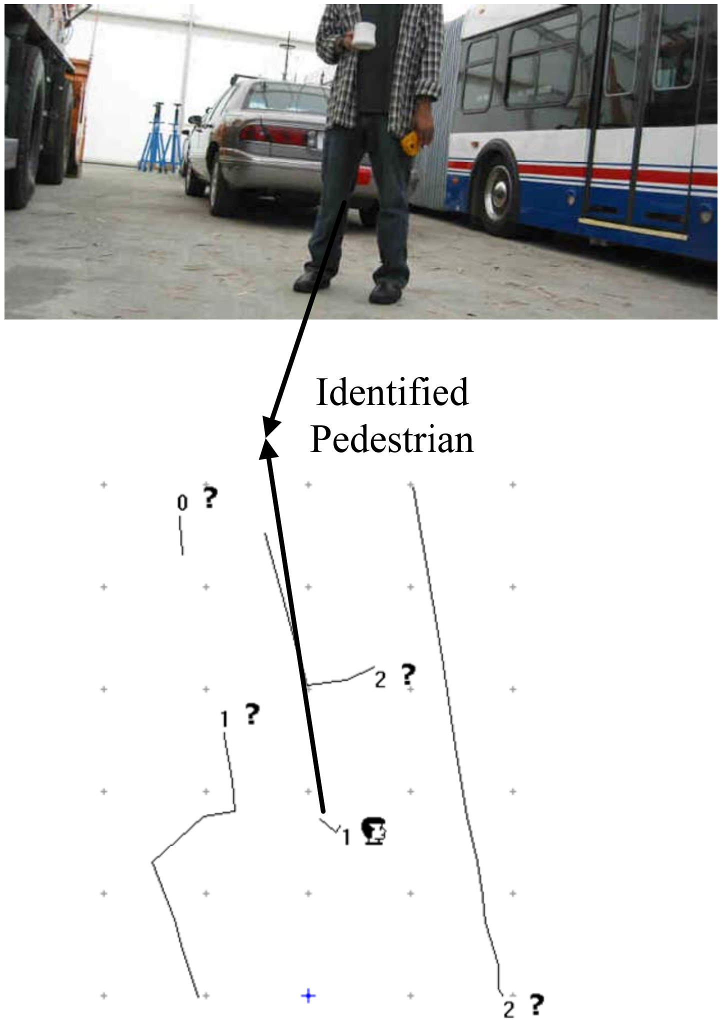

Fig. 4.6 Pedestrian Detection by IBEO Scanner

Fig. 4.7 shows an interesting scenario, with a cart moving in front of the laser scanner. Since the scanning plane cut across the middle of the cart, the cart was actually recognized as two pedestrians by the laser scanner. Two closely-spaced legs of the cart were identified as a pedestrian due to their size and velocity. The Buick behind the cart was also divided into two objects because of the cart's interference.

Fig. 4.8 shows a pedestrian walking his bicycle in front of the laser scanner. The bicycle blocked the pedestrian completely in the scanning plane. So the laser scanner only detected a bicycle-sized object and could not detect the pedestrian behind. The bicycle also blocked part of the Buick. The remaining part detected by the laser scanner was about the size of a pedestrian, so it was recognized as a pedestrian although it was a Buick car.

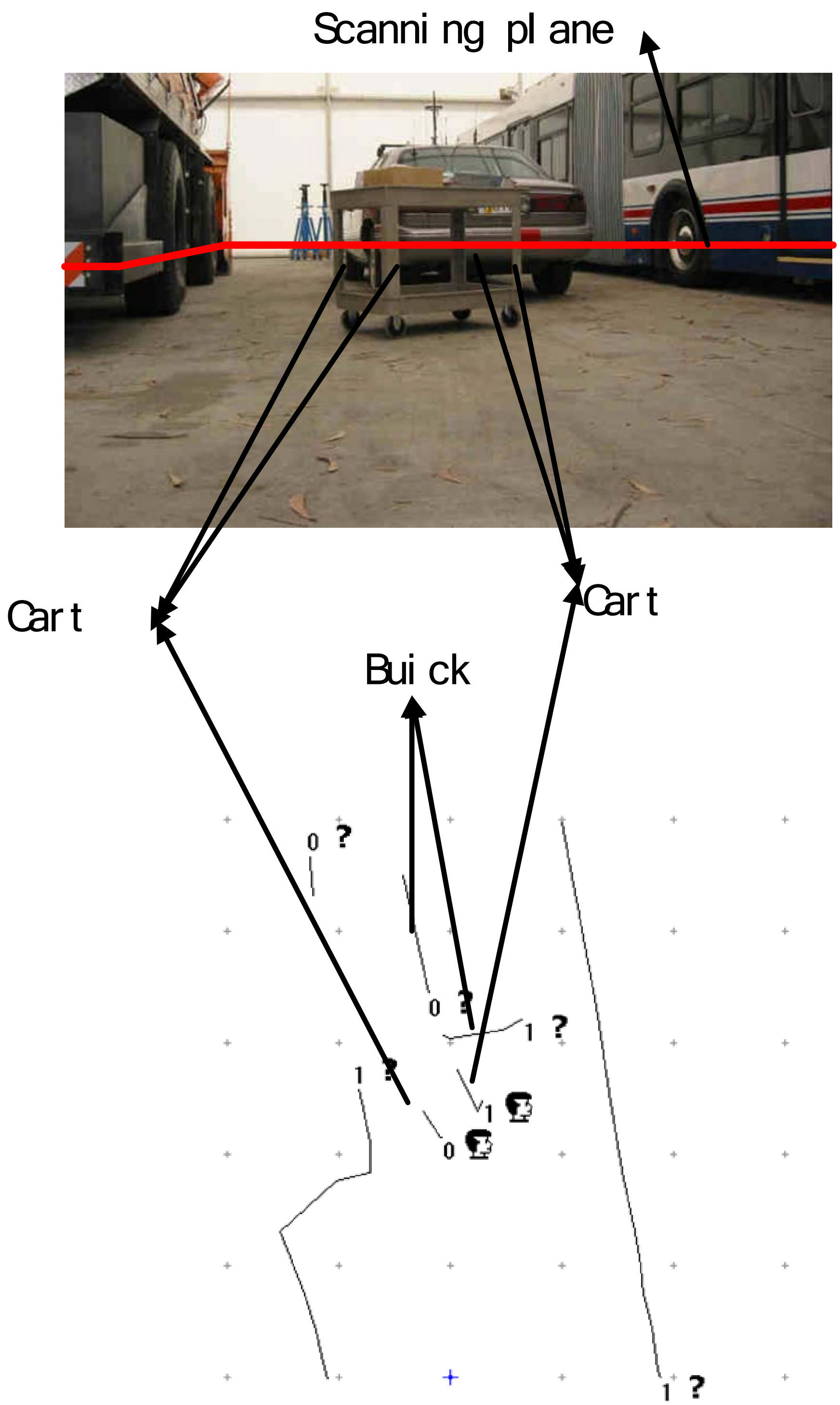

Fig. 4.7 IBEO Scanner Detection of A Moving Cart

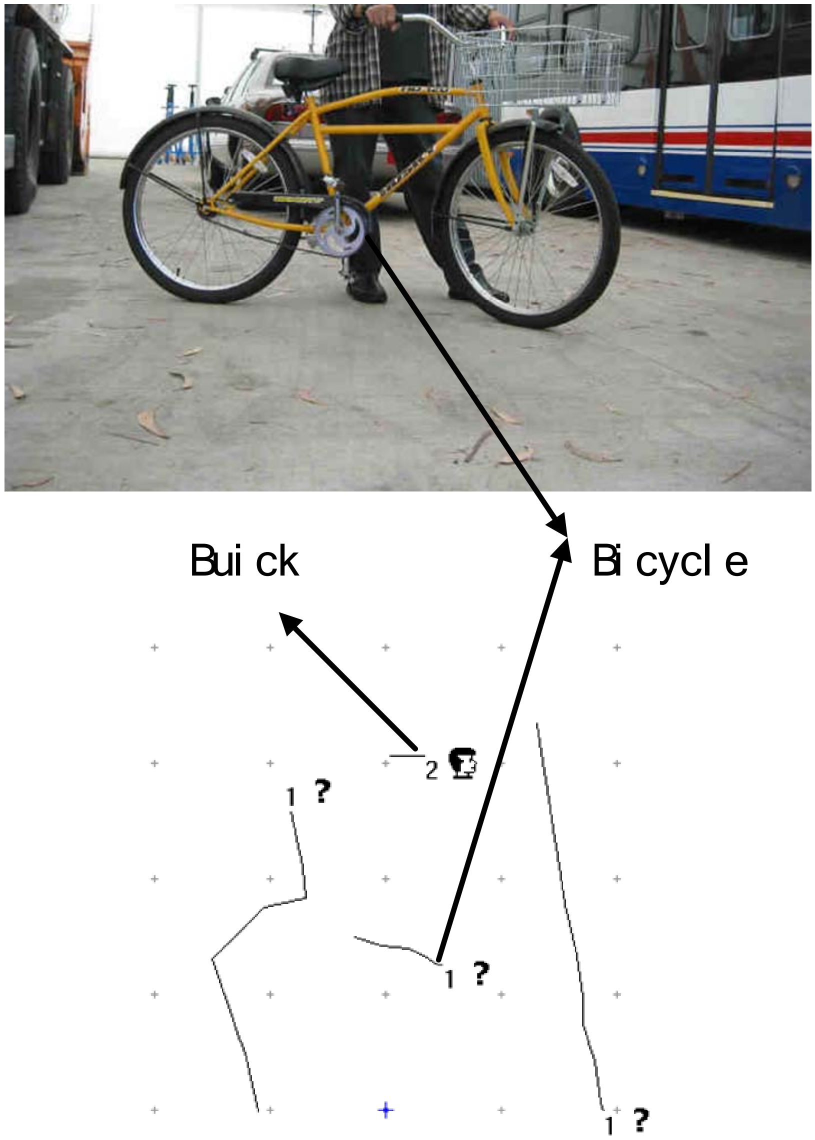

Fig. 4.8 IBEO Scanner Detection of a Bicycle

4.1.4 Conclusion

The IBEO Laser scanner can provide object information with accurate distance (centimeter level) and azimuth angle (from 0.25 degree to 1 degree depending on scanning frequency). However, since the laser scanner we tested can only provide object contours in one scanning plane, the information is quite limited for pedestrian detection in the complex urban scenario and false detections or missing targets will happen if the decision is solely based on such limited information (see Fig. 4.7 and Fig. 4.8). Alternative methods could be used to address this problem. One was proposed in [3], where a multi-scanning-layer laser scanner was designed. Sensor fusion is another method to take the advantages of the laser scanner's accurate range and azimuth measurements and avoid its target discrimination disadvantages.

4.2 Eaton VORAD Radar

4.2.1 System configuration

Fig. 4.9 shows the system configuration of the Eaton VORAD EVT-300 Doppler radar system we installed behind the front bumper of a New Flyer CNG-powered 40 foot bus. The central processing unit processes information received from the antenna assembly. Target information such as target ID, distance, azimuth angle and target velocity is sent out through the J1587 data bus by the central processing unit. A J1587 to RS232 converter was installed so that the onboard PC104 computer could read and log such information through a serial port.

