An integrated approach to automotive safety systems

The industry strategy for automotive safety systems has been evolving over the last 20 years. Initially, individual passive devices and features such as seatbelts, airbags, knee bolsters, and crush zones were developed for saving lives and minimizing injuries when an accident occurs. Later, preventive measures such as improving visibility, headlights, windshield wipers, and tire traction were deployed to reduce the probability of getting into an accident. Now we are at the stage of actively avoiding accidents as well as providing maximum protection to the vehicle occupants and even pedestrians. Systems that are on the threshold of being deployed or under intense development include collision detection/warning/intervention systems, lane departure warning, drowsy driver detection, and advanced safety interiors. In this article, Delphi researchers discuss the concept of the safety state diagram, a unified view of the automotive safety system, and the technologies required to implement this vision. Advanced ideas such as pre-crash sensing, anticipatory crash sensing, X-by-wire systems, advanced safety interiors, integrated vehicle electrical/electronics systems, data networks, and mobile multimedia (telematics) are also addressed.

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The expanded use of electronics, microcontrollers, sensors, actuators, high-speed data buses, and X-by-wire technologies in the automotive industry will have a major impact on the architecture of future safety systems. Many traditional safety technologies are beginning to merge. Looking at the vehicle as a personal safety system, one can describe five vehicle driving scenarios: normal driving state, warning state, crash avoidable state, crash unavoidable state, and post event state. The first three states focus on accident avoidance, while the last three states focus on damage mitigation (with an overlap of the third state). Using the state diagram, it is apparent that automotive safety concerns should be addressed with an integrated system approach.

The Integrated Safety System state diagram
As depicted in Figure 1, an integrated automotive safety system may be thought of as a series of interdependent safety states.

The avoidance zone
The three states that comprise the avoidance zone include normal driving state, warning state, and collision avoidable state. It is important to note that all the safety actions occurring in these states reduce the probability of a collision. This is also known in the industry as active safety.

Normal driving state—Under the normal driving state, a driver enjoys many of the comfort and convenience features afforded by modern automotive electronics. For instance, a millimeter wave or laser-based adaptive cruise control (ACC) system maintains either a constant vehicle cruising speed or a constant...
headway between vehicles. In addition to the conventional AM/FM radio broadcasts, the onboard telematics system provides cell phone and wireless data capability, as well as GPS, map, and navigational aids. If desired, real-time traffic information can also be accessed through either the Internet or a preferred call center.

These features not only provide the needed information in a timely manner, but also offer added safety and security protection for vehicle occupants. For example, the navigation system with its turn-by-turn audible instructions lets the driver concentrate on the task of negotiating the traffic because there is no need to take one’s eyes off the road to look for the destination. Additionally, the telematics system allows the vehicle occupants to stay in touch with the dealer or repair shop should anything go wrong with the car.

The next generation of ACC systems will be able to handle low-speed stop-and-go traffic situations as well. This is especially significant since a large percentage of accidents take place under these driving conditions. Some vehicles are already equipped with the night vision system that provides enhanced vision at nighttime for the driver. The system is implemented in such a way that the infrared (IR) image of the scene is projected via the head up display (HUD) unit and superimposed on the driver’s natural field of view. With this implementation, drivers enjoy enhanced vision without having to take their eyes off the road.

Some driver monitoring systems have made their way into commercial fleet vehicles because of the desire to ensure public safety and to minimize costly accidents. Most likely, these systems will soon appear in passenger cars as well. Using a combination of biological sensors, eye tracking devices, and vehicle steering information, it is possible to infer the degree of driver alertness. Appropriate countermeasures then can be employed to stimulate the driver or warn the driver that it is time to pull off the road and rest.

A roadway condition sensor that can reliably indicate to the driver whether the roadway ahead is wet, dry, icy, or rough is a valuable safety tool especially during the winter. With this sensor information, the vehicle could issue an advisory to the driver to adjust his speed accordingly. Ultimately, the vehicle may automatically adjust its parameters to help the driver maintain control of the vehicle. In short, system development can allow drivers and passengers under normal driving to be well protected by a large array of safety, comfort, and convenience features. The interior of the vehicle will not only provide the maximum level of protection possible, but also will adapt according to each occupant’s preference. The telematics functions will be working in concert with the safety features of the vehicle through a well designed human/machine interface (HMI).

