1. Vehicle detectors

There is a wide range of sensor technologies available for vehicle detectors. Some of the most common and some developing technologies are described in this section.

1.2 Video Image Processors

A video image processor (VIP) is a combination of hardware and software which extracts desired information from data provided by an imaging sensor. This imaging sensor can be a conventional TV camera or an infrared camera. A VIP can detect speed, occupancy, count, and presence. Because the VIP produces an image of several lanes, there is potential for a VIP to provide a wealth of traffic information such as vehicle classification and incident detection. A VIP generally operates in the following manner: the operator selects several vehicle detection zones within the field of view (FOV) of the camera. Image processing algorithms are then applied in real time to these zones in order to extract the desired information, such as vehicle speed or occupancy.

Advantages of VIPs are that they are mounted above the road instead of in the road, the placement of vehicle detection zones can be made by the operator, the shape of the detection zones can be programmed for specific applications, and the system can be used to track vehicles. Disadvantages are the need to overcome detection artifacts caused by shadows, weather, and reflections from the roadway surface. The disadvantages can be overcome through design and installation of the hardware and design of the software algorithms.

1.3 Infrared Detectors

There are two types of infrared (IR) detectors, active and passive. Active infrared sensors operate by transmitting energy from either a light emitting diode (LED) or a laser diode. An LED is used for a non-imaging active IR detector, and a laser diode is used for an imaging active IR detector. In both types of detectors the LED or laser diode illuminates the target, and the reflected energy is focused onto a detector consisting of a pixel or an array of pixels. The measured data is then processed using various signal-processing algorithms to extract the desired information. Active IR detectors provide count, presence, speed, and occupancy data in both night and day operation. The laser diode type can also be used for vehicle classification because it provides vehicle profile and shape data.

A passive infrared system detects energy emitted by objects in the field of view and may use signal-processing algorithms to extract the desired information. It does not emit any energy of its own for the purposes of detection. Passive infrared systems can detect presence, occupancy, and count.

Some of the advantages of infrared detectors are that they can be operated during both day and night, and they can be mounted in both side and overhead configurations. Disadvantages are that infrared detectors can be sensitive to inclement weather conditions and ambient light. The choice of detector materials and construction of the system, as well as sophisticated signal processing algorithms, can compensate for the disadvantages.

1.4 Ultrasonic detectors

Ultrasonic detectors have not become widely used in the United States, but they are very widely used in Japan. Japan uses ultrasonic detectors in traffic applications as much as the U. S. uses inductive loop detectors in traffic applications. There are two types of ultrasonic sensors available, presence-only and speed measuring. Both types operate by transmitting ultrasonic energy and measuring the energy reflected by the target. These measurements are processed to obtain measurements of vehicle presence, speed, and occupancy.

The advantages of ultrasonic are that they provide all-weather operation, do not need to be approved by the FCC, and provide fixed or portable mounting fixtures above the road. Their disadvantages include their need to be mounted in a down-looking configuration as perpendicular as possible to the target (as opposed to side mounting), a difficulty in identifying lane-straddling vehicles and vehicles traveling side by side, and susceptibility to high wind speeds. Some of these disadvantages may be compensated for through more sophisticated data processing techniques.

1.5 Microwave/Millimeter wave radar

Microwave detectors have been used extensively in Europe, but not in the United States. They operate by measuring the energy reflected from target vehicles within the field of view. By processing the information received in the reflected energy, the detectors measure speed, occupancy, and presence. Some of the advantages of microwave detectors are that they are a mature technology because of past military applications, they detect velocity directly, and a single detector can cover multiple lanes if it is placed properly and appropriate signal processing techniques are used. In addition, FCC approval is not required if it operates in the X-band or Ku-band, and the output powers are within specified limits. Some of the disadvantages are unwanted vehicle detection based on reception of sidelobe radiation, and false detection due to multipath. Most of these disadvantages can be overcome, in whole or in part, through proper placement of the detectors, signal processing algorithms, and antenna design.

1.6 Passive Acoustic Detector Arrays

Another type of vehicle detector is the passive acoustic array. An array of microphones may be used to determine the passage of a vehicle. The signals from the microphones in the array are processed and correlated to obtain information about vehicle passage. The design of the array determines its directionality and field of detection. These types of detectors have not yet been thoroughly investigated, at least in terms of traffic related applications. Video-conferencing companies have been developing sophisticated microphone arrays for their systems, and it is possible that some of their techniques or designs could be adapted to traffic applications.

1.7 Piezoelectric

Piezoelectric detectors are very accurate vehicle detectors, but they do not detect presence of a stationary vehicle, unless it has stopped with its wheels on the detector. The piezoelectric sensor consists of a long strip of piezoelectric material enclosed in a protective casing. It can be embedded flush with the pavement, and when a car passes over it compressing the piezoelectric material, a voltage is produced. This sets off the controller. The piezoelectric detector has the advantage of indicating exactly when and where a vehicle passed by because it is a line detector perpendicular to the path of the vehicle. A series of two of them may be used to measure vehicle speed. A disadvantage is that for a permanent installation, they must be embedded in the pavement. Every time the roadway is repaved, or if a pothole appears, the sensor would need to be replaced. These types of sensors are currently being tested on the Beltway in Virginia. AMP is a manufacturer of piezoelectric traffic detectors.

1.8 Photoelectric

Photoelectric devices commonly consist of two components, the light source and the detector. These may both be in the same place, or placed across from each other. When placed across from each other, the detector is activated whenever something obstructs the illumination from the light source. When placed in the together, the detector is activated when light from the light source is reflected from a target and back onto the detector. There is not enough information on these detectors as applied to vehicle detection. They do not appear to be a competitive technology in the field of vehicle detectors at this time.