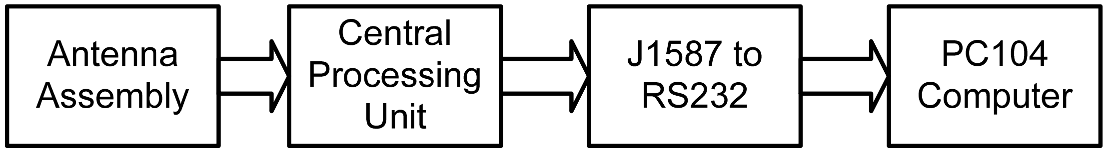

Fig. 4.9 System Configuration of Eaton VORAD EVT-300 Doppler radar for testing

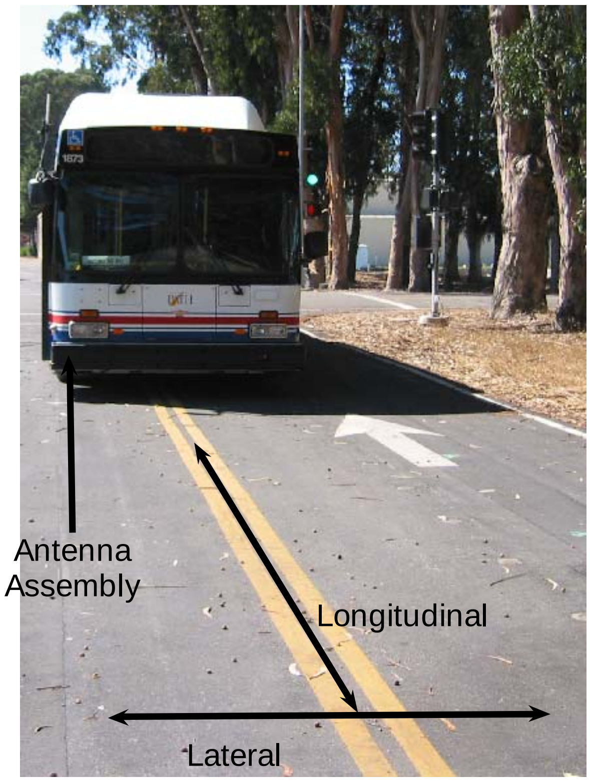

Fig. 4.10 Eaton VORAD EVT-300 Evaluation setup

4.2.2 Evaluation scenario and results

To evaluation the sensor performance, a set of evaluation tests was performed on the PATH test track for both stationary and moving bus scenarios.

a) Stationary bus

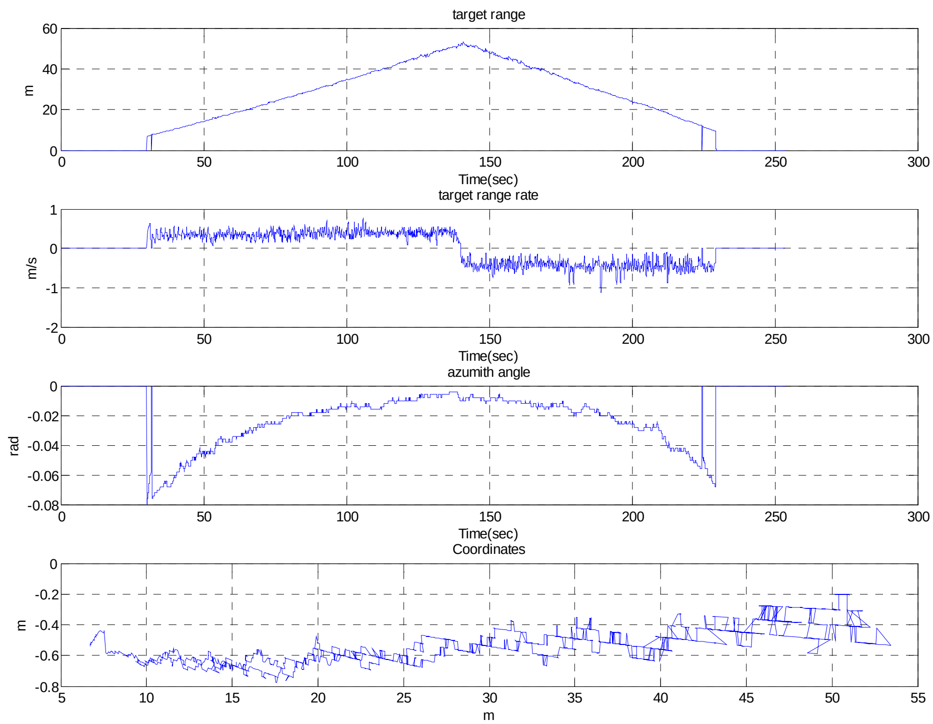

Fig. 4.11 Pedestrian Slowly Walking Longitudinally in Front of Stationary Bus (Measured Data)

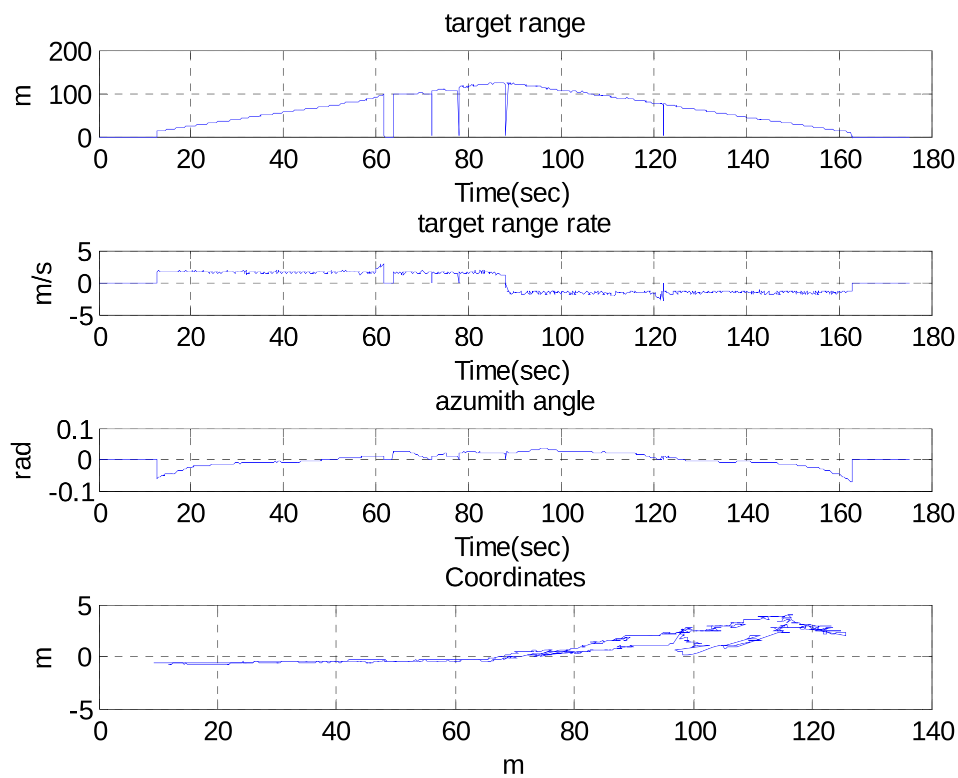

Fig. 4.12 Pedestrian Walking Longitudinally in Front of Stationary Bus at Long Range (Measured Data)

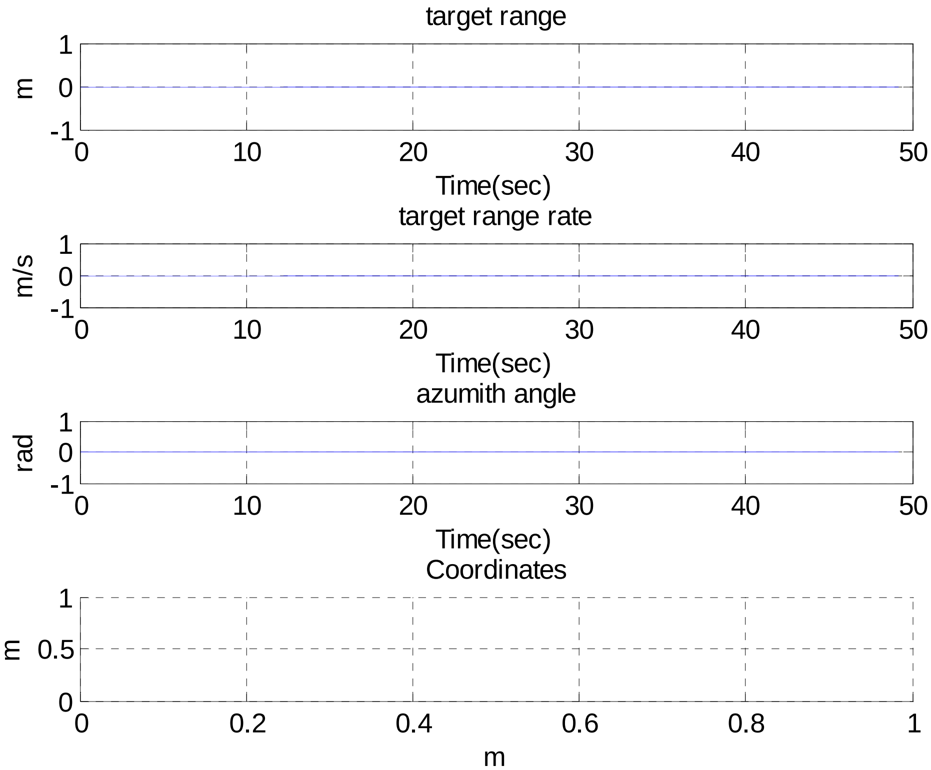

Fig. 4.13 Pedestrian Walking Laterally in Front of Stationary Bus (Measured Data)

A pedestrian walked in front of the parked bus from different directions, as shown in Fig. 4.10. Figures 4.11 and 4.12 show target information acquired when the pedestrian walked longitudinally along the double solid yellow line in Fig. 4.10. Fig. 4.11 shows results when the pedestrian walked very slowly (<0.5m/s), indicating that the Eaton VORAD radar could still pick up the target and continue tracking without problems. Fig. 4.12 shows results when that pedestrian walked far away from the stationary bus, indicating that the Eaton VORAD radar could still detect targets up to about 130 m range. When the pedestrian changed his direction, his speed dropped to zero for a few seconds. At that time, Eaton VORAD could not detect the stationary (relative to the bus) target, so the target was lost for a few seconds but reacquired after the pedestrian picked up his speed in the other direction. Both scenarios show that the minimum distance for the Eaton VORAD radar was about 5 m.

In order to evaluate sensor's sensitivity to pedestrians walking in different directions, we tested with the pedestrian walking laterally in front of stationary bus, as shown in Fig. 4.10. Fig. 4.13 shows the target information acquired when the pedestrian crossed about 10 meters in front of the bus. The Eaton VORAD radar could not detect the pedestrian moving laterally. We did similar tests for pedestrians crossing in front of the bus at 15 and 20 meters with the same results. This can be explained by the Doppler effect principle of the Eaton VORAD radar. The sensitivity of a Doppler radar is low to targets moving perpendicular to its radar wave propagation direction. Since the relative distance change between the radar antenna and the laterally moving target was very small, it was difficult for the radar processor to differentiate such a small amount of frequency drifting from the background noise.

b) Moving bus

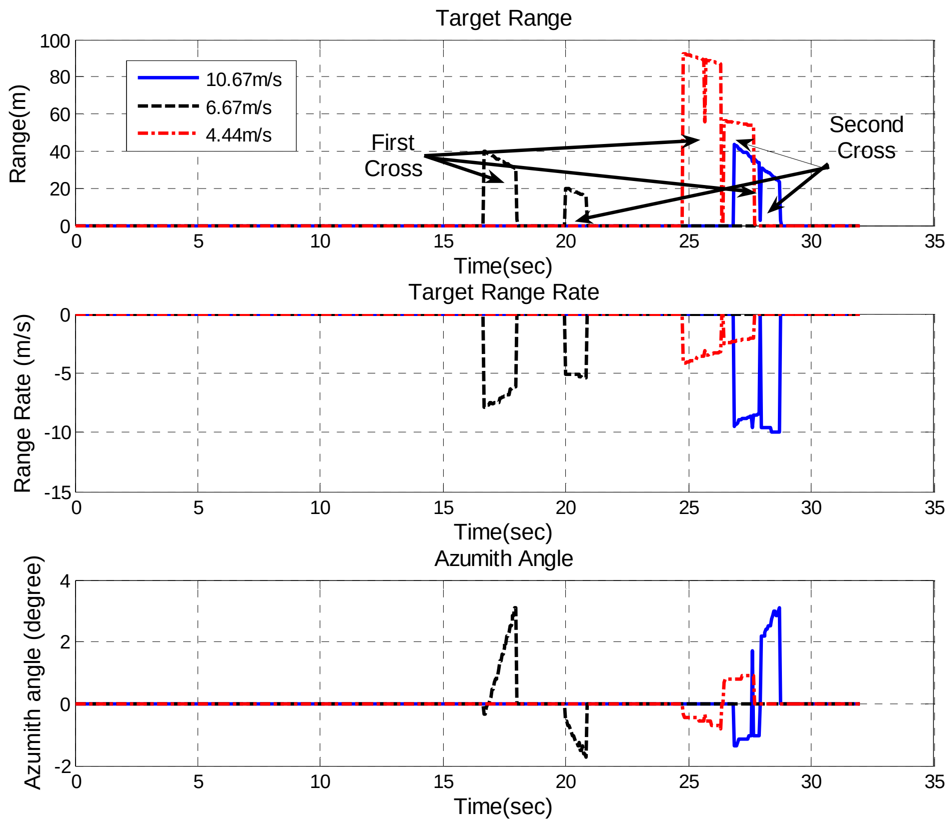

Fig. 4.14 Pedestrian Walking Laterally in Front of a Moving Bus (Measured Data)

Since the Doppler radar can effectively detect a target with relative longitudinal motion, we only tested pedestrians crossing the test track laterally for the moving bus testing scenario. Fig. 4.14 shows target information acquired when the bus was moving at about 10 mph(4.44 m/s), 15 mph(6.67 m/s) and 24 mph(10.67 m/s). A pedestrian crossed the test track laterally twice in the same place at each speed. Both crossings were detected by the radar at the different speeds. Since the pedestrian is walking across the path of the moving bus in a perpendicular manner, the value of the target range rate is approximately the speed of the bus. The azimuth angle changed its sign because the pedestrian crossed the track back and forth.

