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16. Abstract

Continuing advancements in imaging systems and image processing have led to a proliferation of technologies that are potentially applicable to vehicle occupancy verification. The purpose of this synthesis report is to review the range of approaches for both in-vehicle and roadside occupancy verification. The report surveys the extent of peer-reviewed research, and is intended to serve as guide toward identifying and implementing improved methods for automating occupancy monitoring, verification and enforcement. The expanded discussions of the various technical approaches for occupant detection that are contained in the synthesis report provide a useful supplement to the Automated Vehicle Occupancy Verification Technologies white paper.

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Automated Vehicle Occupancy Technologies Study:

Synthesis Report

Prepared for the HOV Pooled-Fund Study
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Table of Contents

List of Figures

LIST OF TABLES

Page

INTRODUCTION

BACKGROUND

High-occupancy vehicle (HOV) lanes have been in operation since the late 1960s. Today, there are over 2400 lane-miles of HOV projects, including arterial examples throughout North America, with many more overseas. Increasingly there is interest in expanding HOV operation to high-occupancy toll, or HOT lane operation. The growing use of pricing as a means to readily manage demand is facilitated by the development of electronic toll collection (ETC) technology as an increasingly practical and inexpensive tool. Pricing helps maximize the use of available pavement and still prioritize operation for HOV use. The introduction of pricing into the HOV operation is seen by some as an opportunity to further manage the facility by spreading peak hour demand and allowing other users into the lanes as capacity allows.

As more and more HOT lanes emerge that cater to a wider array of users through pricing, enforcement is made more complicated in determining who is an HOV that receives free or reduced pricing for travel within a varied traffic stream. For priced lanes, persistent violation problems can breed disrespect for enforcement, resulting in a significant loss of revenue. In the extreme, some sponsoring agencies are considering doing away with rideshare incentives on their managed lanes because of the difficulty associated with monitoring and enforcing these users. HOV and HOT lanes require effective enforcement policies and programs to operate successfully. Enforcement of vehicle-occupancy requirements is critical to protecting eligible vehicles’ travel-time savings and safety. Visible and effective enforcement promotes fairness and maintains the integrity of the facility to help gain acceptance among users and non-users.

Vehicle occupancy verification is a principal impediment to more efficient HOV lane enforcement. Electronic toll collection, license plate recognition, and a myriad of other technologies have been developed and refined in recent decades to improve the integrity of enhanced transportation systems. However the target of many of these technologies has usually been the vehicle, and not the occupants. Several semi-automated and fully automated techniques for determining the number of persons in a moving vehicle have undergone limited field testing, including operator-monitored video cameras and infrared composite imaging. However, no automated solution has yet been developed for permanent field implementation, and no system has been found foolproof enough to satisfy traffic courts in upholding citations issued. As a result, HOV facility operators have traditionally relied on field enforcement to manage occupancy violations. Given widespread plans for development of HOV and HOT lanes in a number of metropolitan areas, improved vehicle-occupancy verification techniques urgently need to be explored.

PURPOSE OF THIS REPORT

This report synthesizes the current state-of-the-practice in technologies pertinent to automated vehicle occupant verification, and is intended to serve as a guide towards identifying and implementing improved methods for automating occupancy monitoring, verification, and enforcement.

IN-VEHICLE SYSTEMS FOR OCCUPANCY DETECTION

Many of the in-vehicle technologies for occupancy detection have been developed as a response to occupant safety concerns. Significantly, the number and scope of research projects investigating in-vehicle occupancy detection and classification have steadily increased. The primary reason underlying this expansion is revision to the Federal Motor Vehicle Safety Standards. The U.S. Federal Motor Vehicle Safety Occupant Crash Protection Standard (FMVSS 208) mandates the use of advanced or "smart" air bags in the front seats of new vehicles sold. Deployment behavior for front passenger airbags is specified as follows:

1. Suppress deployment for an empty seat, rear-facing infant seats (RFIS), and belted small passengers (under 66 lb).
2. Deploy at reduced power for unbelted and belted medium-sized passengers (66 to 130 lb).
3. Deploy at high power for unbelted and belted large passengers (over 130 lb)

The phase-in schedule for the advanced airbag requirement encompasses

- 35% of 2007 model vehicles,
- 65% of 2008 model vehicles, and
- 100% of 2009 model vehicles and thereafter.

Advanced air bags rely on sensors to cancel deployment when the occupant is in a potentially dangerous position. Although the Standard applies only to vehicles sold in the United States, that is the largest single auto marketplace in the world and most global manufacturers respond to the U.S. direction. Similar requirements may emerge in Europe and elsewhere. Some auto manufacturers are also using side curtain air bags, which are even more sensitive to out-of-position passengers than the frontal air bags due to the much shorter distance between the side of the vehicle and the passenger. Occupancy detection systems are consequently a critical part of some side air bag systems. This is creating enormous financial incentives for researchers and represents a major investment by manufacturers – one industry analysis in 2001 put the value of occupant-sensing products to 2006 at $US3.6 billion [1]. Other applications, including Advanced Driver Assistance Systems (ADAS) from the Intelligent Vehicle Initiative (IVI), have contributed to the trend.

The following technologies for in-vehicle occupant sensing are described in the next sections:

- Weight sensors
- Capacitive and electric field sensors
- Ultrasonic sensors
- Thermal infrared imaging
- Optical/near infrared (NIR) sensors
- Biometric sensors
- Smart cards and readers

WEIGHT SENSORS

Weight sensors have been the most widely employed method for occupant detection in vehicles. These sensors determine the size of an occupant by measuring the forces exerted on the seat by the occupant. Over the last ten years, occupant detection systems based on weight sensing technologies have evolved to incorporate increasing numbers of individual sensing elements or arrays of elements, enabling these systems to map the force or pressure distribution of seated occupants and to classify occupants and their location on the seats. These detection systems are generally classified as either cushion-based or frame-based, depending on the placement of the sensors.

Cushion-based systems rely on sensor elements within or adjacent to the seat cushion itself. These sensors detect the force upon the seat cushion to estimate the occupant's seated weight on the cushion. For systems using an array of multiple sensor elements, a pattern of the load across the seat can be used to help differentiate between adult occupants, children, or a child seat. Occupant position (leaning forward or sitting back) may also be inferred by the fore/aft load distribution across the cushion.

Frame-based systems incorporate resistive strain gauges or load cells which are typically built into the seat floor mounts or onto the seat side rails, and measure the weight of the both the seat and its occupant. Estimates of an occupant's location can be obtained by analyzing changes in the relative distribution of loads among the frame sensors over a short time interval while the vehicle is in motion.

Most weight sensing systems are capable of determining little more than the position of an occupant's center of mass relative to the seat [2]. It is therefore relatively easy to trigger a spurious positive occupancy reading by placing heavier objects on the seat. Weight sensors must also be carefully calibrated to control for variations in seat size, weight, or padding thickness. These drawbacks are not generally associated with more sophisticated systems capable of mapping the pressure distribution on seat, however. Table 1 summarizes the pertinent features for this technology.

Table 1. Weight Sensing Systems Features.

Advantages	• Newer frame-based systems integrate easily • Immune to nearly all ambient conditions • Low parts cost
Disadvantages	• Simpler systems can be fooled by weights on the seat, require careful calibration, and are somewhat inaccurate • Frame-based sensors can only be used on front seats • Cushion-based sensors must be built into seats
Development Status	• Production
Developer and Manufacturer Interest	• Large – nearly every manufacturer and parts supplier
Market Forecast	• Continued strong demand

Figure 1. Delphi PODS-B System [3]

The Delphi Passive Occupant Detection System B (PODS-B) is one example of a cushion-based system currently in production. PODS-B uses a silicone-fluid-filled bladder tied to a pressure sensor for measuring the weight of seat occupants [3]. An additional strain gauge sensor measures the cinching force of the seatbelt. The system, shown in Figure 1, is capable of differentiating between large and small adults as well as children. Delphi supplies an Occupant Detection System that helps a passenger control airbag deployment to several car manufacturers including Jaguar, Ford, and General Motors.

A more advanced cushion-based system, developed by International Electronics & Engineering (IEE) in partnership with Siemens VDO Automotive, uses dozens of interconnected sensors. Such a system can not only discern the magnitude and location of the center of a seat occupant's mass, but the detailed shape of the occupant's seat pressure pattern as well [4]. Their Occupancy Classification (OC) system consists of an IEE-developed flexible polymer mat which is integrated into the front passenger seat. The mat contains numerous force sensing resistor (FSR) cells and a Siemens electronic control module integrated into the edge of the mat. The layout of the OC sensor mat is shown in Figure 2.

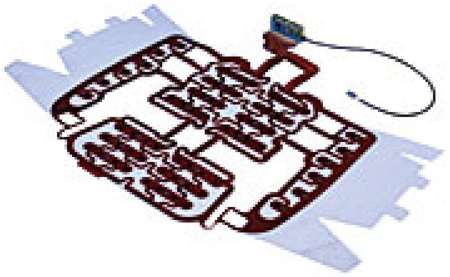

Figure 2. IEE / Siemens OC System [5]

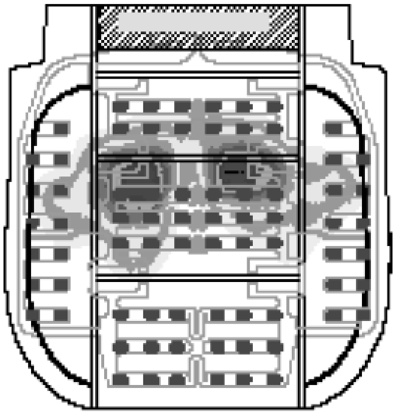

Figure 3. IEE / Siemens OC Pressure Distribution [7]

In operation, the weight of a seat occupant gives rise to discrete occupancy-pressure pattern, as indicated by the contour pattern overlay on the pad layout in Figure 3. The system then determines the occupancy classification using pressure analysis, morphology analysis, and pattern recognition. The IEE OC system is currently fitted to cars manufactured by BMW, Chevrolet, DaimlerChrysler, General Motors, Hyundai, Kia, Rolls-Royce, and Suzuki.