1.9 Spread-spectrum wideband radar

New wideband spread-spectrum radar has recently been developed at Lawrence Livermore Laboratory. It is a significant development because it is very inexpensive and it has extremely accurate range discrimination. It can also penetrate many types of materials, including concrete. It has a range of about 20 feet, so it may be useful as an inexpensive, single-lane vehicle detector. It is predicted that the sensor, when made in production quantities, would cost much less than $10 per sensor. Because of their accurate range discrimination, they have a very well defined field of detection. They could become a cheap alternative to magnetometer probes. Their ability to detect range provides additional information for future traffic control systems.

In addition, Lawrence Livermore has stated that they are developing a broadband transmitter/receiver pair to be used with these sensors. This would eliminate the need for communication lines between the sensor and the controller.

1.10 Inductive loop detectors

Loop detectors are the most widely used technology for vehicle detection in the United States. A loop detector consists of one or more loops of wire embedded in the pavement and connected to a control box. The loop may be excited by a signal ranging in frequency from 10 kHz to 200 kHz. This loop forms an inductive element in combination with the control box. When a vehicle passes over or rests on the loop, the inductance of the loop is reduced. This causes a detection to be signaled in the control box.

The advantages of inductive loop detectors are that they are an established technology in the United States, they have a well-defined zone of detection, and they are generally reliable. Disadvantages are that the detectors are very sensitive to the installation process, they can only be installed in good pavement, and they must be reinstalled every time a road is repaved.

1.11 Magnetic Detectors

There are two other types of magnetic detectors, which are used to detect traffic. Both of them are in the form of probes, and they both operate on the principle of a large metal object disturbing a magnetic field, just as inductive loop detectors work. There are both active and passive types. The active type is called a magnetometer. A magnetometer acts in much the same way as an inductive loop detector, except that it consists of a coil of wire wrapped around a magnetic core. It measures the change in the magnetic field caused by the passage of a vehicle. It can be used both for presence and for vehicle passage detection.

The passive type of detector simply measures a change in the flux of the earth's magnetic field caused by the passage of a vehicle. These detectors can only detect moving vehicles, so they cannot be used as presence detectors. They have a fairly large detection range and thus can be used to observe multiple lanes of traffic.

The advantage of both of these types of magnetic detectors is that they can be used where point or small-area location of a vehicle is necessary. For example, on a bridge, inductive loop detectors would be disrupted by the steel struts, and it is necessary to have a point detector. One of their disadvantages is that multiple detectors need to be installed to detect smaller vehicles, such as motorcycles.

1.12 Acceleration detectors

For the left-turn collision countermeasure system, it is necessary to determine the acceleration of the vehicle, so that it can be determined whether or not the vehicle is slowing to make a left turn. Using Doppler information, the range rate of a vehicle may be determined, but it does not appear that any radar currently being marketed for traffic applications measure the range rate. A simple method is to have three detectors in a linear formation. Measurements from these three detectors will provide an approximation of the acceleration of the vehicle from which the system may determine whether or not to activate the left-turn ahead warning.

Projected technologies

The spread-spectrum wideband radar is a technology that could become established in the vehicle detector market. However, it is likely that inductive loop detectors (U. S.) and ultrasonic detectors (Japan) will continue to dominate the vehicle detector market and will remain the most popular form of vehicle detector technology.

2. Deployment Concepts

2.1 Cooperative warning of the presence of oncoming vehicles on curves

A collision countermeasure system of this type is currently in operation in Japan. It has undergone extensive testing on a test track and has now been installed in actual portions of the highway. The name of the system is Guidelight. One of the Guidelight systems consists of a series of lights around the curve and an ultrasonic detector on each end of the curve. When a vehicle is detected, the lights are activated ahead of the vehicle at a rate dependent on the speed of the vehicle. The lights warn the driver of another vehicle entering the curve from the opposite direction that there is an oncoming vehicle. The ISO standard being developed for "cooperative warning of the presence of oncoming vehicles on curves" is based upon the Guidelight system, so Guidelight may become the standard collision countermeasure system for this type of warning.

Another possible collision countermeasure system would consist of a pair of warning signs, which would be activated as soon as a vehicle enters the curve in order to warn vehicles traveling in the opposite direction. A possible active warning sign would have two flashing lights on top and depict a two-way traffic road (assuming there are only two lanes) with a car in the oncoming lane. Both the flashing lights and the representation of the car will flash when the sign is activated.

The major equipment for this countermeasure system is vehicle detectors and a series of lights if using the Guidelight system or at least 2 warning signs if using the system described above. For hilly areas the sign could depict a straight lane with a car lighting up in the oncoming lane.

The following are possible deployment concepts:

1. In the simplest system, there should be at least 2 sensors and 2 signs. The two sensors are used to detect a vehicle entering the curve, and the active warning signs are placed inside the curve. This prevents the case of both cars entering at the same time and then passing the signs before they are activated.

2. Another option is to have four warning signs, two at the entrances to the curve and two along the curve. One set of signs should be set a good distance ahead of the curve on either side, in order to give the drivers enough advance warning that another car has entered the curve in the oncoming lane. The other set of signs should be set right within the curve so that cars that have passed the advance warning sign will still be notified if another car has just entered the curve.

2.2 **Driver warning on a minor road in the presence of vehicles on a major road**

This system is designed to enhance the driver's ability to assess the safety of entering an intersection on a major road from a minor road. There would need to be an active warning sign for the drivers on the minor road, and detectors to detect vehicles on the major road. A system of this type has already been implemented in Japan as part of the Guidelight program.