Warning state—Sensing systems are the key in the warning state. The Integrated Safety System (ISS) must maintain full awareness of the driving situation in order to detect potential crash situations. Sensing needs range from external object detection (other vehicles, trees, signs, etc.) to internal vehicle states (tire pressure, vehicle stability, etc.). Sensor and data-fusion algorithms will combine information from various sensors to form a model of the current situation. Ultimately, the ISS needs to be able to sense objects around the entire vehicle.

Once the situation is understood by ISS, the appropriate warning can be delivered to the driver. At this point, the driver must take action to avoid the collision. Practical vehicle applications involved in the warning state include:

- Low tire pressure warning
- Impending rollover warning
- Lane/roadway departure warning
- Parking assistance/warning
- Backup assistance/warning
- Blind-spot warning
- Rear-end collision warning
- Lane change warning

One particularly difficult problem arises when sensing objects at longer ranges: the issue of path prediction. If the ISS is unable to project the host vehicle’s path accurately, it will be impossible to determine which objects in the field of view represent a threat to the host vehicle. If, in the scenario shown in
Figure 3, the ISS vehicle is unaware that the road is curving, then there are several objects that would appear to be directly in the path of the host vehicle. The ISS would incorrectly warn the driver of all the supposed threats. For the ISS to be effective, it is important to provide warning or control signals at the appropriate time and to minimize false alarms and nuisance alerts.

Assuming the driver follows the road, the only object actually in the path of the host vehicle is the vehicle around the curve in the same lane. Depending on the vehicle spacing and relative speeds, this vehicle may or may not represent a threat. Correct detection of road geometry would enable the ISS to correctly ignore all objects except the vehicle in the same lane as the host vehicle.

The solution to the path estimation problem is highly dependent on roadway geometry, inter-vehicle kinematics, driver reaction times, and braking behaviors. Yaw-rate sensors can be used to determine roadway curvature, but only when the host vehicle is already in the curve. For scenarios such as curve entry or curve exit, other sensors such as solid-state cameras will be needed. GPS, digital road maps, and roadside transponders also can be used to increase the accuracy and robustness of the ISS path estimation algorithms.

Several other issues surface in the warning state:
• Threat assessment—The ISS must determine whether a particular situation poses a threat and merits warning the driver. Driver preferences must be taken into account as well. One driver may not want to be warned until the threat is severe while another driver may want to be notified at the slightest hint of trouble.
• False alarms and nuisance alerts—It is important to eliminate or minimize false alarms to win the driver’s confidence in the system.
• Human factors—In a critical situation, the ISS must notify the driver in a way that is quickly recognized and that encourages the driver to take the proper action. It is vital that warnings not distract or confuse the driver during an impending collision.

Collision Avoidable State—The collision avoidable state is the last opportunity to avoid an accident and return to the normal driving state. Everything that is done in this state is with the intention to completely avoid the accident. Reaction time as well as vehicle stability and control are extremely important in this state. Examples of features included in this state are:
• Automatic stopping
• Automatic lane change
• Lane keeping
• Chassis and suspension control
• Vehicle rollover prevention
• X-by-wire (steer, brake, throttle)

The implementation of the collision avoidable state is primarily dependent upon two things: a suite of sensors and sensor fusion algorithms that provide information about the state of the vehicle and its surroundings as defined in the warning state; and a suite of X-by-wire products (steering, braking, throttle, and suspension) that de-couple the actuation from the mechanical input provided by the driver (Figure 4). This de-coupling is a key enabler as it allows the vehicle to be commanded to perform various maneuvers without direct driver input.

Consider the current anti-lock brake systems that are prevalent on passenger vehicles and light trucks today. In these systems, the braking function is augmented by a computer controlled brake release and then re-applied to mitigate the effect of wheel slippage.
It is important to note that the initiation of the brake function today still requires the driver’s input. Collision avoidance features will evolve into three modes:

• Driver initiated
• Vehicle initiated
• A blend of both

Consider again a simple braking maneuver in a vehicle equipped with the necessary sensors and a brake-by-wire system. Under any driving conditions, the vehicle will know its speed, closing speed of approaching objects, road surface conditions, driver intended path, and vehicle attitude (pitch and yaw). Once the driver requests braking, the system will provide the appropriate level of braking effort to effect a normal stop.