The Advanced Weight Sensing II (AWS) system from Siemens is their latest generation frame-based occupancy detection system [6]. Strain gauge sensors (Figure 4) located in the seat track at the four corners of the seat classify the occupant's weight and center of gravity in the seat. The system is also able to compensate for that portion of the occupant's weight that is transferred to the vehicle floor through the occupant's legs.

Figure 4. Siemens AWS II Sensor [6]

Figure 5. Bosch iBolt [8]

The Bosch iBolt system is one example of a highly compact frame-based sensor [8]. Each iBolt strain sensor is little larger than the normal seat securing bolt (Figure 5), and can be easily integrated into the seat structure by replacing existing bolts. There is usually no need to alter existing seat designs or modify the system for different kinds of vehicle seats or for differing seats.

CAPACITIVE AND ELECTRIC FIELD SENSORS

This technology determines occupant presence and position by reading changes in an oscillating low-level electromagnetic field generated by the system. The field is generated between two fixed electrodes which effectively act as signal antennas; i.e., one electrode behaves as a transmitter and the other forms a receiver. The strength of the field detected by the receiver electrode will decrease if a dielectric (insulating) material is placed near or between the electrodes [9]. Sensors utilizing this principle are alternately known as capacitive or capacitive-coupling sensors, since the capacitance of the two-electrode system varies in direct proportion to the insulating properties of the "gap" between the electrodes. Electric field sensing technologies exploit the fact that the human body, composed primarily of water, has a dielectric constant approximately 80 times that of air. The electric field between the electrodes therefore changes markedly depending on whether a human body is present within the field. The magnitude of the change is proportional to how much of the electric field is blocked; therefore, this technology can be used to determine the distance of a body to the detector or to estimate a body's size. Multiple sets of electrodes may be used to triangulate the position of a vehicle occupant as well.

Applications for this technology include roof- or dashboard-mounted detectors which sense the presence of an occupant's head. Multiple electrodes can also be located under the surfaces of a seat for approximate classification of occupants. This technology is highly discriminatory, since many inanimate objects (hats, newspapers, etc.) have much lower dielectric constants than that for water. However, highly conductive materials such as metals can defeat the system by creating a short circuit between the electrodes and "blinding" the sensor. The sensing range of this technology is also limited to at most 0.6 m, so the sensors must be located very close to an occupant's body or head. Table 2 summarizes the pertinent features for this technology.

Table 2. Electric Field Sensing Systems Features.

Advantages	• Detects a signature biometric characteristic • Cannot be blocked by non-conductive objects • Immune to nearly all ambient conditions • Can be used for front and rear seats • Low parts cost
Disadvantages	• Must be integrated into seat surfaces or located directly overhead • Limited sensing range • Can be blocked by conductive materials such as foil
Development Status	• Production
Developer and Manufacturer Interest	• Moderate – systems have been investigated by NEC/Honda/Elesys, IEE, Allied Signal, Siemens, and TRW
Market Forecast	• Wider application foreseen for rear seats with side curtain airbags

A current production example of an electric field sensing system is the Occupant Position Detection System (OPDS) from Elesys [10]. Elesys is a cooperative venture between Honda and NEC and was formed to commercialize parallel electric field sensing research efforts by Honda Research & Development Corp. [11] and NEC [12]. The OPDS uses a series of flexible, conductive cloth capacitive sensors embedded in the seatback. Six sensors are affixed laterally across the seatback, while another vertically oriented sensor is located at the seat side support where the side airbag is installed. The lateral sensor array measures the height of the seat occupant, while the side sensor is used to detect the head of a small occupant or child. The OPDS control unit and transmitter is installed in the seat frame. Figure 6 illustrates the arrangement of the OPDS components. The system can reliably determine the size and position of the seat occupant, and is not affected by seat position, wear, water, or seat ventilation. The OPDS offers effective protection for children in the event of side airbag deployment, and fully complies with the National Highway Traffic Safety Administration (NHTSA) FMVSS-214 mandate for Side Impact Protection: Dynamic Performance. The OPDS system is currently available on Honda and Acura vehicles.

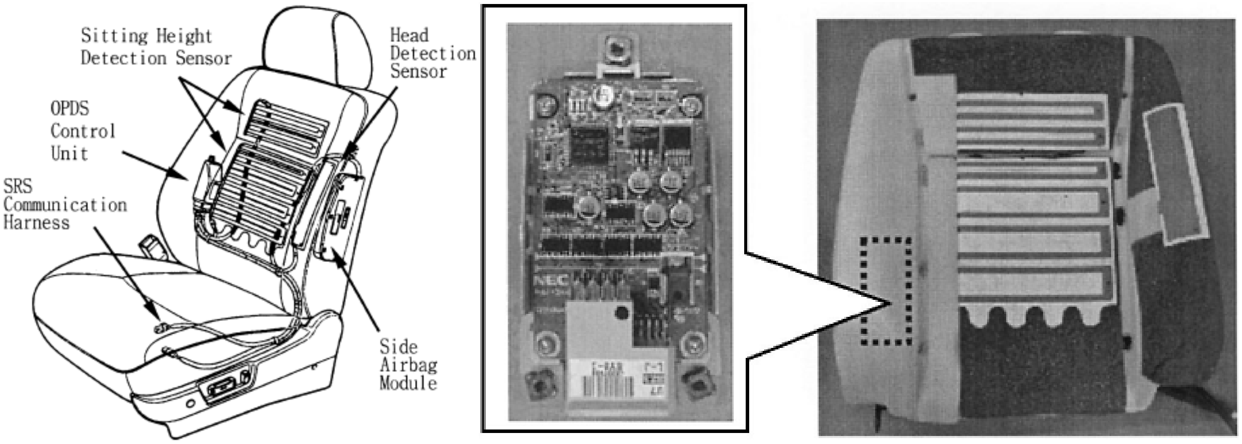

Figure 6. Elesys Occupant Position Detection System [11]

Earlier examples of electric field sensing systems include the Proximity Array Sensing System (PASS) from Advanced Safety Concepts [13], and the Total Occupant Recognition System (TOR) from IEE [14]. The PASS system used a roof-mounted transmitter and sensors to generate and monitor a low-level hemispherical electric field for the detection of an occupant's head. The roof-mount location of the PASS system limited its applicability to driver alertness detection, and the relatively short detection range of 0.25 m impaired its performance in the case of short drivers. The TOR system incorporated a total of five flexible electric field detection (EFD) units installed in the seat cushion, seatback, and the passenger airbag cover in the dashboard. The arrangement of seat sensors permitted discrimination between a non-human object and a vehicle occupant, as well as the aggregate size of the occupant. The system was capable of detecting out-of-position occupants with respect to the dashboard, but had limited abilities for detecting the exact torso position of the passenger. The TOR system has apparently been discontinued, with no further development indicated past 2001.

ULTRASONIC SENSORS

Ultrasonic sensing utilizes acoustical echo-location to determine the position of vehicle occupants. Multiple transducer/microphone sets are needed to triangulate the position of an object in three dimensions.

For reliable detection of an occupant's seating position, at least four transducers should be used to ensure adequate coverage of the seating area and provide redundancy, as ultrasonic detection can be impaired by interposing an extraneous reflecting object between the transducer and the occupant [15]. The beam width, frequency, and intensity of the ultrasound pulses must also be carefully selected to maximize detection capability, minimize unwanted reflections and acoustical interference, and ensure safe exposure levels for people and animals [16]. Also, since the propagation speed of sound waves depends on air temperature, ultrasonic systems must use robust pattern detection methods to preserve accuracy against biasing effects arising from extreme cabin temperatures, as well as diffraction effects caused by thermal gradients or thermal instabilities [15]. The features of these sensors are summarized in Table 3.

Table 3. Ultrasonic Sensing Systems Features.

Advantages	• Immune to ambient lighting conditions • Low parts cost
Disadvantages	• Requires careful integration and accurate setup/calibration • Affected by temperature • Multiple seat systems may be unfeasible due to mutual interference • Can be blocked by newspaper
Development Status	• Production
Developer and Manufacturer Interest	• Low – only one production system from ATI/Autoliv
Market Forecast	• Minimal – will most likely be replaced by optical & NIR systems

Commercial development of ultrasonic occupant detection systems has been sparse, and only one system has entered production in passenger vehicles. Automotive Technologies International (ATI) developed a system for Autoliv as part of the Swedish airbag supplier's Adaptive Airbag System [15]. Using four ultrasonic transducers, it determines the presence and position of the front-seat passenger's head and upper torso with respect to the passenger airbag deployment door. The various system components are illustrated in Figure 7. A neural network pattern recognition system discriminates between adults, children, and rear-facing infant seats, and can also detect out-of-position occupants. Autoliv's airbag system was first introduced in 2001 for the Jaguar XK series as the Adaptive Restraint Technology System (ARTS). The current version of ARTS is standard equipment for the 2006 Jaguar XJ sedan.

