Improved Safety Performance Due to Vehicle Wide Pre-Crash Sensor Data Availability

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Abstract: Many vehicle safety systems require real time assessments of the vehicle's dynamics and external environmental conditions. In most cases, these systems contain independent sensors that help make determinations of vehicle motion and external object classification and motion with respect to the vehicle. Recently, more advanced pre-crash systems have been installed on vehicles using active sensors that not only provide information relative to real time vehicle dynamics, but also give indications of future vehicle dynamics as well as external object assessments. Some of these active technologies include cameras, ultrasonics, and radar. Traditional vehicle architecture has limited vehicle wide availability of sensor data taken by separate Electronic Control Units (ECUs) with some minor exceptions such as vehicle speed, braking status, and hand wheel angle that are available on the vehicle bus.

Sharing pre-crash sensor data across safety systems will allow for more advanced algorithms that can provide a higher level of safety for all occupants of the vehicle. Not only will vehicle impacts and rollover events result in less severe injuries, but the number of these events and near events can be reduced. The sharing of sensor data not only provides the opportunity for improvements in safety performance, but with a well defined electrical system architecture this will also allow for up integration of what was once generally independent ECUs that will lower vehicle cost and help ease packaging and wiring constraints.

Keywords: active safety, electrical architecture, passive safety, pre-crash, rollover

1 Introduction

The primary objective of vehicle safety systems is to provide the best possible protection for drivers, occupants, and pedestrians. The integration of active safety and passive safety systems will provide the added benefit of crash avoidance, reduction of crash severity, and injury reduction.

Initial safety initiatives emphasized crash worthiness (e.g.: saving lives and minimizing injuries when a crash occurs) and focused on passive devices and features (e.g.: seatbelts, airbags, knee bolsters, and crush zones). Additionally, passive preventive measures (e.g.: improving visibility, headlights, windshield wipers, tire traction) were introduced to further assist in reducing crash opportunities. These passive safety initiatives have resulted in dramatically reducing the rate of crash-related injury severity and fatalities. However, in spite of these impressive improvements, still 6.3M vehicle crashes involving over 11.3M vehicles occur each year in the US that accounts for staggering deaths, injuries, and property losses [1]. The annual society costs for these crashes are over $230B [2].

Lately, a variety of "Active Safety" products have been introduced to further enhance the safety objective to achieve additional crash safety benefit improvements. Theses products utilize a variety of detection sensors (e.g.: radar, lidar, camera) to provide a variety of features (e.g.: forward collision warning, lane departure warning, pre-crash, etc.). The U.S Government has recognized the benefits of Active Safety systems and has indicated it would be re-focusing its efforts from Crash Worthiness to Crash Avoidance, since it is expected to provide a higher return value [3][4].

Collectively, these "Active Safety" products provide a means to further enhance roadway safety by enabling sophisticated technologies to recognize precursor collision events and then to actively assist the driver to avoid the crash. In the case when the crash can not be avoided, "pre-crash" systems will activate safety devices to further improve occupant safety protection performance.

A pre-crash system provides the capability to detect and assess an imminent crash event that a driver would not otherwise be able to avoid with any possible evasive maneuver action (e.g.: swerve or brake). The pre-crash technologies estimate the hazardous object kinematic parameter characteristics (e.g.: speed, direction, impact point, time-to-collision, object width, object classification, etc.) and activate appropriate countermeasures prior to the impact to assist in reducing the crash severity. These countermeasures could include resettable devices (seatbelts, articulating energy absorbers), active vehicle control actions (braking, steering), and adaptive crash sensing thresholds to enhance passive safety restraint deployments, to assist in reducing the crash severity by: (i) properly positioning the occupants of the vehicle for maximum benefit of the on-board restraint systems; (ii) preparing the vehicle to optimally absorb the crash energy; (iii) decelerating the vehicle to reduce the overall crash energy. Thus, pre-crash systems offer the opportunity to improve the effectiveness of passive safety restraint systems (seat belts, pretensioners, and airbags) by using the time between the initial recognition of the imminent crash and the actual impact to tune the restraint system and position the occupants. Through the use of pre-crash system, this precious extra time can now be made available allowing new types of passive safety devices to be conceived, and preventive active and passive safety systems can be linked.

2 Discussion

Pre-Crash System as Component to a Total Integrated Safety System Approach

The Integrated Safety System (ISS) philosophy is a total systems approach that describes the interaction of active / passive safety systems to the complete driving experience [5]. It is comprised of five interdependent safety states: (i) Normal Driving State: enable the driver to remain comfortable, alert, and aware of the driving environment, (ii) Warning State: assess crash precursor events and enable an alert to cause the driver to initiate crash avoidance actions, (iii) Collision Avoidable State: if appropriate corrective action is not sufficient or not taken, enact autonomous vehicle control actions to avoid crash, (iv) Collision Unavoidable State: enhance occupant protection through pre-crash severity-reducing initiatives and post-contact enhanced passive safety devices, and (v) Post Collision State: enact automatic rescue effort notification. The ISS states can be distinctly represented by either the Avoidance

Zone (e.g.: safety initiatives focused on crash elimination) or Mitigation Zone (safety initiatives focused on reducing crash severity).