4.2.3 Conclusion

Based on the experimental results, we can conclude that:

c) Eaton VORAD radar can detect pedestrians at a range of about 5 m to 120 m.

d) Eaton VORAD radar can only detect targets that are moving longitudinally relative to the radar due to its Doppler principle. Any target that remains stationary relative to the radar can not be detected.
e) Furthermore, unless this relative motion can create a minimum relative distance change, targets with relative motion can not be detected either. For example, the test data show that the sensitivity of the radar drops significantly for targets with relative motion along the direction perpendicular to the radar wave propagation direction.

4.3 SENIX Ultra 100 Ultrasonic Sensor

4.3.1 Single SENIX Ultra 100

The SENIX Ultra-100 is an acoustic sensor that works as a proximity switch. The sensor output is an on-off relay, which can be read directly by an electric meter or connected to an input channel of a computer. The sensor is also equipped with a status LED to indicate if a measurement is being made. The specifications of the unit are given below in the Appendix.

We have chosen this sensor to be one candidate for pedestrian detection at short ranges around a transit bus. The main considerations for use of this sensor are its small size and low cost. The objectives of the preliminary evaluation are: (1) to validate the performance specifications; and (2) to explore the configurations and limitations that may be encountered for applications on transit buses.

The experimental setup was aimed at answering the following questions:

(1) What is the maximum range that the unit can detect the presence of an object?
It was determined that the sensor can function up to 224 inches (5.69 meters), which is longer than the vendor's specification. This is probably due to the embedded features of adjustable switching distance as well as sensitivity.

(2) What is the field of view of the unit?
The product specifications show that the unit has a conical coverage zone within a 15-degree field of view. However, based on our testing, the conical area is not exactly linear. Figure 4.15 depicts the results of our observations. At various distances from the unit, the width of the cone is as listed in Table 4.1:

Table 4.1 SENIX Ultra 100 Sensor Field of View Test Results

Distance (inches)	Width (inches)
60	18
152	30
224	50

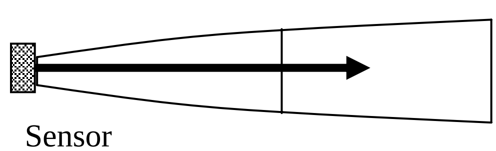

Fig. 4.15 SENIX Ultra 100 Sensor Field of View

(3) Does the unit works as a switch only when an object crosses the set boundary or a presence detector when there is an object inside the boundary?

The unit output is on whenever there is a detectable object within its coverage area.

4.3.2 SENIX Ultra 100 sensor array

4.3.2.1. System configuration and installation

Ultrasonic sensors are low-cost near-range sensors. Multiple ultrasonic sensors can be installed as a sensor array to increase their detection range and cover the perimeter around the vehicle. Fig. 4.16 shows a representative configuration for a sensor array, made of three SENIX Ultra-100 devices, to be mounted on a desired location on a transit bus. The number of sensors in an array and the separation distance between them can be chosen to provide the intended coverage area. A candidate location for the use of an ultrasonic array will be areas near the doors of the bus.

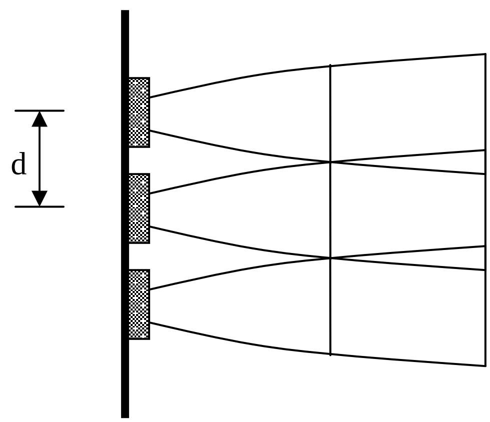

Fig. 4.16 Ultrasonic Sensor Array Configuration

Fig. 4.17 Ultrasonic Sensor Array Installation on a Buick

To facilitate sensor evaluation, the ultrasonic sensor array was installed on a Buick car as shown in Fig. 4.17. An onboard computer logged the outputs of the sensor array together with vehicle speed. The output of the sensor is an analog voltage. A voltage level larger than 3 volts indicates that an object is present in the sensor's detection zone. The distance d between adjacent sensors on the Buick was 0.762 m.

4.3.2.2 Calibration

Calibration was performed as shown in previous section. The detection range of each ultrasonic sensor was tuned up to 3 meters.

4.3.2.3. Ultrasonic Sensor Array Test Scenarios

A set of tests was performed to test the performance of the ultrasonic sensor array. Figures 4.18 - 4.21 show the results when a pedestrian walked around the stationary vehicle. In Fig. 4.18 - 4.20, the pedestrian walked parallel to the sensor array at different speeds. Three sensors were triggered sequentially when the pedestrian passed by. The speed of the pedestrian could be estimated roughly from the time difference between the triggering of each sensor. Fig. 4.21 shows the result when a pedestrian walked towards sensor number 2. Only sensor number 2 was triggered in this case.

Fig. 4.22 shows the results when the vehicle drove slowly past a pedestrian and stopped. This simulates a bus stopping at the bus station. Fig. 4.22 shows the results when the vehicle stopped at a intersection and turned right in front of a pedestrian. In both cases, the three sensors were triggered sequentially.

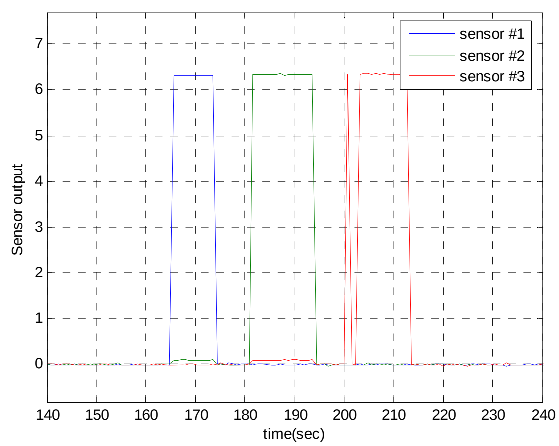

Fig. 4.18 Pedestrian Walking Slowly Parallel to the SENIX Ultrasonic Sensor Array

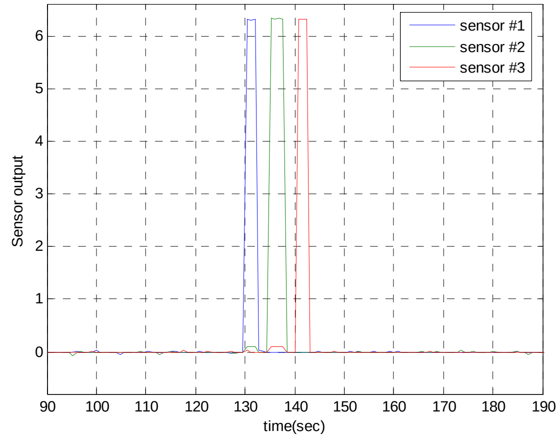

Fig. 4.19 Pedestrian Walking Quickly Parallel to the SENIX Ultrasonic Sensor Array

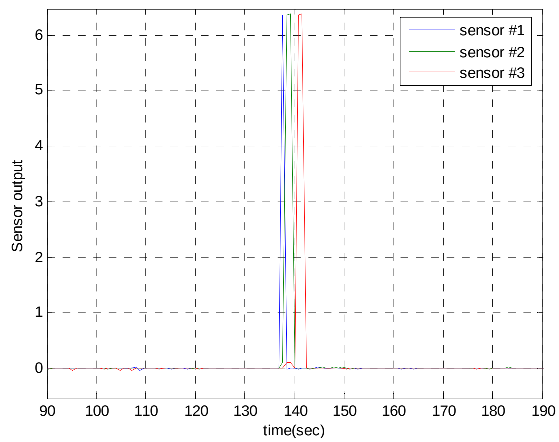

Fig. 4.20 Pedestrian Running Parallel to the SENIX Ultrasonic Sensor Array

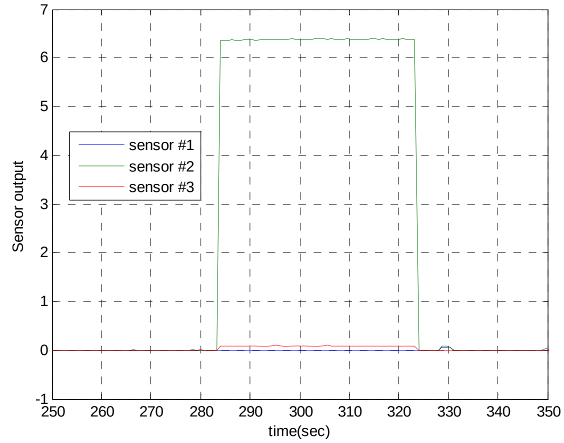

Fig. 4.21 Pedestrian Walking Toward SENIX Ultrasonic Sensor #2

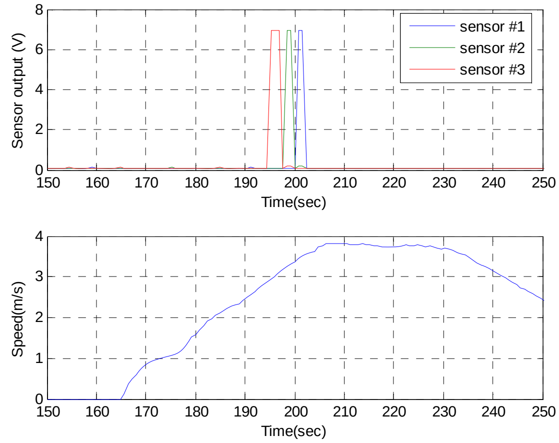

Fig. 4.22 Vehicle with SENIX Ultrasonic Sensor Array Driving Past Standing Pedestrian

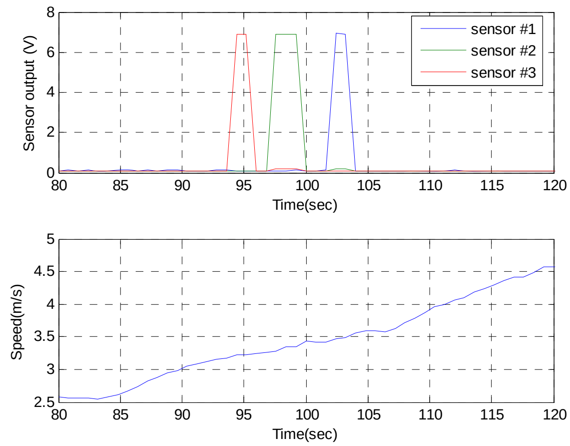

Fig. 4.23 Vehicle with SENIX Ultrasonic Sensor Array Turning at Intersection

4.3.3 Conclusion

The ultrasonic sensor can reliably detect objects presented in its small detection area. An array of multiple ultrasonic sensors can increase the detection area significantly and can be used to monitor the perimeter of a transit bus. Rough information regarding pedestrian movements can be calculated from the outputs of multiple sensors. However, the information from the ultrasonic sensor is very limited binary object presence detection. It will detect any objects in its detection area and cannot distinguish pedestrians from other objects.