Figure 7. Autoliv Adaptive Airbag System

THERMAL INFRARED IMAGING

Thermal imaging systems detect the heat emitted by objects and people in the long-wave infrared (LWIR) band. In high-resolution applications, thermal imaging has excellent discrimination abilities between animate and inanimate objects, as well as good occupant size and location sensing capability. Such systems have until recently been prohibitively expensive, requiring integrated mechanical systems for cooling and image scanning. Advances in semiconductor manufacturing are now yielding compact sensor arrays which can capture high-resolution thermal images at video frame rates and can operate at room temperature. Thermal imaging suppliers CEDIP Infrared Systems [17] and Raytheon subsidiary Thermal Eye [18] offer sensors with integrated signal processing capabilities for better resolution and higher sensitivity. Infrared Integrated Systems (IRISYS) uses a low cost, lower resolution sensor suitable for short-range detection within a vehicle [19]. The IRISYS thermal imagers are also radiometric; i.e., they can measure temperatures within the thermal image. This is achieved by calibrating the imager against "black body" temperature references while simultaneously compensating for ambient temperature changes within the image itself, as shown in Figure 8.

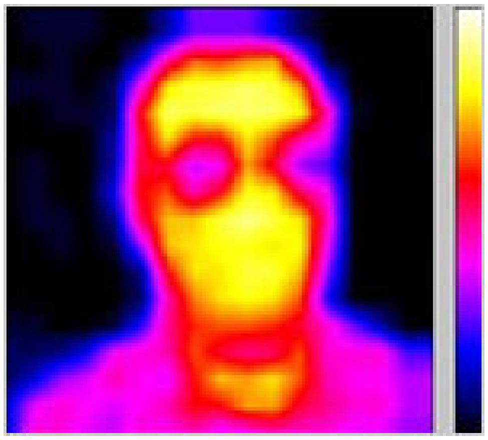

Figure 8. IRISYS Thermal Infrared Face Image [19]

For occupancy detection purposes, one disadvantage of these systems is that the thermal signature of the occupant can be distorted or reduced by everyday objects that may come between the occupant and the sensor. Such objects include gloves, hats, newspapers, and child seat-mounted sunshades. Thermal infrared sensors may also have trouble discriminating a passenger from the surrounding vehicle cabin in high temperature cases; this problem is avoided for all but the lowest resolution imagers. The pertinent features for this technology are summarized in Table 4.

Table 4. Thermal Infrared Systems Features.

Advantages	• Detects a signature biometric characteristic • Immune to all ambient lighting conditions
Disadvantages	• Image can be distorted by hot drinks • Can be blocked by objects • Less effective in high cabin temperatures
Development Status	• Proof of concept
Developer and Manufacturer Interest	• Low – only research interest
Market Forecast	• Wider application foreseen for head tracking, occupant monitoring, and trapped occupant detection

Thermal infrared imaging has been recently investigated for its suitability in detecting and tracking the heads of vehicle occupants [20][21]. Researchers from the Computer Vision and Robotics Research Laboratory at University of California San Diego used a miniature infrared focal plane array to acquire images of the passenger occupant in the 7–14 µm infrared band. The Raytheon 2000 AS infrared camera used in the test does not require cooling, but needs periodic software image recalibration to correct drift in sensitivity with temperature. This was accomplished by empirically by rescaling the brightness/intensity to generate high-contrast faces. Pattern recognition algorithms then detect the head of the occupant by identifying the thermal signature of the human face. The test system was able to correctly detect occupant faces 90% of the time for a variety of occupant postures and head positions, and was reasonably robust at distinguishing between a face and other body parts such as a hand. Detection accuracy was impaired, however, when the face was occluded by a hat or when the only the back of the head could be seen. The researchers were unsure how well the algorithms will perform when subjects have features such as facial hair, are wearing very light or revealing clothing, or are eating and drinking, as these variations were not tested.

OPTICAL / NIR SENSORS

Optical and near-infrared (NIR) sensing methods are arguably the most active area of occupant sensing research. Virtually all major automotive manufacturers and parts suppliers have systems under development, and their research is well represented in the literature. The rapid development of CMOS photodetector arrays has dramatically improved the potential feasibility of optical systems. The latest generation of CMOS cameras for automotive applications offers small size, high performance, and rugged operation at relatively low cost.

Monocular (2D) Systems

Table 5. Monocular (2D) Imaging Systems Features.

Advantages	• Smaller form factor than stereo imagers • Lower parts cost
Disadvantages	• Must be integrated into seat surfaces or located directly overhead • Occupant classification is restricted to using only texture and area-based methods
Development Status	• Prototype
Developer and Manufacturer Interest	• Moderate – systems have been researched Eaton Corp., Siemens, and Delphi
Market Forecast	• Obsolescence to 3D time-of-flight (TOF) imagers predicted

Researchers at Eaton Corporation and the University of Michigan have been investigating the suitability of monocular (single camera) images for an occupancy classification system [22]. Their prototype system uses a monochrome CMOS camera and NIR illumination located in the roof liner of the vehicle along the centerline and near the edge of the windshield. The classification algorithm uses statistical features extracted from a foreground subject, which itself is identified by two parallel edge detection methods. A neural network determines the occupancy class based on the shapes of various area-based features; this occurs every 3-5 seconds. Subsequent efforts [23][24] use a modified method that combines foreground/subject identification with the classification step. This method is claimed to yield faster and reliable identification and classification of vehicle occupants; as shown in Figure 9, the identification of occupants is usually quite precise. A trial of the improved system achieved 91% detection accuracy at speeds of up to 80 times faster than the prior effort. The researchers suggest that the accuracy of the system can be improved by using a larger and more varied training data set.

Figure 9. Raw Image (Left) and Extracted Image (Right) of Passenger [24]

Researchers from Siemens Automotive and LAAS-CNRS examined the feasibility of using 2D area-based methods to locate the head of a passenger seat occupant [25]. Features such as shape and size and relative location in the image frame were extracted by a pattern classification system that was augmented with a priori knowledge of expected head positions. The accuracy of this approach was limited, however, with only a 72% rate of correct head position detection.

A monocular vision-based Interior Protection System from Delphi Automotive includes a single monochrome camera and a NIR illuminator mounted near the rear-view mirror. The active light-emitting diode (LED) and the associated NIR pass filter create a relatively constrained illumination environment that is less sensitive to occupant color and ambient lights. The proposed occupant classification approach consists of image representation and pattern classification. The representation step computes Haar wavelets and edge features from NIR video frames. Based on these representative features, a support vector machine (SVM) classifier next classifies the occupant into five categories including empty seats, adults in normal position, adults out of position, front-facing child infant seats, and rear-facing infant seats. Tests of the prototype system reveal a 97% average correct classification rate [26]. The system is expected to enter production around 2008 [27].

Omnidirectional Imaging Systems

Omnidirectional systems use a special parabolic mirror in conjunction with the imaging camera to obtain a view of the entire vehicle cabin. This type of camera has properties that enable the easy reconstruction of perspective or panoramic views from a single omni-directional image. The pertinent features for this technology are summarized in Table 6.

Table 6. Omnidirectional Imaging Systems Features.

Advantages	• Potential to detect all occupants in cabin
Disadvantages	• Large size • High parts cost • Computationally intensive
Development Status	• Prototype
Developer and Manufacturer Interest	• Moderate – systems have been researched by DaimlerChrysler and Siemens Automotive
Market Forecast	• Wider application foreseen for occupant monitoring and emergency rear seats with side curtain airbags

A novel approach to occupancy detection is demonstrated by researchers with DaimlerChrysler Research and Technologie [28]. This research built on video data collected under the Accident Information and Driver Emergency Rescue (AIDER) project. The AIDER project introduced telematic technologies for gathering and transmitting information about the crash severity and the post-crash state of health of the vehicle occupants, thereby improving the performance of the rescue chain in terms of efficiency and time savings [29]. The test vehicle for the project included a roof-mounted 360° camera that produced a bird's eye view of all passengers. The camera and the resulting image are shown in Figures 10 and 11, respectively. A combination of

Figure 10. AIDER 360° Camera [29]

NIR illumination and a camera-mounted filter was used to provide a consistent lighting source and minimize ambient lighting variations. The classification scheme developed by the researchers is capable of detecting the heads of occupants from front, back, or side views presented in the 360° image.

The omni-directional image is first split into predefined subregions. These subregions are selected a priori to bracket the likely locations where passenger heads and upper torsos are situated in the vehicle cabin. The detection algorithm uses multiple classifier cascades to detect each combination head position within each occupant seating location (subregion), so that each classifier cascade is able to learn both the possible size and the position of the objects that must be detected. The cascades were trained using 300 images of varying numbers of occupants, and the performance of the classifier was evaluated using 600 different images. Results of the test indicate an 85% detection rate with a false alarm ("false positive") rate of 13%. While these initial results are somewhat promising, the computational requirements are fairly high, as each 360° image requires 0.3 seconds to process on a 2.8 Ghz Pentium 4 computer.

Figure 11. AIDER 360° Camera Image [29]

Siemens had been investigating an automotive monitoring system in 2000 that used an omni-directional sensor (a standard camera plus a mirror assembly) mounted in the center of the headliner [30]. Initial experiments used a video stream obtained from the camera and processed offline to investigate the potential for occupant monitoring within the vehicle, as well as monitoring the external surroundings of the vehicle.

