Vehicle-Infrastructure Integrated Approach for Pedestrian Detection
– A Feasibility Study Based on An Experimental Transit Vehicle Platforms

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ABSTRACT
Pedestrian safety is a primary concern in transportation, especially in an urban environment. A variety of technologies, either infrastructure-based or vehicle-based, have evolved and emerged in recent years that offer promising prospects for detecting pedestrians. The sensing technologies can be utilized in the implementation of pedestrian collision warning systems. In these systems, timely warning signals are provided to subject vehicle drivers to avoid collisions. However, the complexity of operating environment on roadways and the limitations inherent in individual sensing devices present significant challenges in achieving reliable and all-situation performance of many safety systems, especially for vehicle-based solutions. Besides seeking an enhanced on-board vehicle-based solution, an approach based on vehicle-infrastructure integration has now emerged as a powerful alternative. This paper describes the rationale for such an approach as well as the configuration of an experimental system for feasibility evaluation. An experimental transit platform is highlighted as a candidate for the proposed solutions, although the discussed approach is applicable to all vehicle platforms.

BACKGROUND
Pedestrian safety is a primary concern in transportation, especially in an urban environment. Pedestrian deaths and injuries caused by traffic accidents are most prevalent in urban areas; about 70 percent of pedestrian deaths occur in urban settings. (1) Pedestrians in urban areas are more likely to be injured in crashes at intersections. (2) A review of the national crash statistics, www.nhtsa.gov, shows that about 15% (4,882 out of 42,116 in 2001) of fatalities result from pedestrian-type accidents. The California statistics compiled by the Office of Traffic Safety (OTS), www.ots.ca.gov, also reflect a significant number of pedestrian incidents with 712 out of 4,225 fatalities in the year of 2003 in all collisions being pedestrians. Even though the numbers of these 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 pedestrian fatalities. (3) It is therefore a great incentive to deploy modern sensing technologies to assist drivers in detecting and tracking pedestrian presence and movement. The detection and tracking of pedestrian 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 are further complicated by the crowded background and the issue of varying visibilities 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 paper, a transit experimental platform is selected as the target of the feasibility study described in this paper 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) Accident involving transit vehicles also lead to operational problems and costs.
(4) Transit vehicles are 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 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 vehicle equipped with necessary components such as computers, data acquisition processors, sensors, and driver-vehicle interface is readily available at the authors’ organization 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 and inclement 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 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 paper provides a summary of such VII operating concepts and the experimentation carried out to illustrate the feasibility of such approach.

LITERATURE REVIEW AND TECHNOLOGY SURVEY FOR PEDESTRIAN DETECTION

From an application’s point of view, pedestrian detection devices can be used for traffic flow monitoring, intelligent pedestrian crossing or on-board vehicle for driver assistance. An extensive review and survey of existing literature and the latest developments in commercial products is conducted. A variety of sensing technologies such as piezoelectric (4-5), ultrasonic (6-8), microwave radar (9-10), laser scanner (11-14) and computer vision (15-26) have been suggested and developed for pedestrian detection. In general, piezoelectric, infrared, radar and video are candidates for infrastructure sensors, while radar, laser scanner, infrared camera and computer vision offer prospects for vehicle-based solutions. Some selective yet representative references are mentioned below.

For the application of pedestrian detection, piezo-cables with piezoelectric material are usually fabricated into a “mat” (4). When a person steps onto such a mat, an electrical signal is generated
until the person leaves the mat. In (5, 6), piezoelectric detectors are used to detect the presence of 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). In (7), ultrasonic sensors placed at un-signalized crossing for pedestrian detection received more false calls during rainy weather. In (9), the effect of wind from different directions is studied for an ultrasonic sensor system.

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 a 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 (10). 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 (11) can be used to achieve large coverage area.

A laser scanner provides a high-resolution image of surrounding objects (12). Pedestrians can be classified by the characteristics of their moving legs (13). A multiple-hypothesis classification approach is used to separate the images of close targets acquired by multi-layer laser scanner in (14). A pedestrian tracking system consisting of multiple laser scanners is proposed to track pedestrians in a wide and open area with networked computer systems (15). A pedestrian detection system based on a multi-layer laser scanner was built. (16) The excellent range accuracy and fine angular resolution make laser scanners suitable for applications in which a high resolution image of the surrounding area is required. Since laser scanners are optical sensors, different weather conditions like fog or snow may limit their detection range. However, newer technologies are now possible to overcome this drawback. The signal processing is a little more complex for laser scanners compared with ultrasonic or microwave radar sensors, therefore a dedicated processor may be needed.