What will happen if the ISS vehicle has detected a slowed or stopped object in its path and the driver has ignored all of the warnings or is unable to command the brake function by stepping on the brake pedal? Because of the brake-by-wire product, the vehicle will have the ability to initiate braking without input from the driver.

These examples can all be accomplished with only a brake-by-wire system in the ISS vehicle. The options to enhance vehicle performance and stability are greatly increased when by-wire steering, throttle, and suspension are added. If the ISS vehicle detects that it is closing upon an object too quickly, then a simple vehicle-commanded throttle reduction might be a viable response.

Figure 4. Future “by-wire” vehicle control.

Alternatively, perhaps the driver has initiated a very quick turn that will take the vehicle into an unstable condition. This could be from lack of driving experience, or over reaction to a driving situation. With an effective ISS system, the steering angle may be reduced, throttle reduced, independent differential braking applied and the suspension stiffened all simultaneously without input from the driver to keep the vehicle stable.

Figure 5. Near-term, high-content occupant restraint system.

The mitigation zone
The three states that comprise the mitigation zone include collision avoidable state, collision unavoidable state, and the post event state. All safety actions that occur in these states focus on reducing the effects of a collision.

Collision avoidable state—Note that this state appears in both the avoidance and mitigation zones. It is obvious that the best way to protect an occupant, pedestrian, or property is to avoid an accident. If the accident cannot be avoided, then the goal is to reduce its effects. Many of the systems used in collision avoidance come into play for damage mitigation. With automatic braking, for example, the vehicle can be slowed down as much as possible to minimize injury and damage.
Using the same sensors and fusion algorithms described in the warning state, the ISS vehicle could prevent the driver from directing the vehicle to cross the roadway centerline and into the path of an oncoming vehicle. Or, it could inhibit the driver from a collision with a utility pole or bridge abutment that can possibly be at the right side of the vehicle.

In essence, when all the vehicle control authority of braking, steering, throttle, and suspension has been used, the ISS vehicle will attempt commands for the “softest possible landing.”

Collision unavoidable state—
Since this is the point of no return, everything should be done immediately before as well as immediately after the crash to reduce the effects of the accident.

The collision unavoidable state has traditionally encompassed the realm of occupant protection. These features include everything from crashworthy vehicle structures and interior padding to seatbelts and airbags. Interest in “smart” or advanced airbag systems has intensified recently to provide improved occupant protection under a variety of real-world accidents, as well as to minimize the potential adverse effects caused by airbag deployments. Smart restraint systems are intended to be more adaptable to various real-world factors such as crash type, crash severity, seat belt usage, and occupant type and position.

As occupant protection countermeasures increase in number and sophistication, electronic sensing requirements continue to grow. The finer the sensing resolution of both vehicle dynamics and occupant kinematics, the smarter the complete occupant protection system becomes.

Although these technologies provide significant benefits in the area of occupant protection, the advent of collision avoidance technologies has now made it possible to incorporate new functionality into the vehicle.

Anticipatory, or pre-crash, sensing is a key enabler not only to post-impact countermeasures (such as variable stage airbags and seatbelt tensioners), but also for resettable, pre-impact countermeasures (such as adaptable interior and exterior structures and pedestrian protection countermeasures).

Post event state—After an accident has occurred, the ISS vehicle will automatically assess the severity of the event based on a number of sensory indications:
• Did the airbags deploy?
• Did the vehicle roll over?
• What is the rest position of the vehicle?
• How many occupants are there?
• What are the vital signs of the occupants?
• Is there a fuel leak?
• Is there a fire?