A basic system would have two active warning signs, one on each approach to the major road. The signs should indicate not only that a car is approaching on the major road, but also from which direction. There will also need to be as many detectors as there are lanes on the major road, and they will need to be a sufficient distance away such that the warning can be given in an adequate amount of time. The signs should be visible to the car on the minor road until he actually makes the turn. Thus, if it is in the position of most stop signs, it may not be visible as the vehicle prepares to make a turn, so there is the possibility that a vehicle appears right after the driver has moved passed the sign. In Japan, in a "T" intersection, they have placed the sign across the road, so there is no possibility of not being able to see it because of preparation for a turn. That may well be the optimum placement. The major equipment needed for this countermeasure system is a vehicle detector for every lane on the major highway and at least one active warning sign.

2.3 **Driver warning on a major road in the presence of vehicles on a minor road**

This implementation will be similar to that for the previous collision countermeasure system except that it is the vehicles on the major road that will be warned. The detectors will need to be placed on the minor road sufficiently far back to provide adequate warning to the driver on the major road. If there is a stop sign at the intersection on the minor road, then a detector could probably be placed in the intersection and right before the stop sign. If there is only a yield sign, it may be appropriate to place the vehicle detector farther back along the minor road. The sensors in the middle of the intersection should remain in either case.

The detectors will provide information as to whether there is a vehicle on any of the minor roads, and whether or not there is a vehicle in the middle of the intersection. The detector in the middle of the intersection needs to discriminate between cars crossing the intersection from the side road and cars crossing with the flow of traffic. A variety of sensor configurations can accomplish this. One radar sensor can detect directionality, and two piezoelectric sensors could also determine directionality.

A smart controller would combine the information from all of the detectors to determine where the vehicle that has entered the intersection has come from. The major equipment needed for this countermeasure is a vehicle detector to detect the vehicles on the side roads and in the intersection and at least 2 warning signs.

2.4 **Approaching vehicle warning for drivers making a left-hand turn and warning of vehicles turning left ahead**

This system needs to perform multiple functions. First, it must identify that a vehicle is slowing down to make a left turn. It then needs to determine whether or not there is enough time to make the left turn based on the speed and location of oncoming traffic, and to activate an active warning sign appropriately.

The system must also activate a warning sign for vehicles following the driver making the left turn. An additional option is to have another sign to warn the oncoming traffic that a vehicle is making a left turn ahead. Sensors are needed to detect the acceleration of the vehicle that will be making the left turn, to detect the vehicle if it is still waiting to make a left turn, and to detect vehicles in the oncoming traffic lanes.

The most challenging aspect of this concept is to detect that a vehicle is slowing to turn left. Doppler radar can measure the range rate directly, whereas inductive loop detectors and spread-spectrum wideband sensors need to take multiple measurements and integrate them.

In an example multiple detector system for detecting the acceleration of a vehicle, a central controller would observe the timing between successive activation of the detectors. When the spacing increases above a certain threshold and indicates a predetermined amount of deceleration, the controller activates the left-turn ahead warning signal. The left-turn ahead signal will stay activated for a preset amount of time before turning off. If a speed threshold is used instead of an acceleration detector, the central controller should use memory of the most recent average speed so that the current speed can be checked against that. This would allow the system to adjust to changes in the flow of traffic.

The major equipment needed for this collision countermeasure system is: vehicle detectors to calculate acceleration and presence of vehicle waiting to turn left, vehicle detectors for the traffic in the oncoming lanes, one controller, and four active warning signs. The following are three potential implementations of this collision countermeasure system:

1. A series of sensors can be set up to measure the acceleration of the vehicle. If it is decelerating at a rate greater than some threshold, then the left turn-ahead sign can be activated. In addition, there should be another sensor in the area where the vehicle would be turning left. If the sensor detects a stationary vehicle in this area, then it will also activate the left-turn ahead warning sign.

2. If congestion reaches high levels, then determining whether or not a car is slowing due to congestion or to make a left turn is more complicated. In this case, a sensor to detect slowing and a sensor to detect a stationary vehicle in the left turn position can be installed. The sensor which triggers based on a deceleration level can be deactivated in cases of heavy congestion, and so can the sensor, which triggers on a stationary vehicle.

3. If there is a stop-light ahead of the left turn area, the same setup that is in example 1 can be used, but the information about the phase of the stop light should be used when deciding whether or not a car is decelerating to make a left turn.

2.5 Traffic and Infrastructure Impacts

The systems discussed in this report are safety-oriented systems and apply only in very specific circumstances, so it is unlikely that they will have any significant traffic flow impacts. The main traffic impact should be a reduction in the number and severity of accidents. The infrastructure impacts will be much greater, especially in the areas of installation and maintenance of the systems, and liability.

Cooperative warning of the presence of oncoming vehicles on curves

Traffic Impacts

This collision countermeasure system is intended to reduce the number of accidents around blind curves, so its only potential traffic impact is a change in the number of collisions around blind curves.

Infrastructure Impacts - Installation and Maintenance

Both of these systems should be relatively inexpensive. The system described in this report may be cheaper because it does not require a sensor for speed and has fewer components than the Guidelight system. The Guidelight system has many more components to service because it consists of a string of lights around a curve, whereas the system described in this report only uses a maximum of four signs. The Guidelight system requires no cutting of the pavement because it uses ultrasonic sensors and the light elements are mounted along the guardrail. The other system may not require any cutting of the pavement either, depending on the type of sensor chosen.

Infrastructure Impacts - Liability

This is the most important consideration. As always, there is the potential for a suit for every malfunction or perceived malfunction of the system. Interpretation of the meaning of the active warning signs in the one system and the lights in the Guidelight system could lead to some initial difficulties. However, tests on the Guidelight system indicate that most drivers were able to understand their use or at the very least, they did not misinterpret them in such a way as to cause an accident. When using active warning signs, it is important to clearly convey the warning to the driver. Unless the warning sign is very clear, the driver may think that only one car is permitted to enter the curve at a time, and thus he may stop and cause a rear-end collision. This should not happen once drivers become accustomed to the sign. Because of the many possible interpretations of a sign, the simpler implementation of lights in the Guidelight system may be best.