Stereo Imaging

Although passive stereo vision is one of the oldest research topics in the computer vision community, its use has been restricted in the past by the large amount of computation required. Beyond the computation issues, stereo suffers from limitations due to the triangulation geometry. Specifically, the trade-off between high resolution (large baseline) and reduced ambiguity in matching (small baseline) is exacerbated in the case of passive systems. Table 7 summarizes the pertinent features of stereo imaging systems.

Table 7. Stereo Imaging Systems Features.

Advantages	• High quality imaging
Disadvantages	• Requires feature such as edges or texture for greatest accuracy • Limited to front seat occupants • More sensitive to ambient lighting changes • Computationally expensive • Line of sight operation
Development Status	• Near-Production
Developer and Manufacturer Interest	• Moderate – systems have been researched by ACV, HRL, Siemens, and TRW
Market Forecast	• May be displaced by 3d TOF systems

Researchers at Advanced Computer Vision recently investigated robust statistical classification algorithms for stereo imaging of the passenger seat, using a set of overhead cameras mounted by the rear-view mirror [31]. Their method is claimed to cope with varying illumination, moving shadows, and changing image contrast, and is equally applicable for active NIR illumination and sufficiently bright ambient lighting conditions. Initial image acquisition is in the form of two intensity images. A fast stereo matching algorithm generates a disparity image, which is in turn used to determine the range map. Relevant features are extracted from these data and evaluated by an occupant classifier. Researchers claim 99% accuracy in distinguishing between child, adult, RFIS, and empty seat categories on a limited test sample of different occupancy and position combinations.

Hughes Research Laboratory researchers have experimented with an active NIR illuminated stereo camera system [32]. The system consisted of two charge-coupled device (CCD) cameras and a pulsed NIR LED illumination source mounted near the rear-view mirror. Consistent illumination and a rejection of ambient lighting variations were accomplished by synchronizing the camera shutters to the short-duration NIR pulses. The three types of features utilized in the system are range, edge densities, and multiple scale redundant wavelets. The researchers claim the system is able to operate at real-time frame rates (30 fps) with classification accuracies of up to 98% for a large variety of situations and lighting conditions. A hierarchical classification scheme is used, where each main class of features is individually analyzed and classified by a neural network. The separate results are then combined using by a “fusion engine” to obtain a final output classification. Both the subclassifiers and the fusion engine are statistical classifiers trained using examples of typical situations and occupants. The researchers cite the advantage of their approach as being able to generate very different features from the same stream of images.

Researchers at Siemens Automotive and LAAS-CNRS experimented with a stereo pair of cameras mounted overhead near the rear-view mirror to monitor the passenger seat area [33][34]. Initial investigations attempted to determine the optimum feature set from a disparity map of the stereo image pair. Subsequent work by Siemens resulted in a prototype system [35], shown in Figure 12. Further development was recommended towards greater miniaturization.

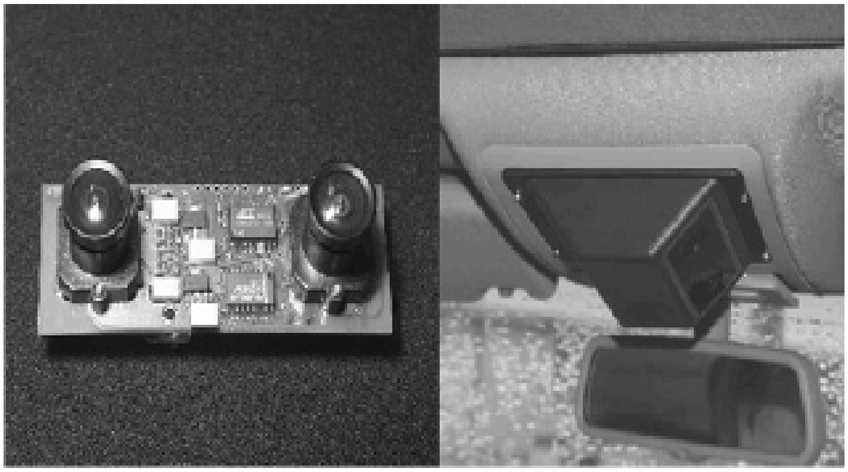

Figure 12. Siemens Stereovision Prototype [35]

TRW's Occupant Sensing System uses a stereo camera to monitor the vehicle passenger compartment from its mounting location in the overhead console, shown in Figure 13 [36]. The system is capable of discriminating between different size occupants and infant seats, and can also perform dynamic out-of-position detection by identifying and tracking the position of an occupant's head in the vehicle. The system had been expected to reach production with 2007 vehicles [37].

Figure 13. TRW Occupant Sensing System [36]

Structured Lighting

Structured lighting is an active stereo vision method which calculates the three-dimensional shape of the object based on the deformation of geometric light patterns projected on the target's surface. This method only requires one camera but needs special lighting equipment. The computation requirements for this method are relatively small; therefore, the method is fast. Structured lighting systems are typically robust to rapid light changes such as sweeping shadows. They are able to process scenes that ordinarily do not contain sufficient features (edges or corners) for reliable stereo matching. The efficiency of a structured lighting system is dependent on several parameters, including the resolution of the sensor and illuminator, the gap between the illuminator and the sensor, the calibration accuracy, the radiance of the beams, and the correct cabin placement for adequate coverage.

The chief advantage of structured lighting also contributes to several of its disadvantages. The greatly reduced amount of image information in a structured light image means that the accuracy and resolution of these systems will be relatively low unless a dense pattern (more information) is used. This may present problems for occupancy classification in the case of complex scenes; e.g., distinguishing between an empty and occupied rear-facing infant seat. The system depends on proper calibration, as the calibration determines the transformation of 2D measurements to 3D positions. Since structured lighting systems project focused laser patterns, a compromise must be struck so that the beams are powerful enough to produce high contrast patterns while presenting a low enough exposure risk to vehicle occupants.

Table 8. Structured Lighting Systems Features.

Advantages	• Immune to nearly all ambient conditions • Computationally cheap and fast
Disadvantages	• Possible eye risk from laser LED exposure • Course depth imaging – poor interpretation of complex scenes • Requires careful setup and calibration • Line of sight operation
Development Status	• Prototype
Developer and Manufacturer Interest	• Low – no current development efforts
Market Forecast	• Obsolete technology

Siemens VDO automotive developed a prototype structured lighting system for classifying vehicle occupants [35]. The ATSOS prototype used a 20 × 20 array of NIR laser LEDs to project a dot pattern onto the passenger seat area. The pattern was monitored by a CCD camera, with 3D reconstruction occurring every 30 milliseconds. Both the illumination source and the camera were located overhead near the rear-view mirror. An illustration of the ATSOS concept is shown in Figure 14. Initial results showed that the system was able to give a good approximation of the volumetric distribution for an occupant within the observed scene. Distance resolution for the system was reported as within 2 cm. No further development has occurred since 2001, however.

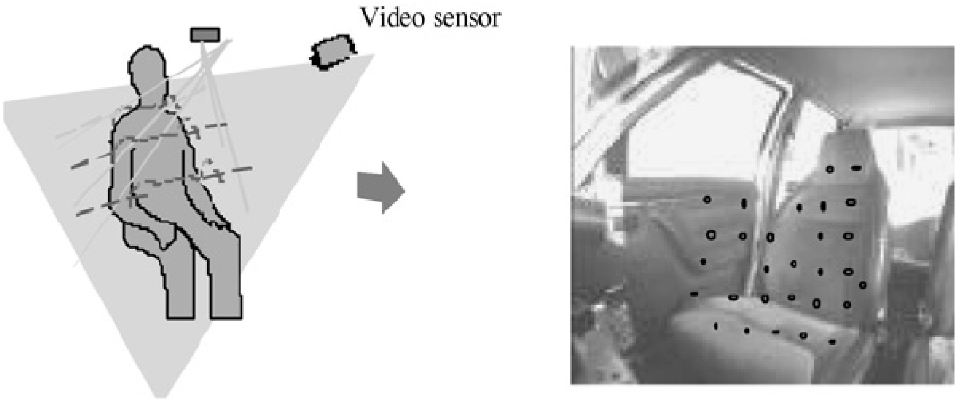

Figure 14. Siemens ATSOS System Principle [35]

The Occupancy Detection System (ODS) from TEMIC (now part of ContiTEMIC) is another example of a prototype structured lighting system [38][39]. The ODS used two in-line patterns of dots projected along different planes of the passenger seating area. The intersection of these LED lines with an occupant produced two contour images that were detected by a CCD array and compared to a stored image of an unoccupied seat. This system also employed a differential detection measuring method to eliminate environmental illumination interference. In operation, two measurements were obtained for the seat contours – one under ambient lighting conditions, then another with LED illumination. The subtraction of the external illumination permitted the system to determine the actual occupant category without these environmental influences. Further work on this system appears to have ceased after 1999.

Researchers at the Fraunhofer Institute of Microelectronic Circuits and Systems described a more limited application of structured lighting employing a dashboard-mounted system [40]. Their proposed method used a light striping technique to generate a range image of the passenger seat area. A NIR laser diode provided pulsed illumination, which was passed through collimating and cylinder lenses to generate a fan-shaped beam. A CMOS camera system monitored the seat area. The fan-shaped beam appeared as a stripe in the image plane, and changes to the contour of the stripe were used to determine the distance between an occupant and the dashboard. Narrow band filtering of the camera restricted its sensitivity to the wavelength of the laser beam; this was used to minimize intensity variations arising from changing ambient lighting conditions.