In the case of a severe accident (i.e., airbags were deployed), the vehicle’s telematics system will automatically dial 911 (or equivalent) and summon help. If the occupants are still able to communicate with the dispatcher, the extent of injuries can be obtained and passed on to the paramedics. If the occupants suffered severe injuries and could not communicate with the dispatcher, then onboard biosensors can be used to assess the situation. If the vehicle is equipped with a video camera in the passenger compartment, video images can be used to aid in situation assessment.

In addition, the vehicle will have enough intelligence to detect and extinguish fires, release seatbelts, and unlock car doors (allowing easy egress as well as greater ability to be reached by rescuers).

To prevent fires caused by a ruptured fuel line, the fuel pump can be shut off automatically, the engine can be turned off remotely, and unnecessary electrical power can be disconnected. If the event takes place at night, the vehicle can also provide illumination and road hazard flashing warning lights.

In the post event state, there are many possibilities for enhancing the survivability of the victims. Many of these features are enabled by the telematics system. For these features to be available, the telematics system must survive the accident. Therefore, there is an implied level of robustness that must be built into the system.
A case study—collision avoidance and occupant protection

An interesting phenomenon occurred as we looked at the future of pieces to the integrated safety systems puzzle. No matter how we approached the problem, it was evident that feature/function sets, as well as technology building blocks, tended to merge as time passed. In the following example, we’ll discuss how collision avoidance and occupant protection tend to blend together.

Forewarn® collision avoidance—Collision avoidance systems depend on short- and long-range sensors to characterize the location and motion of objects around the vehicle. A typical system determines object attributes with a suite of sensors, develops a model of the scene around the vehicle, and issues a set of vehicle control commands depending on the desired system function.

In its simplest form, the function would be to issue a warning to the driver so that the driver can take the appropriate avoidance action. In a full collision avoidance system, the desired function involves automatic lateral or longitudinal control of the vehicle.

To develop this capability, the industry has been following a path similar to the one shown in Figure 7. Several enabling technologies are needed to achieve the vision of a true collision avoidance system: long- and short-range object detection sensors, X-by-wire systems, appropriate human-machine interfaces, etc.

Short-range proximity sensing needs—Collision avoidance systems are being developed to do as the name implies—avoid accidents. As we’ve shown, short-range proximity sensing is one of the key enablers. We know, however, that there is a long list of needs for short-range sensors as well. Some of these potential applications include:

• Power doors and liftgates
• Express close window and sunroof systems
• Occupant position sensing
• Security system applications
• Pre-crash sensing systems
• Active pedestrian protection systems
• Parking/back-up aid

Figure 7. Collision avoidance system mechanization.

Figure 8. Collision avoidance systems development.

• Close cut-in detection
• Anti-trap trunks

The main point to understand is that features that traditionally have been looked at separately by product-focused teams basically need the same fundamental technical solutions.

Anticipatory (pre-crash) sensing—By integrating long-range cruise control and collision warning sensors with short-range sensors needed for urban automatic cruise control (stop-and-go driving), pre-crash sensing systems will have the ability to perform object detection and tracking up until the actual time of impact. This ability now provides the capability to calculate angle- and region-of-impact, both critical parameters to understand crash type and to deploy the appropriate occupant protection countermeasures.

The logical next step is to integrate the vision systems utilized for lane tracking/lane departure into the system to provide object classification. This feature will provide the remaining information needed to truly predict crash severity.
Conclusion

No matter how you approach it, the future of automotive safety systems is certainly an integrated, vehicle systems-level approach.

Safety technology roadmaps are beginning to look alike. Collision avoidance sensors and occupant recognition sensors employ basically the same technologies. The same can be said about vehicle dynamic control sensors and vehicle crash sensors, as well as distributed safety architectures and distributed mobile multimedia architectures.

Safety features and functions are blending. The best way to protect an occupant is to avoid the accident. Subsystem information can and should be shared (vehicle dynamic state estimation information, occupant information, airbag status, scene information, etc.). Subsystem blending can enhance vehicle (and integrated safety) performance (e.g., a collision threat can mute a radio and cell phone, etc.). Proximity sensors can be used for a multitude of applications including:

- Security
- Collision avoidance
- Occupant position and recognition
- Pre-crash sensing
- Pedestrian protection systems

As a result, a systems approach to integrated safety is driving our future developments.

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