Driver warning on a minor road in the presence of vehicles on a major road

Traffic Impacts

The goal of this collision countermeasure system is to reduce the number of accidents at intersections of a minor and major road. Thus, the traffic impact is hoped to be a reduction in the frequency and severity of accidents at these types of intersections. It should not have a significant effect on the traffic flow patterns unless widespread use in an urban environment is achieved.

Infrastructure Impacts - Installation and Maintenance

The installation of this system will require the installation of vehicle detectors in every lane of the major road, and they will need to be connected to the active warning signs on the minor road. The elements of this system are well known, so there should not be any significant or unusually high costs for the implementation of this system.

Infrastructure Impacts - Liability

In this collision countermeasure system it is particularly important that drivers do not interpret the inactivated signs as a guarantee that the intersection will be clear. The signs are meant to encourage the driver to look more carefully for oncoming traffic, not for the driver to blindly trust in the signs and to cross the intersection. However, someone will probably make the assumption that since the signs were not activated, the intersection was clear, and try to cross it and perhaps run into another vehicle. The probability of a missed detection in combination with a driver on a minor road crossing the intersection without looking anywhere except the signs should be estimated. It may be low enough to be tolerable. The government's responsibility for the drivers' safety in such a system should be investigated thoroughly, as well as the government's liability in the case of a malfunction of the system.

Visibility at the intersection can greatly affect the usefulness of these devices. If the driver on the minor road can see far enough in both directions on the major road, then the driver can easily discount a false alarm. In cases where visibility is at least somewhat restricted, false alarms become very important and need to be minimized, because the driver is putting his trust in the reliability of the sensors and the party responsible for the system could be liable for any errors. The warning signs are mainly designed to cause the driver to look again in cases where he may not have been very observant. If drivers begin to take the fact of the signs in the inactive state as an indication that there is no oncoming traffic, then these signs would tend to increase the likelihood of an accident. For example, drivers who are in a hurry and who are approaching a major road from a minor road and who see that the sign is not activated may assume that the road is clear and attempt to cross it. If one of the sensors had failed, then there is potential for a fatal accident. Because some drivers depend on signs and not on their own powers of observation, when a sign fails, especially an active warning sign, many accidents could occur. When an active warning sign fails, it is not necessarily clear that it has failed, as in the case of a stoplight, so it can be a lot more dangerous.

Driver warning on a major road in the presence of vehicles on a minor road

Traffic Impacts

This collision countermeasures system is also designed to reduce the number of accidents at the intersections of minor and major roads. It is not expected to affect traffic flow.

Infrastructure Impacts - Installation and Maintenance

The installation and maintenance of this system should be straightforward. Vehicle detectors need to be installed on the minor roads and connected to the active warning signs on the major roads. Any maintenance required should be minimal, as the systems will need to be highly reliable.

Infrastructure Impacts - Liability

The liability issues in this countermeasure system are just as important as in the previous countermeasure system. In this case, a missed detection can result in the driver on the major road running into a driver from the minor road who has entered the intersection. Of course, this assumes a lack of visibility or the driver's assumption that a sign in the off state guarantees that the intersection is clear.

Approaching vehicle warning for drivers making a left-hand turn and warning of vehicles turning left ahead.

Traffic Impacts

This collision countermeasure system is designed to reduce the number of crossing-path accidents for vehicles making left turns. The warning of a vehicle waiting to turn left ahead is intended to make the drivers aware that they need to either slow down or change lanes. However, it probably will not impact traffic flow, because most drivers tend not to merge until necessary, especially in heavy traffic.

Infrastructure Impacts - Installation and Maintenance

The system will need several sensors to be installed to detect vehicles and to detect acceleration, as well as a simple processor to calculate the acceleration and to decide whether or not the car is slowing to turn left. The costs of installation could vary depending on the type of highway involved. If there is a median, sensors could be installed in the median, minimizing the interruption of traffic flow for both installation and later maintenance. If there is no median and no overhead mounting area, sensors will need to be embedded in the pavement. This involves considerably more cost and a disruption of the flow of traffic.

Infrastructure Impacts - Liability

Again, there is the problem of how an inactivated sign will be interpreted by the general driving public. A sign in the inactivated state does not guarantee that there is no oncoming traffic. This system and the previous system have the greatest potential for fatal accidents in that both of them are meant to aid drivers in crossing oncoming traffic. In both cases, if the driver depends exclusively on the signs, which would be an inappropriate use of them, he may cause a serious accident.

Conclusion and recommendations

This report has presented an overview of available sensor technologies for friction/ice detection, vehicle detection, and acceleration detection. A description of the five collision countermeasure systems and a summary of possible traffic and infrastructure impacts have been presented as well.

For the friction/ice detection sensors and the cooperative warning around curves countermeasure systems, the following are recommended for the Collision Warning and Avoidance (CWAS) task:

- Monitoring developments in implementation

- Monitoring test results

- Monitoring development of new sensor products

These recommendations are based on the fact that both friction/ice detection sensors and cooperative warning around curves countermeasure systems (Guidelight) have been implemented and are being tested in the field. The rest of the CWAS are mainly concerned with intersection warnings. For these CWAS, the following are recommended:

- Determining possible scenarios. Maps can be used to determine locations of intersections where these CWAS apply and use data from NHTSA to determine which intersections could benefit most from the CWAS, based on the number of incidents.

- Developing system options. Drawing from the deployment concepts presented in this report, candidate systems can be determined, which meet the specific needs of each scenario. Systems can be compared based on different detector technologies, determining which technologies or combination of technologies provide the best system performance in each scenario.