The Occupant Position and Recognition System (OPRS) developed by Delphi Automotive Systems [41] used an array of infrared light to monitor the head position of the passenger seat occupant. Mounted near the rear view mirror, the system was reported capable of discriminating between a head and a hand [2]. This system does not appear to have advanced beyond the prototype stage.

Shape from Silhouette (Volumetric Modeling)

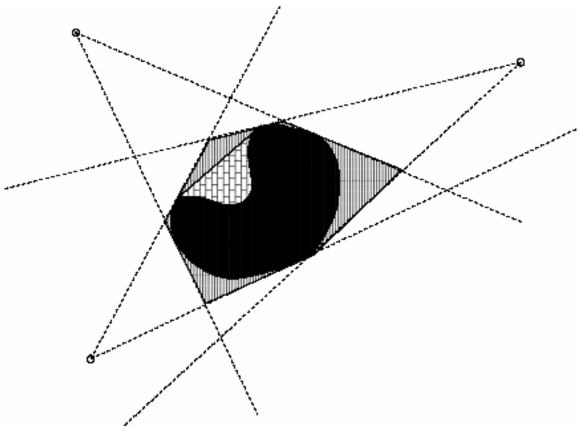

Figure 15. Shape-from-Silhouette Reconstruction Principle [42]

Shape-from-silhouette (SFS) is a volumetric reconstruction technique which uses multiple silhouettes of an object to create an approximate three dimensional representation within a defined scene volume [42]. Coordinates within this volume are represented by voxels – discrete volume elements obtained by subdividing the scene volume into cubes. The reconstructed volume only approximates the true 3D shape, depending on the number of views, the positions of the viewpoints, and the complexity of the object. Figure 15 illustrates the concept for three cameras, where the black region is the actual object, and the gray shaded region is the reconstruction.

Table 9. Shape-from-Silhouette Imaging Systems Features.

Advantages	- Accurate biometric measurements
Disadvantages	- Computationally very expensive - Limited sensing range - More sensitive to ambient lighting changes - Requires multiple cameras for a single seat
Development Status	- Proof of concept
Developer and Manufacturer Interest	- Low – research only
Market Forecast	- Poor in the near term

Researchers at University of California San Diego have been investigating this volumetric reconstruction technique for the purpose of determining vehicle occupant position and posture [43][44]. Four color cameras were used to obtain different images of the passenger seat occupant; these were located in the middle of the dashboard near the windshield, near the passenger side-view mirror, overhead near the rear-view mirror, and above the passenger window. To partially address the issues of volatile lighting conditions, the system used a statistical background subtraction technique in which features of an unoccupied passenger seat scene are stored. This information is used to distinguish background elements (seat, windows) from a foreground body when the seat is occupied; the outcome of this processing is shown in Figure 16. The automatic model acquisition proceeds in two steps; first, initial estimates of body part sizes and locations are found, using a heuristic procedure that incorporates knowledge about average shapes and sizes of the body parts. These estimates are then refined and combined, using an iterative fitting scheme that assembles a model of the head and upper torso based on the known proportions of the human body. Figure 17 illustrates the results for head and torso reconstruction for a sequence of image sets in which a passenger rocks side-to-side (top row) and sits back from a forward leaning position (bottom row).

Figure 16. SFS Foreground Segmentation [44]

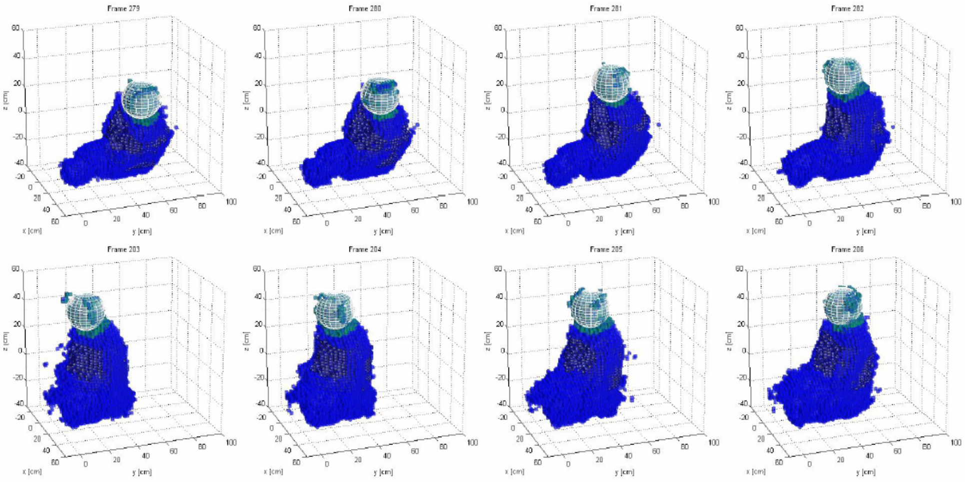

Figure 17. Spherical Shell Heuristic (SSH) Reconstruction of Seat Occupant [44]

The system was tested using 300 image sets which included various head orientations in combination with forward-leaning and seated-back body positions. For this initial test, only head detection was performed in real time (7 images/second); full upper body reconstruction occurred off-line. Head detection results indicated 94% correct identification. No further development appears to have occurred past the last published results in 2004.

3D Time-of-Flight (TOF) Imaging

3-D optical time-of-flight imaging methods are a type of range measurement. These methods employ active sources (mostly lasers) that emit either short pulses or continuous wave modulated beams and evaluate the delay or phase shift of the beam reflected from a distant object. The general principle of the TOF measurement is described in [45]. A sensitive photodiode imaging array with a high-speed synchronous electronic shutter is synchronized to a NIR laser diode illumination source. The NIR source generates extremely short duration pulses (on the order of nanoseconds) which illuminate the entire imager field of view. The amount of the received light at the image sensor depends on synchronous timing of the laser diode, reflectance of the objects in the scene, the travel time of the pulse, and the shutter switch timing. Note that the received light contains not only the reflected laser pulse, but the level of background illumination as well. The reflectance of the target object also exerts an influence on the measurement. For these reasons at least three exposures are required. The first measurement uses a long opening of the shutter without NIR illumination to determine the level of background illumination. The second measurement is taken under active NIR illumination with the shutter duration longer than the length of the light pulse in order to measure the total illumination from direct and early reflected sources. Finally, a measurement is taken with the shutter synchronized to open only during an illumination pulse, thereby measuring just the direct illumination intensity only. The two actively illuminated measurements can be subtracted to obtain the reflectance of the targeted object. This process is illustrated in Figure 18. For pulses lasting just several nanoseconds, a higher power laser can be employed which still meets laser class 1 eye safety regulations. Note that short shutter times minimize the effect of background illumination as well.

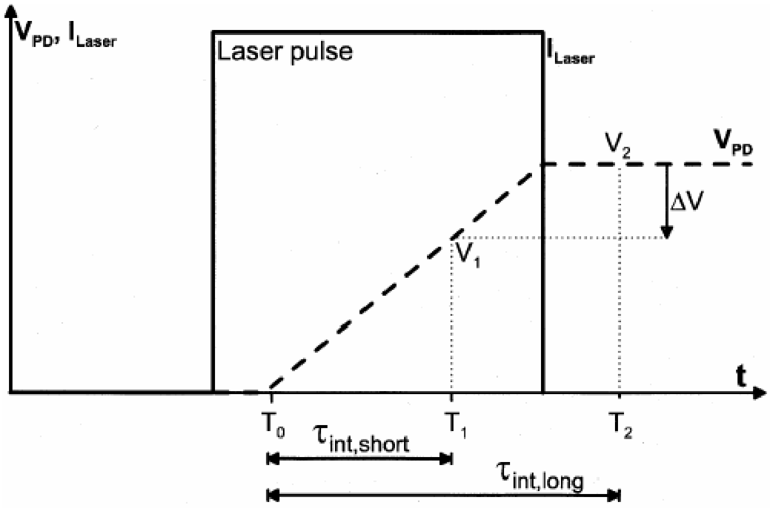

Figure 18. Siemens 3D TOF Camera Principle [45]

TOF-based 3D sensors work reliably on textured and non-textured surfaces, they work regardless of the ambient lighting conditions, and they can be packaged in a small form factor since they do not require a baseline.

The time of flight sensor is different from other depth sensors in various ways, and more suitable for an occupant classification system. First, the system can work in both day and night, regardless of ambient lighting conditions. Second, unlike stereo, it is texture independent. Similarly, the system does not necessitate a baseline between the light source and the camera, and as such there are no parallax shadows. The depth calculation is done in the CMOS circuitry, freeing up central processing unit (CPU) time for application level processing. It uses diffused floodlight, as opposed to structured light. This provides an advantage over structured light systems, since there is no moving light part and no eye safety problem. Finally, the depth sensor is implemented on a CMOS chip, and this provides a small, inexpensive, and relatively high resolution depth sensor for an occupant classification system.

Table 10. 3D Time-of-Flight Imaging Systems Features.

Advantages	• Deals well with complex scenes • Immune to nearly all ambient conditions • Compact form factor • Low parts cost
Disadvantages	• Line of sight transmission
Development Status	• Pre-production
Developer and Manufacturer Interest	• Large – systems have been researched by Fraunhofer/Siemens, IEE, Canesta, DaimlerChrysler/Conti Temic
Market Forecast	• Wide application foreseen

Progress in the CMOS microelectronics is now enabling the production of very compact, integrated TOF sensors suitable for integration into the vehicle cabin. A system from Siemens VDO Automotive is nearing production [35]; it consists of a short integration time (SIT) camera and a pulsed NIR illuminator located near the rear-view mirror. The SIT camera, developed by the Fraunhofer Institute for Microelectronic Circuits and Systems, operates on the principles described above and is capable of 1.5 cm resolution in near-field applications. The system can determine the location, shape, and size of the passenger occupant. Advantages claimed for the system are fast operation, insensitivity to ambient lighting conditions, and small form factor.