4.4 Infrared Sensor

4.4.1 System Configuration

The IRYSYS People Counter manufactured by InfraRed Integrated Systems Ltd. was evaluated for detecting pedestrians near transit buses, mounted on a 40’ New Flyer CNG powered transit bus. The sensor, shown in Figure 4.24, detects the infrared radiation naturally emitted by a person - passive infrared (PIR). .

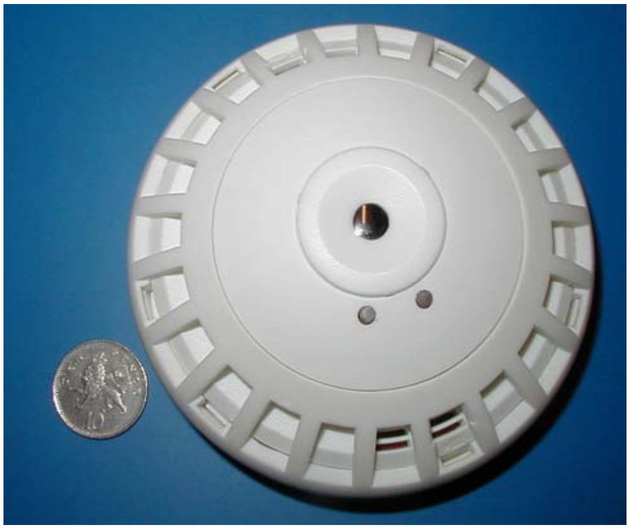

Figure 4.24. IRISYS Infrared People Counter Sensor

As shown in Figure 4.25, the sensor was mounted vertically, “looking down”, and has a square detection area whose side dimension is approximately equal to the mounting height. A person is tracked and seen by the counter as a “hot spot” on a 16 x 16 detection array.

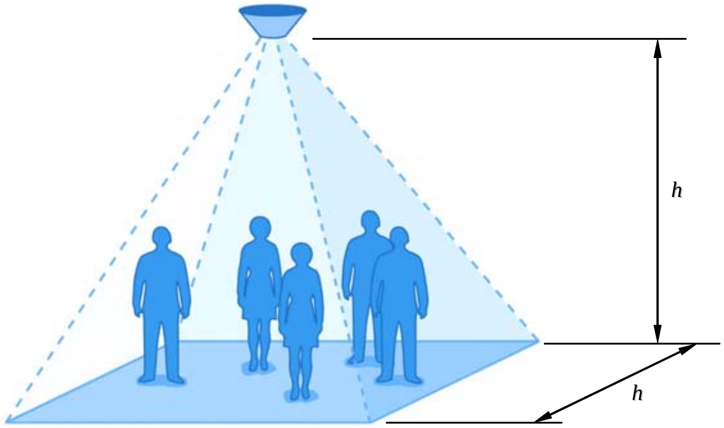

Figure 4.25. IRISYS People Counter Detection Area.

Since this is not a video system, it is not affected by light levels and will even function in complete darkness. Figure 4.26 shows the location of the sensor on the bus.

Figure 4.26. Location of IRISYS Sensor on Bus

4.4.2 Testing scenario

Figures 4.27 and 4.28 show an example of the people counter test with a single person passing through the field of view of the sensor. To start, no person was present and a static background is seen in Figure 4.27. Figure 4.28 shows one person seen as a white spot that is “hotter” than the background. To signify different target (person) states, the counter overlays on top of the display an ellipse around the hot spot. A tracking line is also drawn behind the target. The final array view figure (Figure 4.29) shows the person exiting the scene as a cold wake following the target because the hot target is being replaced by the cold background. Note that this sensor detects changes in temperature, not the temperature itself.

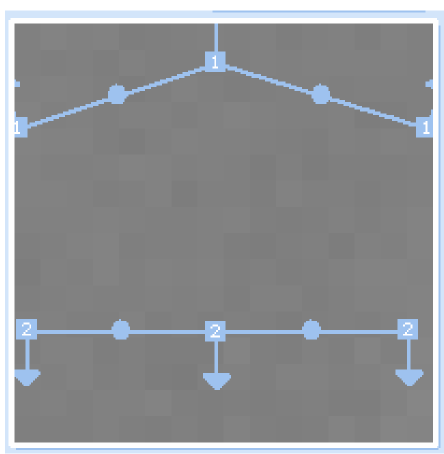

Figure 4.27 IRISYS Infrared Sensor Output with No Person Present (left)

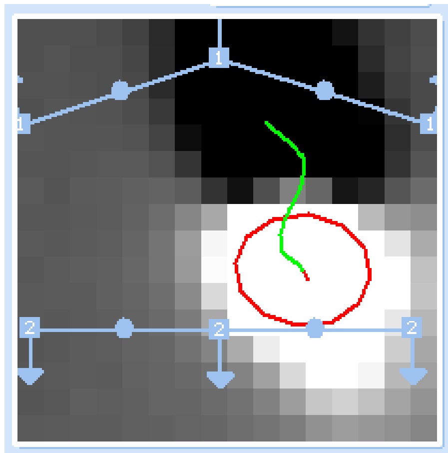

Figure 4.28 IRISYS Infrared Sensor Output with One Person Tracked (right). White Area is "Hotter" than the Background.

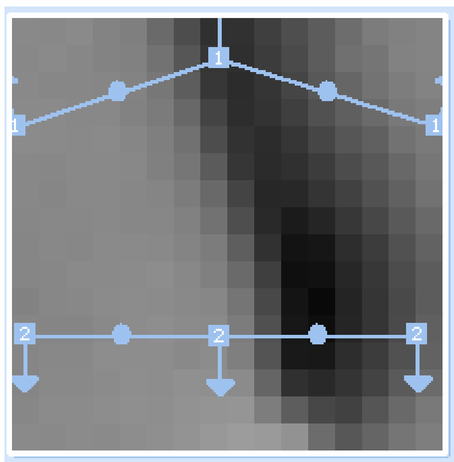

Figure 4.29. IRISYS Infrared Sensor Output After Person has left the Field of View, Leaving a "Cold" Wake.

The two numbered lines labeled 1 and 2 shown on the display are configurable virtual count lines. Each count line has its own total associated with it, which corresponds to how many people have crossed the virtual count line. These lines can be moved and reshaped using the People Counter configuration tool supplied with the unit. If a person crosses a count line, the total for that line will be incremented when the person who crossed the line *leaves the field of view*. Each time a count is incremented, a relay is triggered and a voltage pulse is sent to an analog to digital board in a PC/104 computer system in the bus. This computer runs a program that detects the pulses from each relay. The pulse duration is configurable to 30 ms, 100 ms, and 200 ms. Figure 4.30 shows the real time output of relay 2 logged by the onboard PC/104 computer using a pulse duration of 200 ms and a sampling period of 50 ms (20 Hz). The pulse was not sent until the person left the field of view as shown in Figure 4.29.

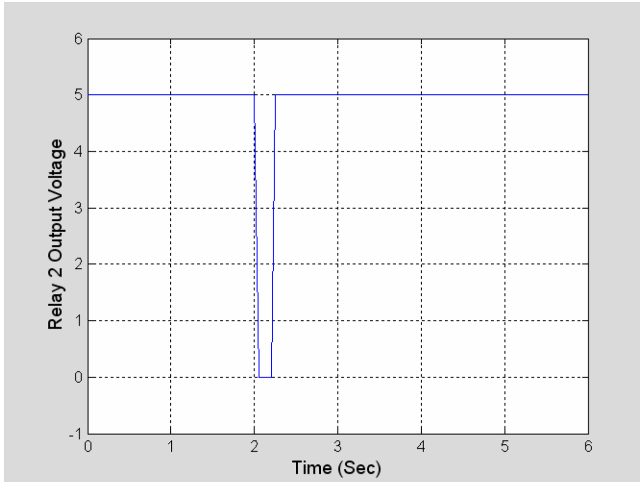

Figure 4.30 IRISYS People Counter Relay 2 Count Pulse related to Figures 4.27, 4.28, and 4.29.

Three different locations on the bus, shown in Figure 4.31, are the potential installation locations. Placements 1 and 2 were above the doors, while placement 3 was located on the left side behind the driver area. This locations was suggested by SamTrans (San Mateo County Transit) drivers since they have experienced many pedestrians crossing in front of the bus from behind. Since the bus is approximately 9 ft (2.75 m) high, the coverage area for each sensor will be approximately 9 ft (2.75 m) x 4.5 ft (1.375 m) since the side of the bus obscures one half of the field of view. Due to maximum width rules for transit buses, the sensor can not be placed farther outboard from the side of the bus.

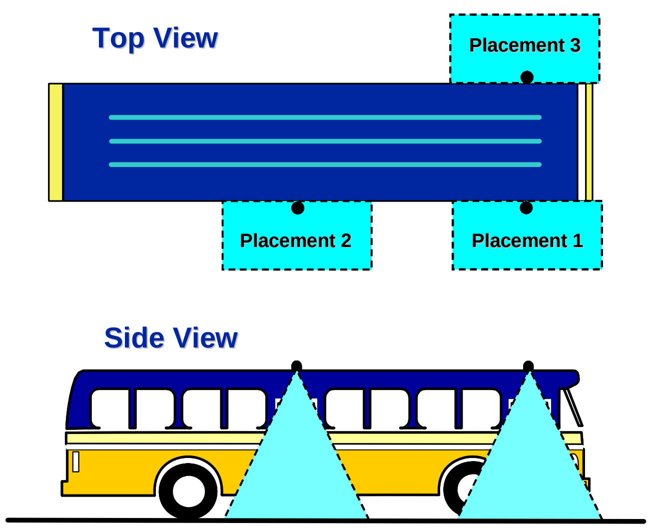

Figure 4.31. Possible IRISYS Sensor Locations and Coverage for a Transit Bus

Using the relay outputs alone to detect the presence of a pedestrian(s) is not sufficient for our needs. Since the relay is not triggered until a person leaves the field of view, the driver will not be alerted in time to take appropriate action. If the pixel information were available directly from the sensor arrays, we would be able to develop our own "pedestrian presence" algorithms that would not depend on the relays.

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5. VEHICLE-INFRASTRUCTURE INTEGRATED APPROACH FOR PEDESTRIAN DETECTION

Pedestrian safety is a primary concern in transportation, especially in an urban environment. The detection and tracking of pedestrians is not trivial. First, in an urban environment the patterns of vehicle and pedestrian movements can be very complicated. On city streets, there are numerous locations where pedestrians may choose to suddenly cross in front of a vehicle. The reliability of detection functions is further complicated by the crowded background and the issue of varying visibility, weather and roadway conditions. Thus, the solution for a reliable and accurate means of identifying pedestrians requires sophisticated design and extensive experimental evaluation.

In this project, a transit bus experimental platform was selected as the target of the feasibility study for the following reasons:

(1) Pedestrian exposure is high along bus routes, especially in the urban environment.
(2) Transit vehicle-pedestrian accidents are a serious problem in their own, yet they are usually further compounded by public perception.
(3) Accidents involving transit vehicles also lead to operational problems and costs.
(4) Transit vehicles are a relatively costly investment, and therefore the addition of safety systems is relatively economically feasible.
(5) Transit vehicles run on fixed routes, so high-risk locations along their routes can be screened and pre-determined.
(6) Since transit buses operate on mostly city streets, the heavy work loads of drivers make the monitoring of pedestrians even more challenging, despite the fact that a great majority of bus drivers conduct their duties professionally and diligently.