Vision-based pedestrian detection can obtain much richer information about the surrounding environment compared with radar or laser scanner. How to extract useful information from available image sequences is quite challenging due to the complexity in environment, pedestrian appearance, and signal processing. Different algorithms are 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. (17-18) On the other hand, the shape-based approaches rely on shape features to recognize pedestrians. (19-22)

Compared with cameras operating in the visible spectrum, infra-red (IR) cameras (23-24) are not as sensitive to the change of lighting conditions. The advantage of a passive infra-red sensor is the ability to detect pedestrians without illuminating the environment. (25-27). Infrared was suggested for near-range detection with a sensor array (28) and for longer-range recognition with infrared camera images (29). In the former, an array of passive infrared thermopile sensors was aided with probabilistic techniques for detection improvements. In the latter, an approach was
based on the localization and distance estimation of warm areas in the scene. A micro-bolometer technology sensor, sensitive between 7 and 14 micrometers in the far infrared band was used (30) to provide a recognition scheme. Honda has developed an intelligent night vision system to be made available for some latest models (31). Pedestrians can be identified by the shape recognition and their movements are tracked through vector analysis. The system provides the driver with visual and audio cautions when it detects pedestrians in or approaching the vehicle’s path.

Given the diversity and respective constraints of various 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. Computer vision and microwave radar are combined for pedestrian detection in a moving vehicle. (32) The radar information is used to generate a potential target list and vision is used for fine searching. The combination of dynamic passive infrared detection and active ultrasonic ranging in a single detector provides pedestrian presence information with high reliability in the intelligent crossing application. (33) In a recent publication (20), the next generation vehicles surround sensing system was suggested to use a combination of different sensors. Ultrasonic sensors could be used for very short range sensing when parking or reversing. 24 GHz Short Range Radar (SRR) will be used to cover vehicle perimeter up to 20 meters. 77 GHz long range radar or LIDAR will be used for long range sensing up to 120 meters. Computer vision will be used for fine sensing around medium range (0-80 meters) and infra red camera will be used for night driving. A multi sensor system was developed consisting of a far infrared camera, a laser scanning device and ego motion sensors. (34)

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 for a large-scale deployment for broad-based applications. The concept of combining lower-cost sensing devices with wireless communication links to form vehicle-infrastructure solutions is therefore an appealing alternative. Even though costs and reliability ca 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 is 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:

An infrastructure 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 from the intersection or is arriving at
the intersection within two seconds, the infrastructure computer broadcasts a radio signal (802.11b-compatible link). The criteria of transmitting the alert signals can be 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). 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 of the pedestrian presence. Additionally, the infrastructure computer can also illuminate a driver-infrastructure interface (DII) at the corner of the intersection.

**Physical Architecture of Bus On-Board System**

For the vehicle platform, we utilized an experimental bus that was used in the Bus Rapid Transit demonstration in 2003 (35). A data-flow diagram showing the architecture of the experimental bus is depicted in Figure 1. 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 broadcasting by 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) display. 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 under automation 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 2.

4. A communication channel is required for the operations 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.

**Testing of Bus-Intersection Pedestrian Concept**

The testing of the described system is 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 ground loops, Canoga Microloops (3M), radar (EATON-VORAD), video traffic monitoring systems (TRAFFICON and ITERIS), microwave pedestrian detector (MS-SEDCO), etc. The intersection is also equipped with wireless communication links (DSRC and 802.11x) for cooperative vehicle-infrastructure safety studies.
Figure 3 shows the setting of the intersection and the depiction of the test scenarios. A microwave radar pedestrian detector, shown in Figure 4, is mounted on one 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 in a trajectory indicated by the red dash line in Figure 3, 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. 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 6 shows a view from an inside-the-bus location next to the driver 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 7. 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.

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 following considerations:

1. Transit buses run on mostly fixed and pre-known routes, therefore selective locations with critical needs of safety countermeasures can be pre-determined.
2. The exposure of pedestrians on urban bus routes is significant.
3. The implementation of a functioning VII solution requires a minimum level of additional instrumentation, which has less impact on the total cost of a relatively higher-priced bus when compared to those of the typical passenger vehicles.
4. With the three factors above combined, the benefit-cost analysis does lead to a more convincing case for transit vehicles.

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.

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 implementation of suggested systems should be tailored to meet the local needs. In certain cases, the most desirable solution may be a conventional traffic engineering solution, rather than a VII- or ITS-type of systems as proposed herein. Exemplar pedestrian case studies (37-40) demonstrated the local attributes of issues even though common components can be selectively deployed.

A recent NHTSA report (36) provides a breakdown of pedestrian accidents. The crash statistical description provided below focuses on the above ten specific pre-crash scenarios that 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 junction (percentages shown below refer to the frequency of each scenario relative to the size of 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 countermeasures 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.

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 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 the drivers. Similarly, if a nearby infrastructure device such as traffic controllers or message signs 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 network in urban domains and the developments 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 developments 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 typical traffic signal or only a small portion of intersection costs. For the deployment of these IB solutions, it will be sensible to target high-collision concentration and high-risk areas in urban environments. 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 of individual incidents for 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 where drivers of all passing vehicles without the I2V option can be given an alert. 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 developments. 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.

**SUMMARY AND CONCLUSION**

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 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 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 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 (20) 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 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 developments 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-factor studies should include (1) the design of effective driver-vehicle interface (DVI), (2) the experimentation of driver perception and reaction to DVI functionality, (3) the field testing of 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 DVI remain a critical area for future studies.

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