A TOF imager developed by IEE uses a slightly different approach for obtaining range information, in that the scene is broadly illuminated by a modulated NIR LED light beam instead of pulsed NIR. This modulated beam is reflected by an object and detected by the CMOS imager. Due to the travel time of the light to and from the target, the phase of the reflected beam is retarded compared to the phase of the modulation signal in the transmitter, as shown in Figure 19. This phase delay can be measured and directly converted into the distance between the target and the camera. A modulation frequency of 20 MHz is used, which allows the system to determine distances with an accuracy of 1 cm for objects up to 7.5 m distant; in practice, the range is limited by the intensity of the illumination [46]. Figure 20 graphically illustrates the distance map created from a seated adult passenger; the nearest points appear blue in the map.

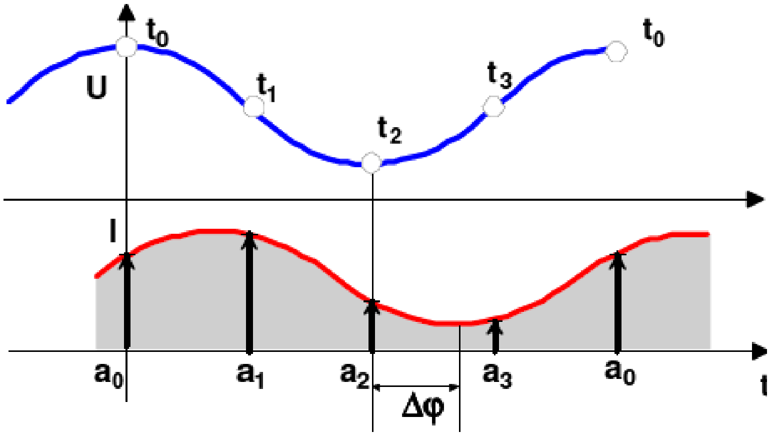

Figure 19. IEE 3D-TOF Camera Principle [47]

The system is capable of performing both occupant classification and occupant head position, depending on the intended application [46][47]. The most recent test results for system performance indicate near 100% accuracy in classifying occupants [48] and an ability to track head movement at 25 fps [46].

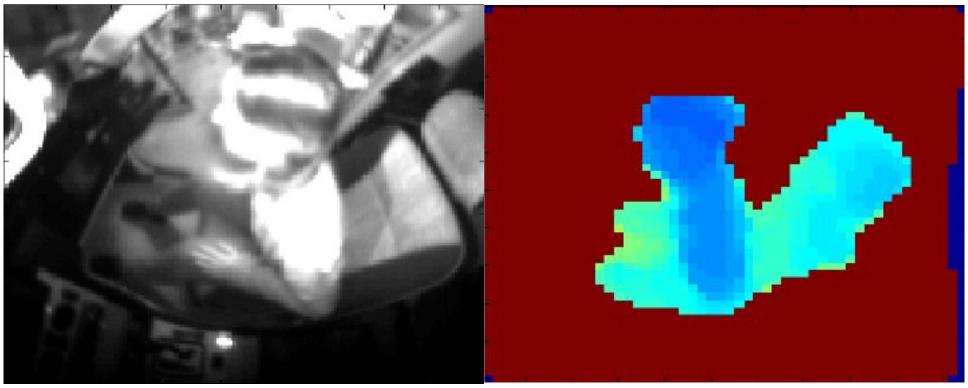

Figure 20. Adult Passenger (Left) and Distance Map (Right) [47]

Researchers at Canesta have also developed a TOF imager that determines distances from the phase delays between original and reflected NIR signals [49]. The imager incorporates a bandpass filter and noise reduction algorithms to minimize artifacts caused by ambient light. In limited testing the system correctly classified over 98% of vehicle occupants.

DaimlerChrysler and Conti Temic are also developing a TOF imaging system that functions similarly to the IEE system [50].

BIOMETRIC SENSORS

The Bone Scanning for Occupant Safety (BOSCOS) project, funded by the UK Department for Transport, investigated methods whereby car occupants, on entering the vehicle, could be measured to assess their skeletal condition and the restraint system parameters adjusted specifically for their biomechanical limits [51]. A consortium of two research institutes (Cranfield Impact Centre and Nissan Technical Centre Europe), two universities (Cranfield and Loughborough), two restraint system manufacturers (Autoliv and TRW Automotive), and an ultrasound equipment manufacturer (McCue) collaborated on the project.

An initial prototype ultrasound device for scanning the index finger was developed and used during the course of the project alongside existing clinical scanning techniques, where ethical considerations permitted. The prototype was evaluated for suitability as the basis for an in-vehicle scanning system and no insurmountable difficulties were encountered.

SMART CARDS AND READERS

Personal data about a vehicle occupant could be held on a “smart ignition key” or “smart card” which is carried by the occupant and locally sensed in the vehicle.

TELEMATICS FOR IN-VEHICLE OCCUPANCY VERIFICATION

Any in-vehicle system will require some means of communicating occupancy information to a roadside reader. There also needs to be a way to retrieve occupancy information from the airbag control system. By far the biggest unanswered technical question for in-vehicle detection systems is whether the information used by the airbag system to classify occupants can be easily retrieved for enforcement purposes. In the ideal case, this information would be obtained through a standardized querying protocol which would allow cross-platform/manufacturer compatibility. However, it may also be the case that such information is “trapped in the black box,” so to speak, or the means of obtaining the information are unique to each manufacturer.

Over the longer term, Digital Short Range Communications (DSRC) will eventually provide a high-speed data link between vehicles and roadside infrastructure. The first production vehicles equipped with this technology are expected after 2008, with widespread availability occurring towards the end of the next decade. A possible future scenario might involve some sort of subscriber-based application, whereby potential HOV users permit vehicle occupancy data to be transmitted to verification readers as a condition of using the facility. In the interim, occupancy information will most likely need to be automatically programmed for each trip into a rewritable transponder that could be read by existing automatic vehicle identification (AVI) infrastructure.

New standards for networking interrelated vehicle systems, such as Safe-by-Wire, Flexnet, etc., should be investigated to determine if these networks can accommodate, or at least not preclude, occupancy enforcement applications/features.

IN-VEHICLE OCCUPANCY DETECTION DRAFT FUNCTIONAL REQUIREMENTS

The functional requirements for an in-vehicle occupancy verification system are shown in Table 11.

Table 11. Draft Functional Requirements for In-Vehicle Occupancy Verification Systems [52].

Attibute	Mandatory Functions	Desirable (Secondary) Functions
Accuracy	Count to see that the number of vehicle occupants equals or exceeds the threshold figure for the facility it is using.	Count all vehicles and all occupants in those vehicles
		Recognize the current threshold figure for each HOV facility (i.e. 2+ or 3+, time of operation)
	Precisely count all seated occupants in vehicles including small children, children in child seats, etc.	Precisely count all occupants in the vehicle including any hiding (e.g. in luggage compartments etc.)
	Precisely recognize non-compliant vehicles and positively identify vehicle registration	
	No false readings (animals, dummies, etc.)	
Reliability	Low rate of "down time"	Tamper-proof
Economy	Capital cost per vehicle less than say ($100?).	Minimal instrument/equipment requirements for new HOV lane infrastructure
	Minimal cost to the individual user	Similar cost to retrofit operating vehicle as for a new vehicle
Utility	Monitoring frequency high enough to discourage evaders	Continuous monitoring rather than point recognition
Privacy	Recognize vehicle, not occupants (per privacy protection)	
Design	Monitor and transmit occupancy data at speeds ranging from 0 to 150 km/h	
	Monitor and transmit occupancy data in all kinds of weather, light, roadway, and traffic conditions	
	Unobtrusive to users	Invisible to users
	Automated – requires no action on the part of vehicle occupants	Feedback to driver (e.g., dashboard light confirming registered number of occupants)
	Minimal additions/changes to vehicle equipment	Can be easily retrofit to existing vehicles

IN-VEHICLE OCCUPANCY DETECTION STATE OF THE PRACTICE

Potentially the most cost-effective approach to in-vehicle occupancy detection involves leveraging the capabilities of advanced airbag systems. Current federal regulations will require 100% new vehicles to have these systems by 2009. These systems must be capable of reliably detecting and classifying front seat occupants. All of these systems will utilize weight/pressure sensors in conjunction with one or more non-contact sensing methods to achieve this. Some examples of systems in or near production include the following:

- Autoliv and Automotive Technologies Intl. have developed a system using weight and ultrasonic sensors. This system is standard equipment on the Jaguar XJ series.

- Siemens and International Electronics and Engineering (IEE) are developing a system utilizing seat pressure sensors and a 3D “time of flight” monocular camera. Similar systems are also being developed by TRW and Advanced Computer Vision (ACV), Daimler Chrysler and Conti TEMIC, Robert Bosch, and Delphi Automotive.

- Elesys (jointly owned by Honda and NEC) has a system that uses pressure sensors in the seat cushion and electric field sensors in seatbacks.

In addition, as rear side cushion airbags become more prevalent, occupant position sensors are increasingly likely to be incorporated into rear seatbacks. Electric field sensors seem the most likely candidate for this application. It is therefore conceivable that over the next decade, most vehicles will include systems which can detect both front and rear passengers.