Additionally, an experimental transit bus equipped with necessary components such as computers, data acquisition processors, sensors, and driver-vehicle interface is readily available at PATH for experimental testing. Thus, the adoption of the transit vehicle platform enables a synergistic utilization of resources in the course of this study.

Given the challenging operating environment of transit buses, a complete and reliable sensing system for pedestrian detection can benefit from the combined use of multiple sensors. For example, the requirements of pedestrian detection are different for situations when buses are stopped at bus stops or near intersections versus when the buses are moving at relatively higher speeds in cruising conditions. Furthermore, any one particular type of technology may have difficulties meeting all necessary requirements in various lighting conditions, or rainy and foggy weather conditions, not to mention that most sensors have a limited field of view to monitor traffic in all directions. In addition, the cluttered background and complex moving patterns of all objects on urban streets demand sophisticated processing of sensor inputs to avoid false detection and recognition.

A promising approach has recently emerged with the advancement of wireless communication technologies. The United States Federal Communications Commission recently allocated the radio frequencies for Dedicated Short Range Communications (DSRC) in the 5.9 GHz band. DSRC can be applied for many applications, a primary one of which is roadway safety. In traffic conditions where drivers have obstructed views or limited visibility of pedestrian crossing areas, an infrastructure-based sensor can be used to detect objects and a wireless signal can be sent to a receiver on the bus, ultimately producing a visual or audible alert to the driver. In other words, a warning system can be accomplished through the cooperation of infrastructure- and vehicle-based capabilities. This chapter provides a summary of such a vehicle-infrastructure integration (VII) operating concept and the experimentation carried out to illustrate the feasibility of this approach.

5.1 Experimental VII System Configuration

As evidenced from the technology overview above, the progress in many technologies has been exciting and promising, yet cost and reliability issues still remain challenging for a large-scale deployment. The concept of combining lower-cost sensing devices with wireless communication links to form integrated vehicle-infrastructure solutions is therefore an appealing alternative. Even though cost and reliability challenges can still exist for vehicle-infrastructure solutions, they are minimized by integrating the strengths of infrastructure- and vehicle-based elements. To evaluate technical issues involved in the suggested VII approach, an attempt was made to develop an experimental platform for feasibility analysis as well as for the demonstration of the operating concept. This section describes the work carried out and the components utilized in the experimentation. It is particularly meaningful that the illustrated system in our work comprises generally low-cost and commercially-off-the-shelf products, which allows potential deployment with reasonable costs and on a flexible scale.

We carried out the feasibility experiments at a test-bed facility at a California PATH facility. Even though in our experiment an intersection was chosen to be the location for pedestrian crossing, *the concept can be similarly applied to non-intersection locations where pedestrian exposure is significant*. The storyline of the experimental scenario is as follows:

(1) Scenario #1
An infrastructure-based pedestrian detector (a microwave sensor) senses a pedestrian walking in a crosswalk and sends a signal to the infrastructure computer (an industrial-standard PC-104 located in the intersection controller cabinet). While a pedestrian is crossing the street, if a vehicle (a bus) is also within 20 meters of the intersection or is arriving at the intersection within two seconds, the infrastructure computer broadcasts a radio signal (802.11b-compatible link). The criteria for transmitting the alert signals are adjusted to match the intended scenarios. The movement of the approaching vehicle is detected by a roadside radar (EVT-300) installed near the intersection; however, a more generic setup can be geographically based if the vehicle is equipped with GPS (Global Positioning System) positioning. An on-board computer (a second PC-104) on the vehicle receives the broadcast alert signal and illuminates a driver-vehicle interface (DVI) to alert the driver to the pedestrian presence. Additionally, the infrastructure computer can also illuminate a driver-infrastructure interface (DII) at the corner of the intersection.

(2) Scenario #2
An infrastructure-based pedestrian detector (a microwave sensor) senses a pedestrian walking in a crosswalk and sends a signal to the infrastructure computer (an industrial-standard PC-104 located in the intersection controller cabinet). While a pedestrian is crossing the street, a vehicle (a passenger car) is approaching the intersection. The infrastructure computer

broadcasts a radio signal (DSRC link) to indicate the presence of pedestrians. The vehicle on-board computer processes the received signal along with the vehicle position data obtained from the on-board GPS receiver. If the vehicle is estimated to be arriving at the potential conflict with the pedestrian within 4 seconds, the on-board computer activates a driver-vehicle interface (DVI) to alert the driver to the pedestrian presence.

5.2 Physical Architecture of Experimental On-Board System

For the vehicle platform, we utilized an experimental bus, shown in Figure 5.1, that was used in the Bus Rapid Transit demonstration in 2003 (*1*). A data-flow diagram showing the architecture of the experimental bus is depicted in Figure 5.2. The diagram includes only the core components of the overall system. Note particularly the following elements:

(1) Besides a suite of sensors that provides real-time measurements of the vehicle and surrounding status, a J-bus provides information about the vehicle dynamics through the data network. The experimental bus has a data network (J-1587 and J-1939) that allows the reading of selected variables provided by the engine/transmission electronic controller units (ECU).

(2) There are two separate computers on the bus. One (the main PC-104) handles the high-priority signal processing and control algorithms, and the other (the auxiliary PC-104) handles the graphic display for the driver vehicle interface (DVI). The auxiliary PC-104 allows a separation of functions with different priorities and avoids interference with critical control functions.

(3) The driver vehicle interface (DVI) is separated into two categories: (a) safety-critical channels including buttons and indicator lights to allow interaction between the driver and the vehicle; and (b) non-safety-critical menu-driven display DVI. The safety-critical interface is used when the bus is placed in the automated driving mode, and can be used by the driver to resume manual control. The menu-driven display with associated buttons, used for this feasibility study, is handled by the DVI PC-104. The DVI unit located to the right of the driver and an exemplar display captured during a bus operation are shown in Figure 5.3.

(4) A communication channel is required for the operation of the suggested VII system. For the experimental platform, commercial off-the-shelf IEEE 802.11b wireless networking units were implemented to enable data transmission and reception.

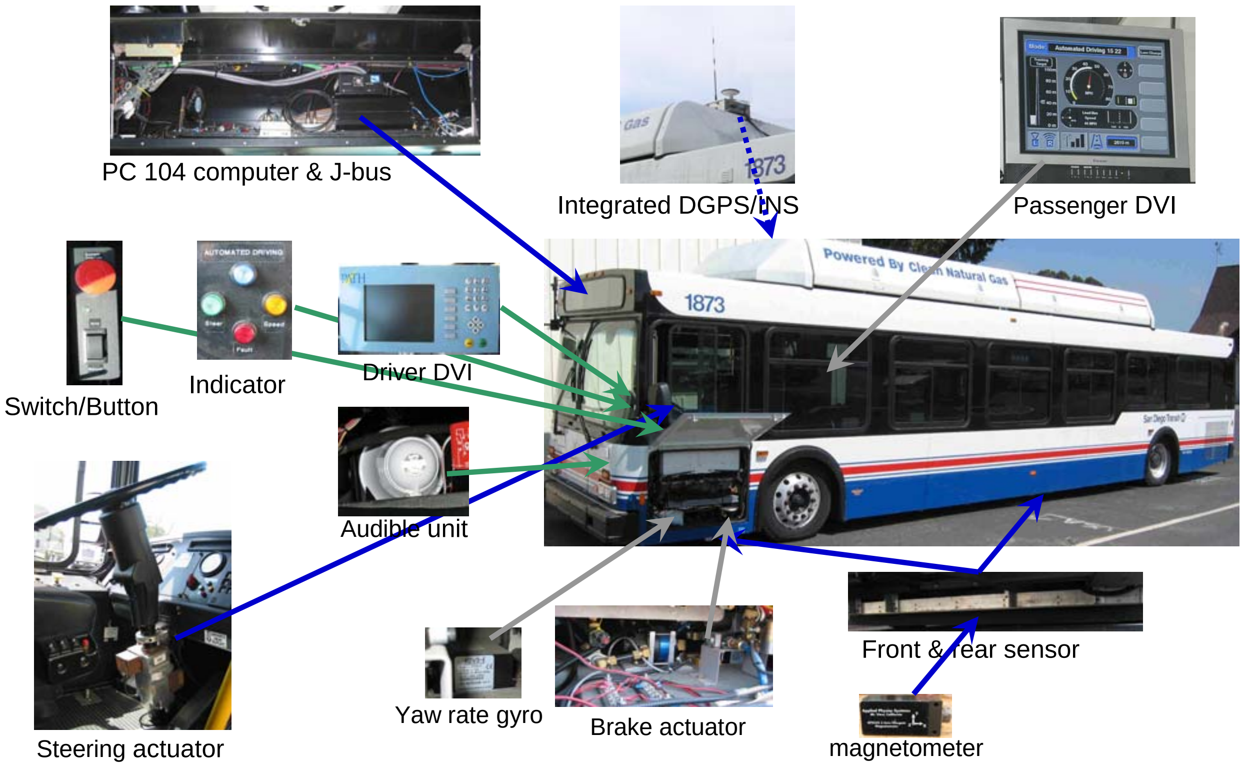

Figure 5.1 Experimental Bus Platform

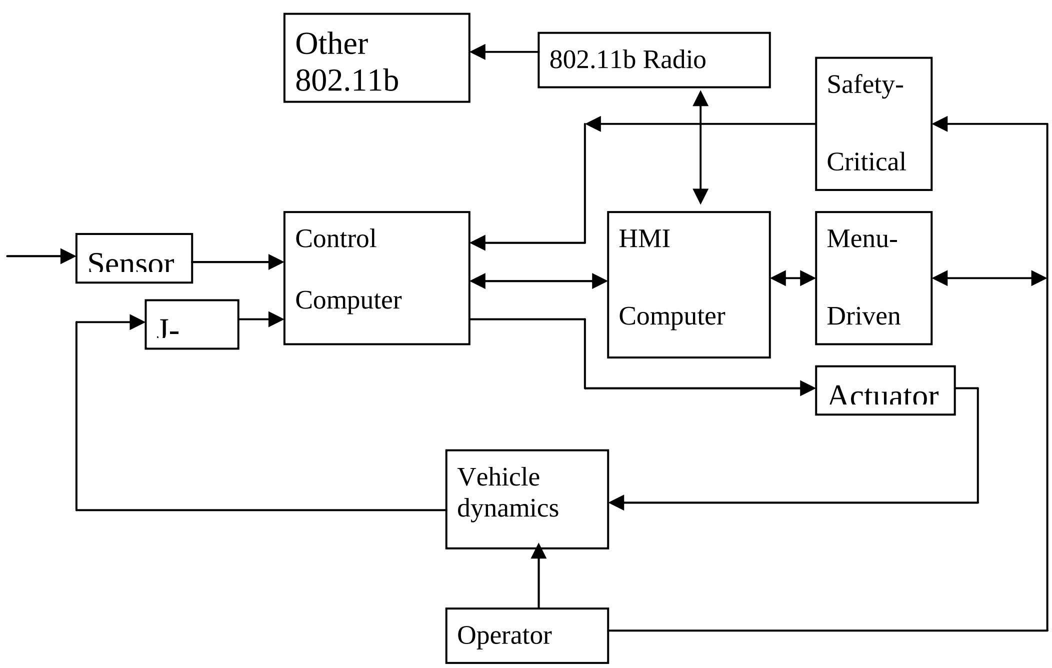

Figure 5.2 Architecture Diagram of Experimental Bus Platform

Figure 5.3 DVI Unit Located at Bus Front and An Exemplar Display

In addition to the experimental transit bus, a regular passenger car was also used for alternative testing purposes. Figure 5.4 shows the instrumentation that was available on this Ford Taurus vehicle. (*2*) This vehicle has been used previously in many PATH research projects, including for driver behavior modeling and field data collection. The major differences in this setup, when compared to the bus, are the inclusion of DSRC at 5.9 GHz for the wireless communication and the DVI mounted on the center dashboard in the car.