- Performing first level cost analysis. For each system, the cost analysis for installation and maintenance should be conducted.

- Performance analysis. Benchmarking the performance of the proposed systems based on the differing sensor technologies.

- Recommendation operational tests for the most likely systems. Possibly incorporate the recommended tests into existing operational tests.

3. Collision Warning & Avoidance Technologies and Current Applications

Collision warning and avoidance systems (CWAS) are technology-intensive approaches in the traffic safety field. Concepts, technologies, and applications are relatively new, and majority of the systems are in test & evaluation phase. Although many collision warning and avoidance systems are being marketed throughout the world, there is no proven system that can be adapted as an industry standard.

Furthermore, the main focus of this research project, roadside-based collision warning and avoidance systems, are in their infancy era. As a sub-group of overall CWAS idea, very limited number of researches have been conducted in this field. Technologies and system architectures are mostly derivatives of the advanced vehicle control systems (AVCS), existing sensor technologies and traffic engineering knowledge. They also depend on the ingenuity of researchers, and evolution of this kind of systems is a matter of time and technology.

Since there is not enough information about the roadside-based CWAS, it would be very beneficial to present as much as possible information in terms of AVCS and sensor technologies. Our research output is based on the synthesis of these techniques, as well as professional insight.

3.1 Advanced Vehicle Control Systems and Applications

While there is a common perception that the Advanced Vehicle Control Systems (AVCS) field is a collection of futuristic concepts with little present-day relevance, in truth there already exists a wide variety of vehicle control systems in ground transportation. The focus of this part of the research is the application and technology of guidance control and safety systems for vehicles that either travel, maintain, or build roads, however several classes of related vehicles will be discussed briefly as well. Roadway-based systems that actively provide real-time roadway condition information are also described. The unifying purpose for these applications is to improve safety, whether by aiding the driver in controlling the vehicle as with an Anti-lock Braking System (ABS), or by actually removing the driver from a hazardous environment as for example with autonomous military vehicles. Of less importance now, but potentially more importance in the future are the efficiency benefits of AVCS arising from the higher speed and precision of automated systems relative to humans. Ultimately these efficiency gains are expected to provide significant growth of roadway capacity and allow for more rapid roadway construction and maintenance operations.

AVCS are applied to cars, trucks, buses and other vehicles with the purpose of either improving mobility and safety, or supporting ground transportation through other means. While ABS and traction control systems are commonly known examples, there are many other systems already available, or very close to production, which should enhance the safety and efficiency of roadway transportation. Vehicle control methods are also being applied to the construction and maintenance of roads as well as the testing of vehicles and the highway infrastructure. It should be noted that the interpretation of AVCS taken here is broader than in much of the ITS literature; not only does it encompass systems that aid and enhance the driving task, it also includes vehicles which incorporate automation to support ground transportation purposes. In this context, everything from collision avoidance systems to automated snowplows to active warning signs is considered an AVCS application.

From the technical base currently available one should expect continued growth in vehicle control and automation, leading to improved safety and efficiency in all areas of the ground transportation system. This growth is driven by auto makers and suppliers who see a large market for new products, and by the government which encourages these technologies as an improvement to ground transportation. In presenting the wide array of in-use AVCS technologies and applications, it is hoped that the readers of this particular research will gain an appreciation for the safety and efficiency benefits currently available, and recognize the impact that AVCS will have on roadside-based collision warning and avoidance systems.

Introduction

AVCS concepts have been discussed for decades, but only recently, through a combination of newly available technology and decreasing costs of processing power, communications systems and sensing systems have AVCS products become available. Along with these technical advances, the driving public has become increasingly willing to pay for safety-related systems, as witnessed by the dramatic increase in ABS installations and other safety-related devices in the last few years. Although several important new AVCS technologies are on the verge of entering the automotive market, the technology already available for many new vehicles makes the driving task significantly safer. These new systems help prevent collisions, and lessen the severity of those collisions that do occur. In addition to the safety technology developments in the auto industry, a transformation of the roadway construction and maintenance industry is starting to take place that will not only improve the efficiency of enormously expensive operations, but make them less hazardous as well.

The strict definition of AVCS in the Intelligent Transportation Systems (ITS) context includes any vehicle or roadway-based system which provides increased safety and/or control to the driver either by means of improving the information about the driving environment, or by actively aiding the driver in the driving task. This part of the research provides a survey of AVCS products, most of which are commercially available, some which are not yet, and others that are closely related, but are not strictly AVCS products under the definition above.

3.2 Road Vehicles

AVCS has already touched every major area of vehicle dynamics: braking systems, propulsion systems, suspension systems, and steering systems. These systems have provided significant improvements in vehicle safety, as well as comfort, convenience, and performance. Systems applied to passenger cars, trucks and buses are considered below, and most require no roadway infrastructure modifications.

3.3 ABS and Traction Control Systems

ABS is one of the earliest AVCS commercially available, and is considered among the most meaningful vehicle safety advances in the history of the automobile. The system's value is in its ability to prevent a vehicle from skidding when braking. When a driver applies the brakes, the system measures the wheel rotation to detect wheel lockup. As long as the brakes are applied, if skidding is detected the system automatically releases and reapplies the brakes, many times per second if necessary, to provide as much braking force as the friction between the road and tire will allow. In this way the driver may continue to steer the vehicle, and at the same time achieve shorter braking distances than would otherwise be possible with conventional brakes.

A development from ABS is the traction control system. These systems also measure and reduce wheel slippage, but under acceleration instead of braking. Depending on the system, either the brakes are automatically applied to the appropriate wheel, the throttle automatically closed, or both. Another traction control system, available on some four-wheel drive vehicles, like some Audi Quattros, is automatically controlled differentials, which regulate engine torque front-to-back and side-to-side to maximize traction.