IN-VEHICLE OCCUPANCY DETECTION OUTSTANDING ISSUES

Limited Coverage for Rear Occupants

All current occupancy detection systems are being developed exclusively for front passengers. While the classification of rear occupants may eventually occur, it is not a near-term federal requirement, and will depend on whether rear side-curtain airbag systems become commonplace.

Most of the technologies that are likely to be employed for rear occupants will primarily be concerned with occupant position (to mitigate potential injury to an out-of-position occupant’s head, for example). Promising technologies for this application include electric field and capacitance sensors, which are relatively inexpensive and can be incorporated into vehicle seatbacks. These sensors could not be easily added as an aftermarket item, however, as they would at minimum require the disassembly of the rear seat.

Accessibility of Occupancy Information

By far the biggest unanswered technical question for in-vehicle detection systems is whether the information used by the airbag system to classify occupants can be easily retrieved for enforcement purposes. In the ideal case, this information would be obtained through a standardized querying protocol which would allow cross-platform/manufacturer compatibility. However, it may also be the case that such information is “trapped in the black box,” so to speak, or the means of obtaining the information are unique to each manufacturer.

Opportunities may possibly exist to encourage the more positive case, as new standards for networking automotive occupant safety systems are currently being developed. In particular, the Safe-by-Wire Plus initiative is perhaps the largest effort among leading automotive systems and component suppliers (Analog Devices Inc, Autoliv Inc., Delphi Corporation, Key Safety Systems, Philips, Special Devices Inc., TRW Automotive, Bosch, Siemens VDO Automotive, and Continental Temic to define a global standard.

Transmission of Occupancy Information

The transmission of occupancy information to roadside infrastructure is an open research question. The implementation of consensual occupancy verification applications within the DSRC framework will depend on the effective advocacy by stakeholders. Shorter-term communication solutions may also be technically feasible, and should be encouraged as well.

Limited Penetration and Retrofit Potential

Assuming the above communications questions could be adequately addressed, it will still be many years before the majority of vehicles on the road come equipped with in-vehicle systems. It is doubtful that older vehicles can economically be retrofit for this capability, unless original equipment manufacturer (OEM) systems can be readily adapted for very low per-vehicle costs. It is therefore likely that in-vehicle based systems can only be used as supplementary enforcement tool over the near term.

ROADSIDE OCCUPANCY DETECTION SYSTEMS

Technologies for vehicle occupancy detection have been developed and tested over nearly two decades. Since vehicle occupancy detection systems are not currently employed on HOV or HOT facilities, this section surveys the various development efforts and in this area, and includes other possibly pertinent technologies. Table 12 compares the principal benefits and drawbacks inherent to each technology.

Table 12. Comparison of Technologies for Roadside Vehicle Occupancy Detection.

Technology	Benefits	Drawbacks
Video	• Commercially available systems	• Poor resolution • Inferior to visual inspection • Unusable in low lighting
Infrared	• Usable under all lighting conditions	• Not developed past custom prototype • Cannot penetrate metallic window tint • Cannot distinguish human skin from other objects of similar temperature • Expensive
Multi-band Infrared	• Can distinguish unique infrared (IR) signature of human skin • Usable under all lighting conditions • Can potentially operate autonomously	• Not developed past custom prototypes • Cannot penetrate metallic window tint • Extremely expensive
Microwave	• Usable under all lighting conditions	• Slow imaging speed • Poor resolution • Cannot penetrate metallic window tint • Extremely expensive
Ultrawideband Radar	• Commercially available systems	• Slow imaging speed • Poor resolution • Inadequate range • Cannot penetrate metallic window tint

VIDEO SYSTEMS

Video systems have been deployed in the past for vehicle occupancy verification. While video continues to serve a useful role in HOV facility monitoring, it has not proven adequate for the task of vehicle occupancy verification. The collective experience from several studies and implementation projects has concluded that video methods are not as reliable as live visual inspection. Further details of these projects are provided below.

The use of video in HOV lane surveillance and enforcement was tested in Los Angeles and Orange County, California, in 1990 [53]. Multiple cameras were used to obtain three or four different views into vehicle cabins, and displayed on split-screen monitors. The study concluded that video cameras operating alone cannot identify the number of vehicle occupants with enough certainty to support citations for HOV lane restrictions. Over one-fifth (21 percent) of vehicles identified by videotape reviewers as violators actually had the proper number of occupants. The high false alarm rate was primarily due to the inability of the cameras to capture small children or sleeping adults in the rear seat of vehicles and was made worse by poor light conditions, glare, and tinted windows.

In 1995, The Dallas Area Rapid Transit and the Texas Department of Transportation (TxDOT) tested the use of real-time video and license plate reading for HOV lane enforcement on the I-30 HOV lanes in Dallas, Texas [54]. The high-occupancy vehicle enforcement and review (HOVER) system employed three-way views of vehicle cabins and license plate recognition (LPR) to record occupancy and vehicle identification. Enforcement agents reviewed the archived images to identify HOV violators. An effectiveness study of the HOVER system revealed that the video and LPR implementation failed to achieve the necessary image quality and accuracy for effective enforcement screening.

Another application of video enforcement, the I-15 Congestion Pricing Project in San Diego, California, initially used gantry-mounted video cameras to provide a record of single-occupancy vehicle (SOV) violators on the carpool-only lanes of the Express Lanes facility. Operators were required to review the videotape and provide a count of SOVs using the Express Lanes. Problems with the video system, however, led to its elimination in 1998. In their 2001 report on enforcement effectiveness, San Diego State University researchers reported that the operators could not reliably distinguish SOV violators on the videotapes and found it difficult to discern the number of vehicle occupants, especially for those in back seats [55].

INFRARED SYSTEMS

No occupancy detection systems based on infrared imaging have ever been implemented on HOV facilities, although a few recent field tests have been conducted. The primary potential benefit offered by infrared systems is the ability to operate in darkness as well as daylight. Infrared systems operating in sufficiently long wavelengths can utilize camera illumination that is outside the visible light range and that consequently would minimize driver distraction. Infrared systems otherwise suffer from many of the same shortcomings as conventional video, especially with respect to heat-blocking or metallic vehicle window tint. Infrared systems are also substantially more expensive than conventional video systems, with costs for a single infrared camera starting in the mid four figures.

Georgia Tech Research Institute (GTRI) developed a roadside infrared vehicle monitoring system for the Georgia Department of Transportation in 1998 [56]. Designed for counting the number of occupants in vehicles passing by at highway speeds, the prototype consisted of a computer-assisted infrared imaging system, utilizing a single near-infrared camera illuminated by an infrared light source. The system was contained in a roadside-mounted camera/processing unit that captures side views of passing vehicles; both the camera and illumination were triggered by radar. A field test of the prototype demonstrated its ability to capture images of vehicles at speeds up to 80 mph. A qualitative assessment of system accuracy involved a real-time comparison with visual observation. Researchers found that the system was superior to visual inspection at identifying rear passenger occupants. The Georgia Department of Transportation ultimately declined further development, and to date, no further work has been undertaken.

MULTI-BAND INFRARED SYSTEMS

In 1998, the Minnesota Department of Transportation and researchers from Honeywell and the University of Minnesota developed a machine vision system for vehicle occupancy detection, utilizing a pair of synchronized NIR cameras to capture dual-band NIR images [57]. The system exploited the infrared (IR) reflection characteristics of human skin. By imaging two infrared bands and generating a differential image (the difference in brightness between corresponding pixels of the two images), the system could isolate the signature of human skin from that of other materials in the vehicle cabin. In operation, the synchronized IR cameras took snapshots of the road scene when triggered by vehicle-detection radar. An image processing and classification system subsequently extracted and counted the number of larger regions of skin in the differential image to estimate the number of vehicle occupants. Researchers conducted a field test of the system in February 2000 [58]. Vehicles containing one or two front seat occupants were driven at 50 mph under both daylight and nighttime conditions. The prototype captured images through the windshield, and the resulting automated occupancy counts were compared to those obtained by visual inspection. Researchers reported 100 percent correct identification of the number of occupants by the system for a randomly selected subset of 100 images. No further development has occurred since the limited field test.

In 2003, the U.K. Department of the Environment, Transport, and the Regions funded a three-year research project to develop an automated vehicle occupancy camera detection system began in Leeds, United Kingdom. The resulting Cyclops system uses visible and near-infrared wavelengths to count vehicle occupants through the front windshield of oncoming vehicles at highway speeds. Like the Minnesota effort, Cyclops exploits the near-infrared absorption properties of human skin; a combination of the visible and NIR images yields a skin signature that contrasts with its surroundings and can be recognized immediately by processing software. Software algorithms then filter the detected skin regions to remove any non-facial features in the scene, and enumerate the isolated “faces.” The occupancy count is overlaid on the final image, along with time stamp and location information.