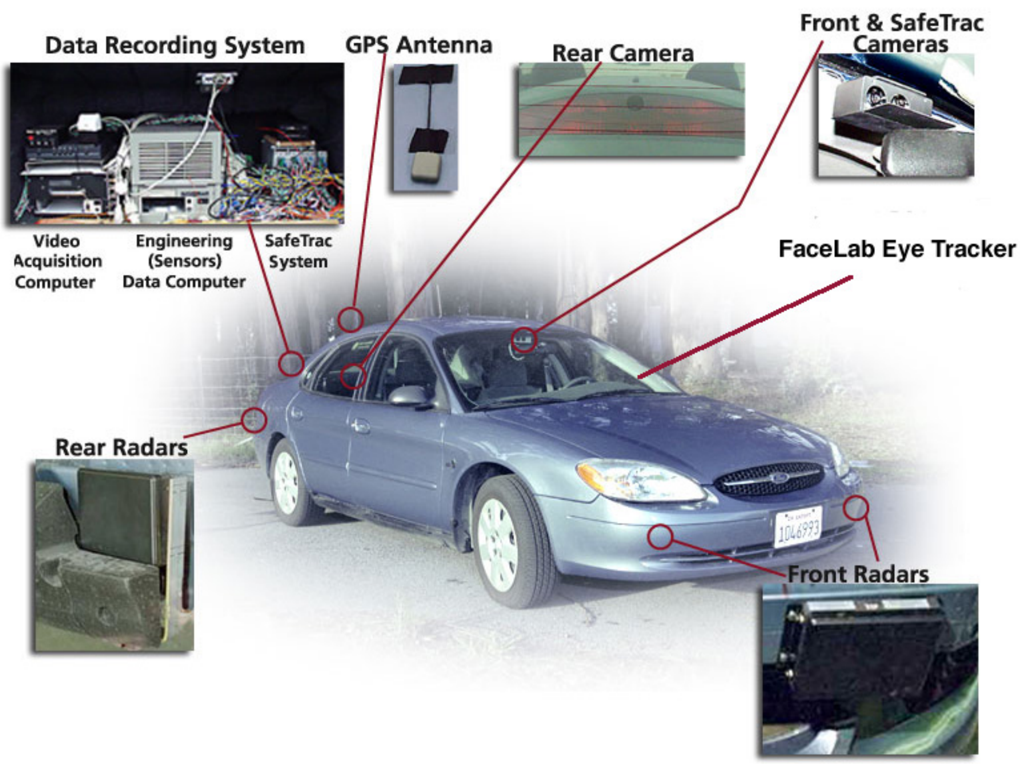

Figure 5.4 Experimental Passenger Car (Ford Taurus)

5.3 Testing of VII Pedestrian Detection and Warning Concept

The testing of the described system was conducted at a full-scale intersection test-bed at the California PATH Richmond Field Station facility. The intersection is instrumented with a traffic controller cabinet, an infrastructure computer, driver-infrastructure interface (DII, a dynamic display sign), as well as traditional inductive loops, Canoga Microloops (3M), radar (EATON-VORAD), video traffic monitoring systems (TRAFICON and ITERIS), microwave pedestrian detector (MS-SEDCO), etc. The intersection is also equipped with wireless communication links (DSRC and 802.11b) for cooperative vehicle-infrastructure safety studies.

5.3.1 Scenario #1

Figure 5.5 shows the setting of the intersection and the depiction of test scenario #1. A microwave radar pedestrian detector, shown in Figure 5.6, is mounted on the signal pole at one corner of the intersection, which is opposite to the corner where the DII is mounted. During the experiment, the bus is driven on a trajectory indicated by the red dashed line in Figure5.5, while a pedestrian is walking in the crosswalk adjacent to the DII. The movements of the pedestrian and the bus are captured by the photograph shown in Figure 5.7. As the bus approaches the intersection, its motion is detected by the radar facing its approach. If the pedestrian is also crossing within a specified time window, the DII is illuminated and simultaneously a wireless signal is broadcast to activate the DVI inside the bus. Figure 5.8 shows a view from an inside-the-bus location next to the driver's seat. It can be seen that the infrastructure DII outside the windshield is illuminated, while the DVI exhibits a different display. For the feasibility study, an exemplar design of DVI display for the test scenarios is shown in Figure 5.9. The appearance of the DVI display can be made to align with the orientation of the bus approach and the actual location of pedestrian presence within the subject intersection.

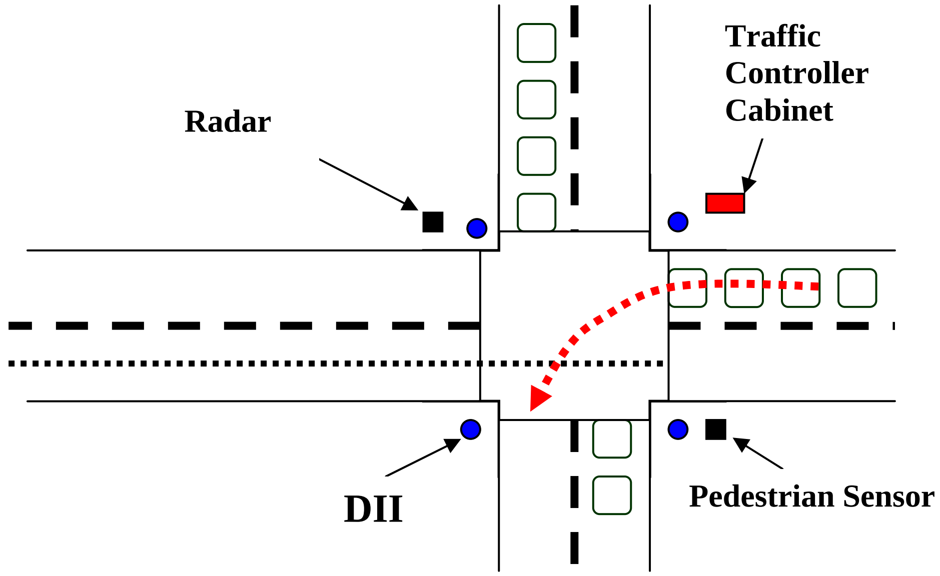

Figure 5.5 VII Experimental Setup at PATH RFS Intersection

Figure 5.6 Pedestrian Detection Sensor mounted on the Signal Pole

Figure 5.7 Pedestrian Crossing and Bus Approaching with DII illuminated

Figure 5.8 View of DVI from Inside the Bus, with the Illuminated DII Ahead

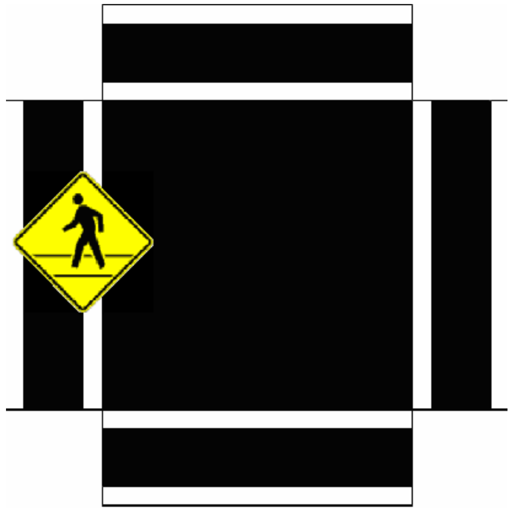

Figure 5.9 Exemplar Design of DVI Display Showing Pedestrian Crossing

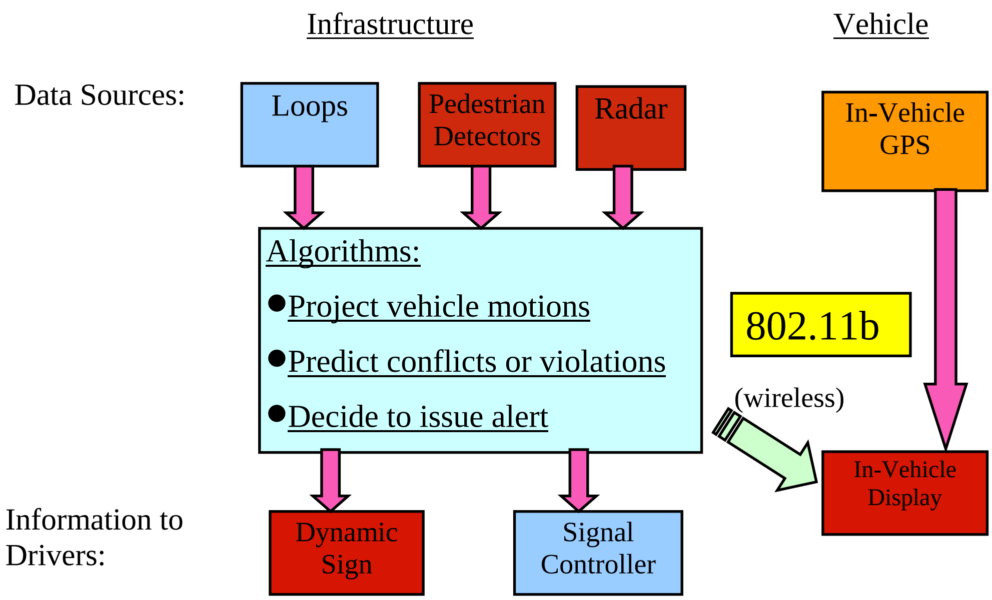

Figure 5.10 Functional Data Flow Diagram of Test Scenario #1

Figure 5.10 provides an overview of the data flow among various components and sub-systems in Test Scenario #1. The illustration shows a combination of infrastructure and vehicle-based inputs to determine and execute an advisory signal to the driver.

5.3.2 Scenario #2

Figure 5.11 shows the setting of the intersection and the depiction of test scenario #2. A microwave radar pedestrian detector, shown in Figure 5.6, is mounted on the signal pole at one corner of the intersection, opposite to the corner where the DII is mounted. During the experiment, the car is driven on a trajectory indicated by the red dashed line in Figure 5.11, while a pedestrian is walking in the crosswalk adjacent to the DII. As the car approaches the intersection, its own GPS sensor is determining its location relative to the intersection. If the pedestrian is also crossing within a specified time window, a wireless signal is broadcast and processed by the vehicle processor to activate the DVI inside the car. Figure 5.12 shows a view from an inside-the-car location next to the driver's seat. For the feasibility study, an exemplar design of DVI display for this test scenario is shown in Figure 5.13. The appearance of the DVI display can be made to align with the orientation of the car approach and the actual location of pedestrian presence within the subject intersection.