3.4 Four Wheel Steering Systems

Four-wheel steering systems employ electronic and/or mechanical means to steer the rear wheels in either the same or opposite direction as the front wheels. In-phase or same direction steering is useful for higher speed maneuvers like lane changes. Opposite phase steering aids low speed maneuvers like U-turns where a smaller turning radius is desirable. Most systems monitor vehicle speed and steering wheel angle, and generate appropriate rear wheel steering angles by actuating hydraulic control valves at a rear mounted steering rack (Nissan 300ZX, Mitsubishi Galant, etc.). While four wheel steering is primarily a convenience feature, it also provides a safety benefit as it increases the stability and maneuverability of the vehicle, particularly at high speed.

3.5 Active Suspension Systems

Conventional, or passive, spring and damper suspension systems generally trade-off good handling and road-holding for comfort and smoothness. A spring-damper combination, which is very compliant and smooth over rough roads, tends to let the vehicle wander and roll more, particularly through turns. Likewise a stiffer suspension which provides better handling will tend to give a harsher, less comfortable ride. Active suspensions provide the benefits of both soft and firm suspensions under the appropriate conditions. This is performed by rapidly varying the spring and/or damper rates to suit the prevailing driving condition as indicated by sensors for wheel displacement, steering angle, and vehicle speed and acceleration. Active springs are generally variable pressure pneumatic systems with control valves adjusting the spring pressure and ride height (Range Rover, etc.). Active dampers typically use controllable valves to regulate damper orifices that control oil flow to and from the damper housing as with the Infiniti Q45a. Truly active suspensions which view the road ahead of the vehicle and move the wheels up and down in anticipation of bumps and ruts have not yet reached production vehicles although at least one auto maker, Lotus, has performed extensive development on such a system. Active suspension systems are generally viewed as both a safety and comfort/convenience improvement.

3.6 Vehicle Stability Systems

This class of safety systems, just now in production, represents an evolution of ABS and traction control technology applied to prevent cars from spinning out. Vehicles tend to spin when driven too fast around turns, particularly on slippery roads. Several vehicle and brake system manufacturers are introducing systems, which measure wheel speeds, steering wheel angle, lateral acceleration, and rotation about the vehicle's vertical axis (yaw rate) to determine whether a spin is imminent. If so, braking at the appropriate wheels is automatically applied, and the drivetrain power reduced to effectively balance and twist the vehicle in the opposite direction from the spin. BMW and Mercedes have newly released systems. Stability systems are not yet available for buses or trucks, but these applications will soon follow.

3.7 Autonomous Intelligent Cruise Control (AICC)

Intelligent cruise control monitors the distance to the vehicle ahead, and either warns or actively slows the subject vehicle if the separation distance and/or relative speed between the vehicles fall within a danger zone. If there are no vehicles or obstacles within range, the system behaves like a conventional cruise control system. Most AICC designs employ either a radar or laser radar sensing system to determine distance and relative speed to the vehicle ahead, and either warn the driver, apply the brakes, reduce the throttle, and/or downshift the automatic transmission if the subject vehicle's following distance is too short, or the closing speed too high. Although most vehicle manufacturers are still testing prototype systems, Mitsubishi has an AICC system available as an option on its Japanese-market Diamante. This AICC views the road ahead with a tiny Charge-Coupled Device (CCD) camera and laser radar, and maintains a preset headway to a preceding vehicle by reducing the throttle and/or downshifting if the vehicles get too close. AICC allows higher levels of comfort and convenience to the driver than conventional cruise control since safety is incorporated into its design.

3.8 In-Vehicle Collision Warning Systems

Currently there are several collision warning systems in use to enhance driver awareness and safety. These systems operate much like an AICC but they warn of hazards within a zone around the vehicle. Radar is typically used to monitor ahead of the vehicle, and much like AICC systems, a warning is given to the driver if he gets too close to the vehicle ahead. Also commercially available are side-viewing radar or CCD cameras which monitor blindspots and warn the driver if it is not safe to change lanes. Several Japanese-market cars and trucks are equipped with such systems, while in America Eaton-VORAD produces front and side-looking radar for its collision warning system for heavy vehicles which have been installed on trucks and buses. Development continues in areas of human factors (how to most effectively indicate the level of threat to the driver) and processing algorithms to correctly determine the level of threat. In the near future collision avoidance systems may automatically take corrective actions if the driver does not.

3.9 Roadway-Based Warning Systems

The Guidelight system, developed by Nissan and tested in Japan warns drivers on road curves of approaching vehicles in the curve. This is done with roadway-based sensors and lights along the perimeter of a curve. Ultrasonic sensors at the entrances to a curve detect an approaching vehicle and illuminate the lights on the road ahead of the vehicle for oncoming traffic to see. Another Guidelight configuration gives warnings of approaching vehicles at unsignalized intersections. BMW is field testing the COMPANION system in Germany which uses illuminated roadside beacons connected to a traffic control center to warn passing vehicles of certain types of hazards ahead (fog, ice, congestion, accidents, etc). Roadway warning studs developed by Astucia are claimed to perform a similar warning function, but hazardous conditions are detected by the studs themselves, and not from a control center. The studs are embedded in pavement as raised pavement markers, and they flash different colors to provide warnings of different hazards.

Another example is the truck rollover warning system installed at two exit ramps from I-495 in Virginia, which uses weigh-in-motion, height detection and speed detection to determine whether approaching trucks are risking rollover by carrying too much speed into the ramp curve, and warning them as needed with active signs.