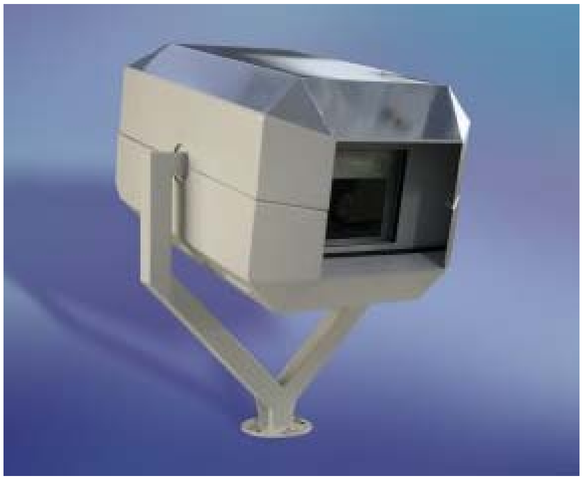

Figure 21. Cyclops Vehicle Occupancy System [60]

Tests of the Cyclops system on the United Kingdom’s first HOV lane (on A467 in Leeds) were conducted in 2005; results indicated a 95 percent success rate in detecting real people and rejecting decoy information such as hands or dummies [59]. Additional trials were recently completed near Edinburgh, Scotland; if successful, the Cyclops system will be used to automatically discriminate high- and low-occupancy vehicles for differential tolling. The trials come before the introduction next year of automatic electronic tolling on the Forth Road Bridge in 2007. That system, while charging peak and off-peak tolls, will also give discounts based on the number of occupants in the vehicle. The Forth Estuary Transport Authority is jointly funding the test with the Scottish government. The cost of a Cyclops installation providing single-lane coverage is estimated to be $165,000.

PASSIVE MICROWAVE SYSTEMS

Passive microwave systems generate imagery from the natural radiation emitted and reflected by the environment. They operate in similar fashion to infrared thermal imagers but use the longer wavelengths in microwave spectrum. Passive microwave systems are able to detect emissions through plastic and other thin, non-conductive material. Some disadvantages of passive microwave systems are their very large size and high cost. The imaging speed of passive systems is relatively slow, as the imager needs time to accumulate sufficient amounts of microwave energy for a good "exposure." The long wavelengths used by this method means that image resolution will be relatively coarse.

A passive microwave system called Joanna has been monitoring stowaways attempting to cross the Channel Tunnel by concealing themselves in the cargo bed of commercial trucks [61]. In Europe 90% of trucks have non-metallic sides and are transparent to microwave radiation, so the 35 GHz linescan (series of detectors) imaging system can be used to detect stowaways hidden in the rear cargo bed. A video-based sensor is used to provide vehicle speed information to the passive microwave linescan system, allowing a microwave image to be built up as the vehicle passes. Contrast is increased by the used of a large reflector panel on the opposite side of the vehicle to the sensor. The linescan operation of the system does not require passing vehicles to stop, allowing all non-metallic sided vehicles to be scanned with minimal interference to flow patterns. The system has achieved considerable success since it entered operation, detecting several hundred stowaways per month.

ULTRAWIDEBAND (UWB) RADAR SYSTEMS

The very short pulse-length of UWB (typically 1 ns) makes it possible to build radar with better spatial resolution and very short range capability relative to conventional radar. UWB pulses generate a wide range of frequencies which are directionally beamed into an area. The pattern of absorption and reflection across this frequency range by materials within the scanning area is sensed by the instrument; this pattern depends on the types of materials being probed and their distances from the instrument. The ultra-wideband device then constructs a representation of the scanned area based on the strengths of the various reflected frequencies and their correspondence to known substances. Typically, hundreds or thousands of such pulses are necessary to gather sufficient information for reliable detection; this occurs within a fraction of a second.

The chief weakness UWB systems are their inability to penetrate any metallic barriers. This severely compromises their use in vehicle occupancy detection settings, where passengers must be sighted though windows surrounded by sheet metal. The presence of metallic window tints, which are already a popular window tinting option, also blocks UWB emissions. UWB devices are also not appropriate for use in high-speed image acquisition, as they require one-third to one-half second to complete the imaging process. They realistically cannot be expected to accurately image anything moving faster than roughly 20 mph. Changes to Federal Communications

Commission (FCC) rules in 2002 also severely reduced the allowable power levels for UWB devices, greatly restricting their effective detection range.

Companies offering UWB products include Camero [62], Cambridge Consultants [63], and Time Domain Corp. [64].

ROADSIDE OCCUPANCY DETECTION PERFORMANCE REQUIREMENTS

Roadside systems must necessarily use remote methods to detect vehicle occupants, and have considerably less options with respect to sensor technologies than is the case for in-vehicle systems. All roadside occupant detection systems must overcome significant obstacles which have thus far limited their effectiveness. Purely considering sensing technologies, the main challenges can be categorized as follows:

- Cabin penetration
- All weather and night-time operation
- Good image resolution
- Fast image acquisition
- Vantage point

The performance of each technology with respect to these criteria are summarized in Table 13.

Table 13. Performance Comparison Roadside Occupancy Detection of Technologies.

Desirable Property	Visible Light (Passive)	Near Infrared	Thermal Infrared	UWB Radar	Microwave
Not blocked by tinted vehicle windows	N	Y	N	N	N
Capable of all-weather and night-time operation	N	Y	Y	Y	Y
Capable of resolving vehicle cabin details	Y	Y	N	N	N
Fast enough to capture vehicles moving at freeway speeds	Y	Y	Y	N	N

To satisfy the requirement of 24-hour operation, nearly all roadside systems must employ active illumination. The exception to this rule occurs with thermal and microwave sensors, which measure the direct radiated heat of the subject. The vantage point for a roadside detector must be chosen to optimize the view into the vehicle cabin. Additionally, roadside systems can only detect unobstructed occupants, which may be difficult in the case of rear-facing infant seats, smaller rear seat occupants, or occupants “curled up” sleeping in the back seat. Additionally, the two most significant development efforts into automated occupancy detection systems have focused on through-the-windshield monitoring, which is only effective for detecting front seat occupants.

From Table 13, it is apparent that the infrared range holds promise for a roadside occupancy detection system. Specifically, a major portion of the reflected-infrared range, the so-called near-infrared range (0.7–2.4 μm) is suited for the application at hand. If this near-infrared range is split into two bands around the threshold point of 1.4 μm, the lower band (0.7–1.4 μm) and the upper band (1.4–2.4 μm), then vehicle occupants will produce consistent signatures in the respective imagery. In the upper band imagery, humans will appear consistently dark irrespective of their physical characteristics and the illumination conditions. In the lower band imagery, humans will appear comparatively lighter. This is because human skin appears to have very high reflectance just below 1.4 μm but very low reflectance just above 1.4 μm

ROADSIDE OCCUPANCY DETECTION STATE OF THE PRACTICE

Roadside occupancy detection systems have been investigated for over two decades. It is only within the last several years that sensor technologies and image processing methods have matured sufficiently to offer a potentially viable approach to the problem.

Sensor Technologies

Roadside detectors are restricted by the type of sensing technology they can employ. Radar systems are not appropriate, as a vehicle’s metal chassis creates too much interference to effectively image anything inside the vehicle. Visible light systems cannot be used at night, since any supplemental illumination would pose a hazard to drivers.

Infrared sensors, especially those sensitive to near infrared wavelengths, have near ideal properties for seeing into vehicle interiors. Near infrared sensing is not affected by weather conditions such as rain, fog, or haze. For use in darkness, near infrared systems can employ supplementary infrared illumination which is invisible to drivers. Most notably, the reflection characteristics of human skin change significantly in the near-infrared region, being highly reflective at shorter wavelengths and almost completely absorbent at longer wavelengths.

Infrared sensors have until recently been prohibitively expensive, requiring integrated mechanical systems for cooling and image scanning. Advances in semiconductor manufacturing are now yielding faster and cheaper sensor arrays which either require no cooling or can be cooled by solid state methods (thermoelectric). Such sensors offer great promise in terms of their speed and mechanical reliability.

Image Processing

The principal image processing problem in roadside occupancy detection has traditionally been reliable segmentation of occupants from other objects in the vehicle cabin. Near infrared fusion techniques have been demonstrated to isolate the “signature” of human skin, making this an ideal method for detecting the faces of vehicle occupants. This method combines short- and long-wavelength infrared images to create a composite image. The pronounced difference in skin reflectance between the two infrared bands results in a unique feature that is readily distinguished from the rest of the vehicle cabin.

No Systems in Current Production

While the potential for roadside occupancy detection systems has never been greater, no system has yet entered commercial production. Currently, the only system in development is the Cyclops system from Vehicle Occupancy Ltd. Results from field trials of this system indicate that additional improvements are needed before the system can be considered sufficiently accurate and reliable.

ROADSIDE OCCUPANCY DETECTION OUTSTANDING ISSUES

Visibility of Hidden Occupants

While active infrared sensing technologies offer the ability to reliably see inside a vehicle, roadside detection systems still must contend with the "vantage point problem." A system can only see unobstructed occupants, which may be difficult in the case of rear-facing infant seats, smaller rear seat occupants, or occupants "curled up" sleeping in the back seat. Additionally, the two most significant development efforts into automated occupancy detection systems have focused on through-the-windshield monitoring, which is only effective for detecting front seat occupants.

The Georgia Tech Research Institute's occupancy detection prototype demonstrated that side window image acquisition of vehicle occupants was possible at highway speeds. However, the GTRI prototype was a single camera, non-automated system. It is not known whether an infrared fusion scheme would have similar success.

Funding/Research Interest

With the exception of Cyclops roadside occupancy detection system, no other current development efforts have been uncovered. In contrast, at least seven major parts suppliers and their research partners are developing in-vehicle systems, although these systems are not specifically targeted at enforcement applications. In the absence of any clear indication of potential markets, development efforts for roadside systems constitute a substantial financial risk, since it is likely that several years of effort are yet required before a viable roadside system can be brought to market. HOT lanes and managed lanes may be able to play an important role in establishing a viable potential market, however.

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