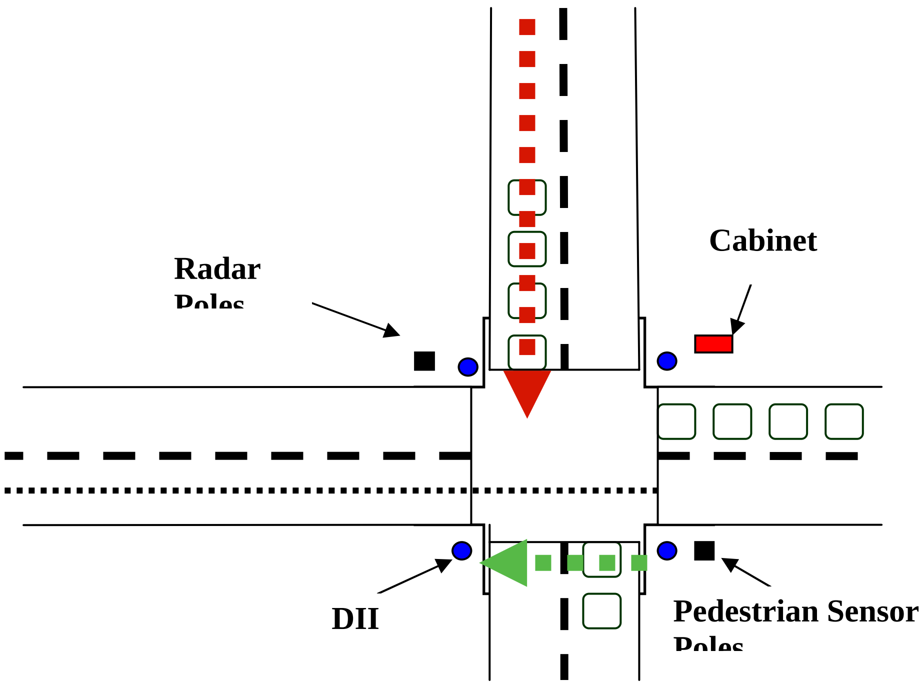

Figure 5.11 VII Experimental Setup at PATH RFS Intersection

Figure 5.12 View of DVI from the Inside of Car

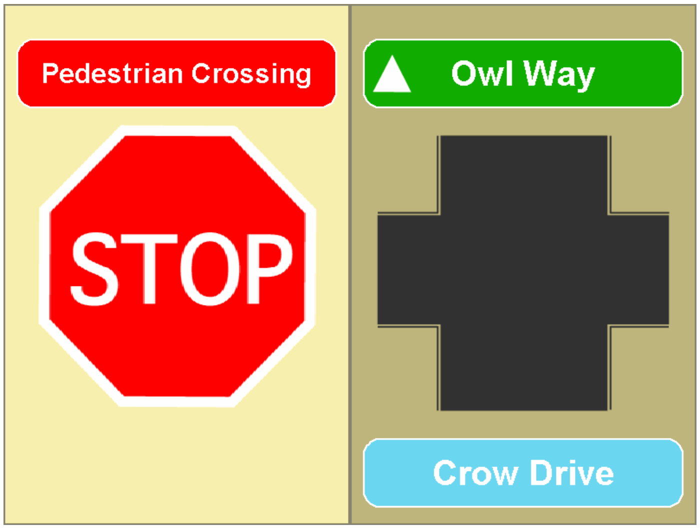

Figure 5.13 Exemplar Design of DVI Display with Warning of Pedestrian Crossing

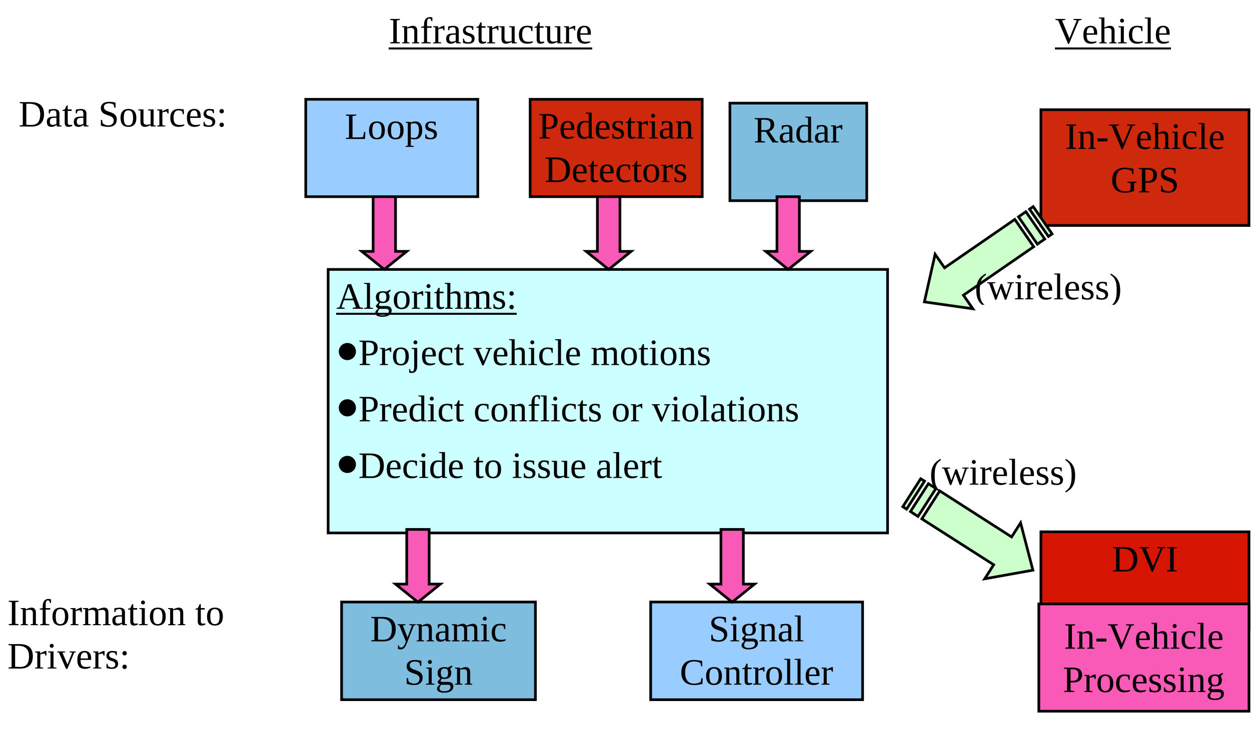

Figure 5.14 Functional Data Flow Diagram of Test Scenario #2

Figure 5.14 provides an overview of the data flow among various components and sub-systems in Test Scenario #2. The illustration shows a combination of infrastructure and vehicle-based inputs to determine and execute an advisory signal to the driver. Compared to Test Scenario #1, this setup relies more on the vehicle-based sensor inputs and processing to activate the DVI within the vehicle.

5.4 Further Considerations of VII Implementation

For the evaluation of VII pedestrian safety systems, transit buses were chosen for the implementation and feasibility studies based on the considerations mentioned at the beginning of this chapter. However, the same operating concept can be applied to all types of vehicles if wireless receivers are readily available in the future and the installation of wireless networks becomes popular in major urban areas.

5.4.1 Applicability of Suggested Approaches

Even though the feasibility demonstration is carried out at an intersection, the concept is not limited to such locations. As a matter fact, the specific implementations of the suggested systems should be tailored to meet local needs. In certain cases, the most desirable solution may be a conventional traffic engineering solution, rather than a VII- or ITS-type of system as proposed herein. (*3*-*6*)

A recent NHTSA report (*7*) provides a breakdown of pedestrian accidents. The crash statistical description provided below focuses on the ten specific pre-crash scenarios listed below, which account for 86.4% of all police-reported pedestrian crashes. About 17% of all pedestrians involved in the 10 pre-crash scenarios were in the crosswalk at the time of impact. The following ten "specific" pedestrian pre-crash scenarios were obtained by correlating the eight basic pre-crash scenarios with information about the crash relation to the roadway junction (percentages shown below refer to the frequency of each scenario relative to all pedestrian crashes):

- i. Vehicle going straight and pedestrian crossing roadway at a non-junction (25.9%)
- ii. Vehicle going straight and pedestrian crossing roadway at an intersection (18.5%)
- iii. Vehicle going straight and pedestrian darting onto roadway at a non-junction (16.0%)
- iv. Vehicle turning left and pedestrian crossing roadway at an intersection (8.6%)
- v. Vehicle turning right and pedestrian crossing roadway at an intersection (6.2%)
- vi. Vehicle going straight and pedestrian walking along roadway at a non-junction (3.7%)
- vii. Vehicle going straight and pedestrian darting onto roadway at an intersection (2.5%)
- viii. Vehicle backing up (2.5%)
- ix. Vehicle going straight and pedestrian not in roadway at a non-junction (1.2%)
- x. Vehicle going straight and pedestrian playing/working in roadway at a non-junction (1.2%)

The most efficient manner of VII deployment should be focused on the high pedestrian accident locations, at intersections or non-intersections alike. Besides the exposure at intersections, an additional advantage can be gained in transit operations identifying high-risk areas of non-junction crossings. The suggested VII system can be used as a countermeasure for cases in scenarios ii, iv, v, vii and a portion of scenarios i, iii, and x.

The testing carried out under this study demonstrates the feasibility of the described VII operating concept with an assembly of relatively low-cost, commercially-off-the-shelf products. It was not meant to be a complete and final solution. For real-world implementation, the selection of components should be made to accommodate the local constraints and requirements. Furthermore, there remain several technical areas that should be investigated in depth:

(1) Performance of pedestrian sensors – sensitivity, coverage area, reliability, false alarm, etc.
(2) Alert and warning effectiveness – relative approaches of vehicle and pedestrian, timing of alert, design of DVI, driver reaction to alert, etc.
(3) GPS-based implementation – alignment of roadway map and vehicle trajectory based on geo-coded map and real-time vehicle data.

5.4.2 Deployment Potential and Preliminary Economic Analysis

The infrastructure-to-vehicle (I2V) VII concept of operation demonstrated in this paper can be extended to other modes of operations, such as Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I), by utilizing the same wireless communication link. For example, if a vehicle is equipped with on-board pedestrian sensing capabilities, it can broadcast a detection signal to neighboring vehicles once a pedestrian is detected. In a sense, this vehicle works as a probe vehicle. The surrounding vehicles, regardless of whether they possess the pedestrian-sensing capabilities or not, can receive the alert signal to assist their drivers. Similarly, if a nearby infrastructure device such as traffic controller or message sign is equipped with compatible communication transceivers, the alert signal can be propagated and communicated to other parties in the vicinity of the probe vehicle. With the increasing popularity of wireless networks in urban domains and the development of DSRC and VII programs, a variety of VII modes (I2V, V2V, and V2I) can be jointly pursued with the most suitable strategies deployed for specific locations. In all, a fully cooperative VII solution (FC-VII) will incorporate the strengths of infrastructure and vehicle subsystems to accommodate the needs of specific applications.

The VII concepts and solutions can be progressively accomplished with the introduction of sensing, warning, and communication devices. An infrastructure-based (IB) solution is a viable option, especially with the advancement of sensing technologies in recent years. The major components are mostly commercially available. Therefore, the deployment potential is very high. The I2V, V2V, and FC-VII solutions are based on two emerging trends: (1) the increasing popularity of vehicle-based pedestrian detection systems, and (2) the development of DSRC and VII programs. The deployment potential is very high, but it will depend on the timeline of the equipment offered by automobile manufacturers.

The overall costs, including equipment and installation, for a stand-alone IB system, can be reasonably and conceivably assumed to be below those for typical traffic signals, or only a small fraction of intersection costs. For the deployment of these IB solutions, it will be sensible to target high-collision concentration and high-risk areas in the urban environment. The overall costs, including equipment and installation, for the infrastructure side of an I2V system can be reasonably assumed to be below the cost of an IB system. The vehicle-based implementation will be considerably under that, but it depends on the market size of products. Like many technological products, the cost can be expected to decrease significantly over the years once an application emerges. This appears to be a highly rewarding investment on the infrastructure side, because the losses from individual incidents of pedestrian-vehicle conflicts can be many times or at least an order of magnitude greater than the system cost. In the initial stage of deployment it is sensible to progress from the IB system, which is able to alert drivers of all passing vehicles without the I2V option. Over the long run, the IB and I2V systems can co-exist. Alternatively, the option of only I2V operation is also possible without the infrastructure-based warning display.

The overall costs of a vehicle-based V2V system are not certain, since the sensing system is only available for a small percentage of the production vehicles and the communication system is still under development. Like many technological products, the cost can be expected to decrease significantly over the years once the market share rises. The discussions of economic analysis from previous sections can be applied for FC-VII. The actual cost-benefit estimation should be evaluated on a case-by-case basis.

5.5 SUMMARY

Significant advancements have been made in a variety of technologies, thus offering potential solutions to contribute to the cause of reducing pedestrian accidents. One latest development involves the inclusion of wireless communication and combines it with sensing devices to form the operating concept of vehicle-infrastructure integration. This paper addresses the technical issues faced by conventional approaches and describes an experimental platform that was built to demonstrate the feasibility of the VII approach. The success in initial testing not only validates the concept, but it was executed with a collection of commercially off-the-shelf products at a reasonable cost. This is particularly meaningful because it has potential for a flexible scale of potential deployment without major infrastructure investments.