3.10 Near-Obstacle Detection Systems (NODS)

Several manufacturers presently sell systems that warn the driver of obstacles out of the driver's viewing range. Some, like Bosch's ultrasonic Parkpilot, are rear-looking systems which engage only when the vehicle is put in reverse. A typical detection hazard might be an otherwise invisible pet or small child behind the vehicle. Many school buses are currently installing Delco's FOREWARN radar-based NODS to monitor the areas around the bus that the driver cannot see when students are boarding or exiting the bus. NODS sensors typically use radar or ultrasonic ranging, although CCD cameras with image processing methods are also available. Generally, a simple warning alarm is triggered if an obstacle is detected. Active systems, which automatically hold the brakes to prevent a collision, are expected shortly.

3.11 Guideway-Based Buses

Guideway-based buses use AVCS to improve service quality relative to conventional buses. These buses are autonomous (no driver) or semi-autonomous (driver present) dual mode buses that can run on dedicated lanes or conventional roads under driver control. The principal example of this system is the O-Bahn in Essen, Germany, and elsewhere. These buses, made by Daimler-Benz, operate either under electronic or mechanical lateral guidance. The electronic system uses an electric wire embedded in the guideway centered between the tracks, and an inductive detection system onboard the bus which continuously steers the wheels to center the bus over the wire. The mechanical system uses small spring-loaded arms off the side of the bus, which follow the high curbs of the guideway. The guidance system adjusts the steering to maintain the same distance from the curb to the bus for arms on both sides. Longitudinal control may be performed autonomously or by an operator.

Like light rail systems, these buses drive on a dedicated right of way, however they can also be driven on roads. As a result, capital and operational costs are significantly lower than for a comparable rail system yet O-Bahn buses offer better service quality than conventional buses.

3.12 Vision Enhancement

Methods for improving the visibility of road hazards at night or in bad weather include infrared and ultraviolet illumination techniques. Infrared imaging is performed by a special camera that passively measures the low-level heat from the viewed scene and displays the otherwise invisible image to the driver. Ultraviolet illumination requires special headlights that dramatically improve the visibility of fluorescent-colored objects in the illuminated area. Saab has been actively developing an UV headlight system, but only infrared technology has reached production. Currently the automotive applications are targeted for police cruisers which use the roof-mounted cameras to see criminals or signs of recent criminal activity (Texas Instruments' NIGHTSIGHT system). For the time being the technology is too expensive for general use in production vehicles.

3.13 Lane Following and Maintaining

These safety methods have been tested extensively, but not yet released to production. The technology studied relies on vehicle-based cameras to monitor the road ahead with the aid of lane recognition algorithms. Daimler-Benz’s truck division, Freightliner, may this year release a system which gives an audible warning to the driver when the vehicle starts to drift from its lane. Another system demonstrated by Jaguar in the European PROMETHEUS program, automatically centers the steering in the lane and provides light resistance to driver steering inputs that would cause lane drift or departure.

3.14 Driver Monitoring

Systems to prevent drowsy driver accidents are under development, which measure the state of the driver by monitoring steering wheel movements, and/or eye blinking (by means of image processing). A warning is emitted if the system detects the driver is falling asleep, for example if the eye blinks become too slow or the steering wheel motions become erratic. Field testing of such systems has been underway in Japan for several years by Nissan and Toyota. This technology should be particularly useful in preventing many single vehicle roadway departures, and other drowsy driver accidents.

3.15 Future Technologies

Much has been written in the last few years about the future of vehicle control systems, particularly with regard to Automated Highway System (AHS) concepts. It may be safely said that the technologies described above will continue to become more sophisticated and less expensive as the costs of sensing, communication, and computing power continue to fall. Systems that currently provide only warnings to drivers may in the future take control from the driver to avoid a collision if the appropriate action is not taken. Already there exist prototype vehicles, like the Mercedes VITA II, which can safely drive autonomously for extended periods in general traffic. AHS concepts which center around dedicated, highly structured driving environments to gain large traffic efficiency gains will require sophisticated control systems, and significant vehicle-infrastructure adaptations to operate.

Enabling Technologies

Like most modern control systems, AVCS applications require sensing and processing hardware to generate control outputs. The outputs may drive a warning device, actuate vehicle controls (steering, brakes, throttle, and transmission), or trigger some other device (sign illuminator, shock absorber valving, etc.). This section provides an overview of two important control system components for AVCS.

3.16 Guidance Sensors

Although almost any sensor could conceivably be used in an AVCS, this section will focus on vehicle guidance methods, the most significant area of sensor technology in AVCS. These fall into four categories:

1. Imaging Methods. These methods involve either the active illumination of an area of interest, or passive measurement of emissions from objects in that area. Active methods include radar, ladar (laser radar), and soundwave propagation techniques; a pulse or pulse train is emitted by the sensor, and measurement of the returning pulse(s) reflected from an object determine the distance and relative speed to the object. Passive methods include video and thermal imaging. In this case a special camera views a scene, and through image processing algorithms a wide range of data can be determined including distance to objects, and identification of targets, etc.

2. Triangulation Methods. These technologies locate a vehicle with extremely high precision based on the distances between the vehicle and at least three independent reference points. Typically, by transmitting a signal from the reference points to the vehicle (or vice versa), and measuring properties of the received signals, these distances (and thus the vehicle location) can be calculated very accurately. GPS (Global Positioning System) is one of several such systems.

3. Trail-Following Methods. For these methods, a roadway path is followed by vehicle-mounted sensors. The path could be embedded magnets, a current carrying wire, a painted stripe, a chemical trail, and so forth. These technologies require dedicated infrastructure modifications to operate.

4. Dead Reckoning. Vehicle-mounted motion sensors (inertial or otherwise) precisely detect vehicle direction and speed. Given a known starting position, the integration of this data over time allows the location of the vehicle to be determined. Because errors accumulate with distance traveled, these systems become inaccurate unless the vehicle's position is periodically corrected by some other means.