In addition to the potential VII solutions, an integrated safety vehicle should be supplemented with on-board sensing systems. For example, a sensor fusion approach mentioned in the technology survey section (*8*) uses multiple sensors to constitute an all-around detection system to overcome the deficiency of any individual sensing device. A near-range on-board system will be most appropriate when the buses are about to leave their bus stops. On the other hand, with the introduction of advanced computer vision, laser scanner, and infrared camera systems, a truly integrated system will become a more mature and affordable safety system that can be expected in the foreseeable future.

One critical issue that should be systematically evaluated is the human factor elements involved in the implementation of the suggested safety systems. The technical problems encountered in the development can be relatively easy to solve, yet the effectiveness of the safety systems hinges completely on the timeliness and the communication of an alert signal to the driver. The human-factors studies should include (1) the design of an effective driver-vehicle interface (DVI), (2) experimentation with driver perception and reaction to DVI functionality, (3) field testing of the warning system through the interaction between driver and DVI, (4) the establishment of performance measures to assess the effectiveness of the overall safety system. The design and evaluation of the DVI remain a critical area for future studies.

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6. SUMMARY AND CONCLUSIONS

Pedestrian safety is a primary traffic issue in the urban environment. According to national traffic safety data, more than 4,000 fatalities were caused by pedestrian-vehicle collisions annually among the 40,000-plus total fatalities in all categories of collisions. [1] Pedestrian crashes account for about 80,000 collisions per year, according to the General Estimate System (GES) data from 1995 to 1998. [2] Over this time, there were, on average, 6000 pedestrian fatalities per year, accounting for about 15% of all roadway fatalities. Pedestrian deaths are primarily an *urban* problem. Many pedestrians are killed at crosswalks, sidewalks, median strips, and traffic islands. Seventy percent of pedestrian deaths in 2002 occurred in urban areas. According to GES data, 55% of all pedestrian crashes occur at non-junctions, while 40% occur at intersections or intersection-related locations. Similarly, in California statewide statistics, more than 3,500 fatalities resulted from 75,000+ pedestrian collisions in the last five years. [3] A regional study has revealed a significant exposure to pedestrian accidents by transit agencies. [4]

As can be seen from the statistical evidence above, pedestrian safety is a major concern and a critical roadway problem in urban areas. In recent years, the prevention and mitigation of pedestrian accidents has become an active research area, with the goal of reducing the number of pedestrian fatalities and serious injuries in roadway collisions. However, timely detection and alerting of drivers to pedestrian presence under all traffic conditions is a challenging task. The characteristics of pedestrian accidents are unique and complex. For example, the movements of pedestrians in urban environment are very difficult to predict and pedestrian crossings may occur at various points along roadways.

6.1 Technical Issues Involved and Proposed Approach

The detection and tracking of pedestrians is not trivial. First, in an urban environment the patterns of vehicle and pedestrian movements can be very complicated. On city streets, there are numerous locations where pedestrians may choose to suddenly cross in front of a vehicle. The reliability of the detection function is further complicated by the crowded background and the issue of varying visibility, weather and roadway conditions. Thus, the solution for a reliable and accurate means of identifying pedestrians requires sophisticated design and extensive experimental evaluation.

Given the challenging operating environment of transit buses, a complete and reliable sensing system for pedestrian detection can benefit from the combined use of multiple sensors. For example, the requirements of pedestrian detection are different for situations when buses are stopped at bus stops or near intersections versus when the buses are moving at relatively higher speeds in cruising conditions. Furthermore, any one particular technology may have difficulty meeting all necessary requirements under various lighting conditions, or rainy and foggy weather conditions, not to mention that most sensors have too limited a field of view to monitor traffic in all directions. In addition, the cluttered background and complex moving patterns of all objects on urban streets demand sophisticated processing of sensor inputs to avoid false detection and recognition.

A promising approach has recently emerged with the advancement of wireless communication technologies. The United States Federal Communications Commission recently allocated radio frequencies for Dedicated Short Range Communications (DSRC) in the 5.9 GHz band. DSRC can be applied to many applications, a primary one of which is roadway safety. In traffic conditions where drivers have obstructed views or limited visibility of pedestrian crossing areas, an infrastructure sensor can be used to detect objects and a wireless signal can be sent remotely to a receiver on the bus, with a visual or audio alert given to the driver. In other words, a warning system is accomplished through the cooperation of infrastructure- and vehicle-based capabilities. This report provides a summary of such VII operating concepts and the experimentation carried out to illustrate the feasibility of this approach.

Transit buses are an ideal platform to experiment with and deploy pedestrian detection technologies cost-effectively for several reasons, including:

(1) Pedestrian exposure is high along bus routes, especially in the urban environment.
(2) Transit vehicle-pedestrian accidents are a serious problem in their own, yet they are usually further compounded by public perception.
(3) Accidents involving transit vehicles also lead to operational problems and costs.
(4) Transit vehicles are a relatively costly investment, and therefore the addition of safety systems is relatively economically feasible.
(5) Transit vehicles run on fixed routes and high-risk locations along their routes can be screened and pre-determined.
(6) Since transit buses operate mostly on city streets, the heavy work load of drivers makes the monitoring of pedestrians even more challenging, despite the fact that a great majority of bus drivers conduct their duties professionally and diligently.

Additionally, an experimental transit vehicle equipped with the necessary components such as computers, data acquisition processors, sensors, and driver-vehicle interface is readily available at PATH for experimental testing. Thus, the adoption of the transit vehicle platform enables a synergistic utilization of resources in the course of this study. However, during the course of the project the research has utilized and extended the testing and implementation studies to other vehicle platforms.

6.2 Summary of Findings

The work presented in this project represents a two-year effort taken by the research team to address pedestrian safety. With a survey of the latest technology developments and available products, a number of sensors were selected for evaluation to assess their applicability for transit bus platforms. In the course of experimental exploration, certain performance characteristics and limitations were investigated. A brief summary of the evaluated sensors is given as follows:

(1) EVT-300 radar is a readily available commercially-off-the-shelf product. It has the capability to detect seven targets simultaneously. In the tests, pedestrians were detected within the range of 5-100 meters. However, since the radar is based on Doppler effects, only a relative motion between the radar and the object is detectable. For example, if a pedestrian walks across the forward direction of the radar, the sensor will not detect the movement or the object. Furthermore, radar waves bounce objects with large radar-cross-sections more reliably, and pedestrians may not be reliably detected.
(2) The IRIS infrared people counter that was evaluated appears to be capable of detecting

pedestrians reliably. However, the product only generates a trigger when a pedestrian completes the crossing of two subsequent boundary lines designated for the people counter. In order to serve as a pedestrian detection sensor, the presence of a pedestrian should also be built into a function of the sensor in addition to the movement across a designated area.

(3) Ultrasonic sensors are relatively low-cost and they can be readily adopted for pedestrian presence detection. However, they are only good for short ranges and they are susceptible to small objects or particles.

(4) Laser scanner, such as the tested IBEO sensor, offers the most comprehensive performances. The IBEO product even includes a module for categorizing the object types, such as a pedestrian. However, the cost of these units is very high and prohibitive. In the future years, these products will be meaningful options if they are accepted by automobile manufacturers and become widely used in the market.

For large-scale deployment, certainly cost considerations will play a big role in the selection of technologies or components. Either to be used for a specific function, or to be integrated within a complete solution, products need to be cost competitive in order to reach broad-based utilization. Even though certain promising and sophisticated technologies may be cost prohibitive currently, they may become more affordable in the future as they find marketable applications and unit costs are reduced in mass production.

With consideration for the distinct operating environment of transit buses, the detection problem is handled with a two-pronged approach: one aiming for short range when buses are near bus-stop or intersections, and the other targeting longer-range detection when buses are cruising at higher speeds. A viable option to provide an integrated solution will be to combine infrastructure sensors, at strategic locations such as crosswalks or high risk areas, and wireless communication links to send detection signals to an on-board unit to alert drivers of potential threats.

An integrated vehicular safety system in the future, for transit, commercial and passenger vehicles alike, will likely consist of multiple functionalities to include adaptive cruise control collision warning, lane departure warning, brake assist, etc. The various functions will be implemented with a suite of sensing devices to provide the all-around capabilities to detect targets. Transit vehicles have the potential to be first equipped with such systems for field evaluation in an urban operating environment, which presents considerable challenges. The development of robust sensing devices and the incorporation of other technologies, such as GPS, geographic mapping, inertial navigation, and DSRC, will allow more promising prospects for the deployment of safety solutions.

One recent development involves the inclusion of wireless communication, combined with sensing devices, to form the operating concept of vehicle-infrastructure integration (VII). The studies carried out in this project addressed the technical issues faced by conventional approaches and described an experimental platform that was built to demonstrate the feasibility of the VII approach. The success in initial testing not only validated the concept, but it was executed with a collection of commercially off-the-shelf products at reasonable costs. This is particularly meaningful because it has potential for a flexible scale of potential deployment without major infrastructure investments.

In addition to the potential VII solution, an integrated safety vehicle should be supplemented with on-board sensing systems. For example, a sensor fusion approach mentioned in the technology survey section uses multiple sensors to constitute an all-around detection system to overcome the deficiency of an individual sensing device. A near-range on-board system will be most appropriate under these conditions, when the buses are about to leave from bus stops. On the other hand, with the introduction of advanced computer vision, laser scanner, and infrared camera systems, a truly integrated system will become a more mature and affordable safety system, which can be expected in the foreseeable future.

One critical issue that should be systematically evaluated is the human factor elements involved in the implementation of the suggested safety systems. The technical problems can be relatively easy to solve, yet the effectiveness of the safety systems hinges completely on the timeliness and the communication of an alert signal to the driver. The human-factors studies should include (1) the design of effective driver-vehicle interface (DVI), (2) experimentation with driver perception and reaction to DVI functionality, (3) field testing of the warning system through the interaction between driver and DVI, (4) establishment of performance measures to assess the effectiveness of the overall safety system. The design and evaluation of DVI remain a critical area for future studies.

6.3 Recommendations

The recommendations as a result of the work described in this report can be summarized as follows:

(1) Advanced technologies for vehicle on-board pedestrian detection are being developed and marketed by automakers and associated industries. The most promising categories of technologies include infrared, laser scanner, and vision sensors, which are mostly aimed at providing warnings of pedestrians in the forward paths of vehicles. The products can be expected to become more affordable when they are deployed as a standard feature on passenger cars. Short-range sensors for alerting drivers of nearby obstacles or pedestrians are already available in the market with various types of sensing technologies such as radar and ultrasonic and computer vision. The adoption of candidate technologies for a non-standard production vehicle, such as transit buses, should be investigated carefully to account for the operational requirements associated with the intended applications.

(2) Infrastructure sensors are readily available for selective usage for pedestrian detection, including infrared, radar and computer vision. The effectiveness of these sensors depends heavily on the operating environment and the particular constraints of local applications. The use of these products is not wide-spread and a comparative evaluation of products will be warranted if a specific deployment is being considered.

(3) Vehicle-Infrastructure integration offers an exciting potential approach that allows the combination of infrastructure-based and vehicle-based technologies to provide the most

favorable outcome. A field operational test in conjunction with other VII research activities would be most desirable.

(4) Regardless of the selected technical approaches, a critical element of pedestrian safety lies in the effectiveness of the driver interface. This is a subject area that will be the most promising arena for continuing research and exploration of safety improvements.

References

[1] *IIHS Pedestrian Fatality Facts* (2002). Insurance Institute for Highway Safety, Arlington, Virginia, http://www.iihs.org/

[2] *GES*, General Estimate System, Maintained by NHTSA. http://www.transtats.bts.gov/

[3] *SWITRS*, Statewide Integrated Traffic Records System, California, http://www.chp.ca.gov/html/aiuswitrs.html

[4] Zhou, K., et al (2004) Studies of Accident and Cost Data for Transit Buses. *Proceedings of the 2004 Intelligent Transportation System World Congress.* Nagoya, Japan, October 2004.