3.17 Drive-by-Wire Systems

Ultimately an AVCS must actuate something, and in the case of vehicles this is usually the steering, propulsion, or braking system. A common approach used for many AVCS is to piggyback automated systems onto the conventional manual systems. A more elegant and flexible approach uses a single actuation system that can be controlled manually, or by an electronic control system. In practice this is done by replacing mechanical linkages (between manual controls and their actuators) with electrical connections. Such systems are called "drive-by-wire" because wires, not linkages, connect the controls to the actuators. For example, where a conventional throttle is directly opened by a cable through the depression of a pedal, a drive-by-wire throttle converts the pedal movement into a voltage, which activates a throttle actuator motor to open the throttle. If one wants to automatically control this throttle (for vehicle speed control, traction control, or other purposes) it is now only a matter of modifying the controller software; no additional actuators or linkages need to be introduced. By replacing mechanical linkages with signal wires, the functionality of the mechanical system is preserved, while the ability to automate the system is greatly simplified.

Even if vehicle automation is not the end purpose, there are still significant advantages to drive-by-wire technology, and it has already reached non-automated production vehicles for throttle, brake, transmission and to some extent steering control as well. As described in the example above, the operating principle is the conversion of the movement of a conventional control, like an accelerator pedal, into a voltage, which drives the actuator (the throttle). Drive-by-wire throttle systems are currently in production (for example, BMW) which allow consolidation of idle speed control, cruise control, traction control and manual throttle control to a single actuator. Another example is a large tractor-trailer drive-by-wire braking system which yields improved braking force distribution and response time relative to a conventional system because electrical signals travel much faster than brake line pressure and can be tailored independently to each braking wheel.

Although the examples above illustrate some technical advantages of drive-by-wire systems, perhaps flexibility is the greatest benefit since the electrical interface allows for system changes. Since the output of a controller is typically an electrical signal, it is much easier to achieve compatibility with a drive-by-wire system than a conventional actuation system. As a result, modifications to the design of the control system (adding new control functions or using a different type of controller, etc.) are much more easily accommodated by drive-by-wire actuators.

3.18 AVCS for Testing and Development

Gains in efficiency and safety may be realized by automating vehicles to perform tedious and/or dangerous tasks. One such area where AVCS can be put to advantage is in the testing of vehicles and roadway infrastructure. At least two auto makers, Mitsubishi and Chrysler, utilize automated vehicle testing grounds for accelerated wear testing of their production cars. These roadcourses are constructed with electric wires in the ground to guide the vehicles, much like the O-Bahn bus guideways described earlier, while actuation of the pedals, gearshift and steering is performed by bolt-on servomotors. Vehicle automation can also be used to test the roadway infrastructure, for example at Mn/ROAD in Minnesota and WesTrack in Nevada, where automated trucks are being prepared to circulate test tracks without driver intervention for the purpose of testing the pavement under heavy loading. Another potential use for vehicle automation is for the evaluation of roadside hardware (guardrails, poles, etc.) for crash testing. Initial development of such a system, which could precisely drive a car at a desired speed into a fixed object, was performed by MIT Research.

3.19 Transportation Infrastructure Construction and Maintenance

The significance of development in these areas cannot be overstated. Roadway construction and maintenance is extremely expensive and hazardous. Even an incremental improvement in the efficiency of these operations could save many millions of dollars annually, and the replacement of man by machine could mean many saved lives. Although there has been a great deal of development in this area, there are relatively few finished products. Some concepts that have been prototyped are: guided snowplows, pavement crack and pothole sealers, lane striping machines, roadside lawn mowing systems, paving machines, backhoes and earthmovers, roadway workzone safety systems, concrete finishing machines, traffic cone laying machines, hazardous waste cleanup vehicles, trash pickup machines, etc. In California several of these designs have been prototyped by the Advanced Highway Maintenance & Construction Technology (AHMCT) Center, a joint project between Caltrans and UC Davis, and are nearing commercial release.

While many of the prototypes above are actually robots mounted to human-driven vehicles, some (like the snowplow) are designed to be autonomously guided. An example of one such vehicle used for maintenance can be seen in the English Channel Tunnel. A separate service tunnel is equipped with an O-Bahn-type vehicle, which is laterally guided by an embedded wire. Use of this system allows the maintenance vehicle to safely and quickly reach any point in the tunnel.

Military Applications

Naturally in a battlefield situation there are many hazardous situations that a soldier could encounter which would ideally be handled by a machine, and even relatively safe tasks like repetitive transport jobs would be excellent candidates for a mobile robot. Since the 1980s the U.S. military has invested substantially in unmanned vehicle research including underwater, air and ground vehicles. Although there are no autonomous ground vehicles in service yet, several prototypes continue development. Some of the tasks for these vehicles are unmanned scouting, security patrolling of an area, vehicle convoying, and land mine clearing.

Other AVCS Applications

AVCS is also applied to a variety of other vehicles from Automated Guided Vehicles (AGVs) to automated agriculture equipment. Benefits for agricultural use are improved safety, efficiency of operations, and greatly reduced vehicle weight and associated benefits like reduced engine size, fuel consumption, and soil compaction damage. Running prototypes are currently under development (Modulaire Ltd.). At least one construction equipment manufacturer, Komatsu, is prototyping vehicles for automated mining operations with trucks, which autonomously run back and forth between loading and unloading points. The AGV market is already using highly developed automated vehicles to drive around factory floors, shipping areas and so forth, collecting and dropping off materials along the route to improve the efficiency of operations. Most of the sensor technologies described in this section are presently used in AGVs. A major shipping port in Singapore is preparing a system of AGVs that will move along designated "roads" using sophisticated AHS-like traffic movement algorithms to maximize the efficiency of goods movement between the ships and the warehouses.

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