The time-line of an evolving crash event, with respect to the five ISS states, is illustrated in Figure 1. In the event a crash event is imminent; the system transitions from the Avoidance Zone to the Mitigation Zone and immediately enters the "Crash Unavoidable State." This state is composed of the "Pre-Crash" and "Post-Contact" Zones. Typically, a driver is unable to perform an evasive maneuver to avoid an imminent crash event with a time period of less that 500ms. Thus, the Pre-Crash Zone countermeasures are typically evoked in the time period horizon ($\approx$0.5s < T_{PC} < impact) before the imminent crash event. Additionally, based upon reducing false alarm warning alerts, the Avoidance Zone countermeasures are typically applied during the time period horizon ($\approx$3s < T_A < $\approx$0.5s) prior to the imminent crash event.

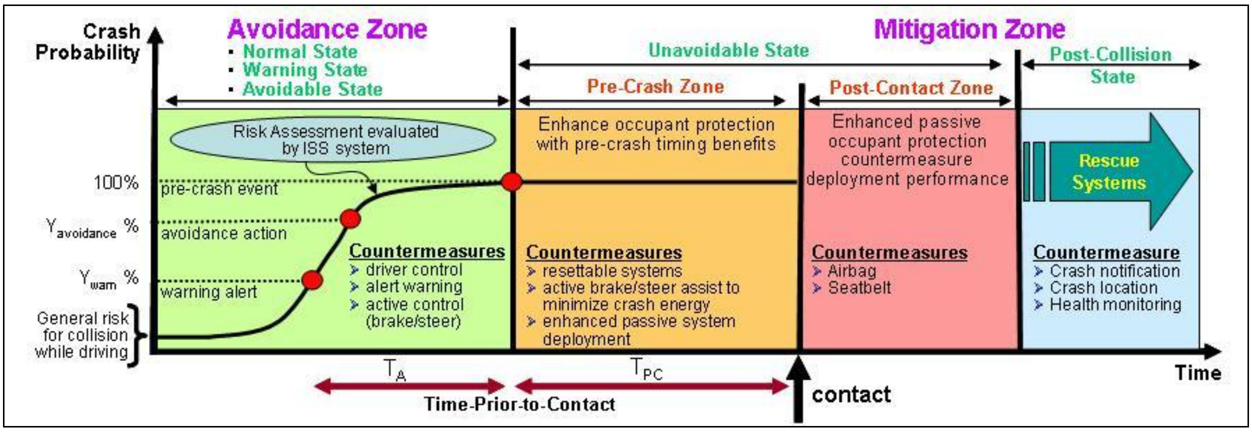

Figure 1: Crash Event Timeline (Avoidance/Pre-Crash/Mitigation Zone Relationship)

Pre-Crash Accident Analysis

The following field data were obtained from the 2000 National Accident Sampling System/General Estimates System (NASS-GES). GES data is a weighted sample of nationally representative sample of 54,000 police-reported vehicle crashes of all types, from minor to fatal. Statistical sampling weights are provided, so that results can be extrapolated to represent U.S. crash experience. The sample in this study consisted of 6.4M crashes, involving 11,3M vehicles and 35,977 fatalities.

From a pre-crash system perspective, the focus should concentrate on defining crash categories with respect to the point-of-impact to the vehicle, such as: (i) Front, (ii) Side, (iii) Rear, and (iv) Rollover. Table 1 summarizes the frequency distribution for the four Crash Categories. As such, nearly half of all crashes are associated with frontal impacts. Table 2 and 3 describes the type of crash object associated with frontal and side crashes, respectively. The side crash object distribution is based upon 2000-2006 NASS-CDS & FARS with AIS2+ injuries. Table 4 summarizes the scenario description for the frontal in-lane crashes [6]. The crash environment is quite complex and varied.

Table 1: Pre-Crash Crash Distribution

Crash Category	Crash Distribution	
	Total (11,346,185)	**Fatalities (35,977)**
Front	46%	39%
Side	29%	25%
Rear	22%	3%
Rollover	2%	31%
Other/Unknown	1%	2%

Table 2: Crash Object Type Distribution (Frontal)

Crash Object Type	Distribution
Vehicle	70%
Wide Object (barrier, ditch, fence, wall, building, curb, bridge)	12%
Narrow Object (trees, poles, fire hydrant)	11%
Other Object	6%
Other/Unknown	1%

Table 3: Crash Object Type Distribution (Side)

Crash Object Type	Distribution
Vehicle	81%
Large Tree (diameter >10cm)	10%
Medium Pole (10cm < dia ≤ 30cm)	3%
Large Pole (diameter > 30cm)	2%
Other Object	4%

Table 4: Crash Scenario Distribution (Frontal in-lane)

Crash Scenario	Distribution
Lead Vehicle Decelerating	57%
Lead Vehicle Stopped	28%
Lead Vehicle Moving	10%
Following Changes Lane	2%
Lead Vehicle Changing Lane	2%
Lead Vehicle Accelerating	1%

Frontal Pre-Crash System Implementation and Operation

Sensors based on radar, laser, and vision technologies, used to detect objects and identify their kinemetic characteristics, along with in-path object selection and crash prediction algorithms, utilizing the object kinematics data and vehicle dynamics knowledge, form the basis of a pre-crash system that can assess when a collision event becomes practically unavoidable. At this point, the PCS system will activate appropriate countermeasures to reduce the crash severity.

Pre-Crash – Collision Imminent Braking (PCS-CIB) System

One such PCS countermeasure feature is the activation of the brake system to reduce the crash speed and crash energy. The benefit of a PCS-CIB system operation is illustrated in Figure 1. It shows that through the reduction of crash speed, a reduction of MAIS3+ injuries is able to be achieved. Two types of Collision Imminent Brake (CIB) countermeasure functions exist; they are Panic Brake Assist (PBA) and Autonomous Brake Assist (ABA).

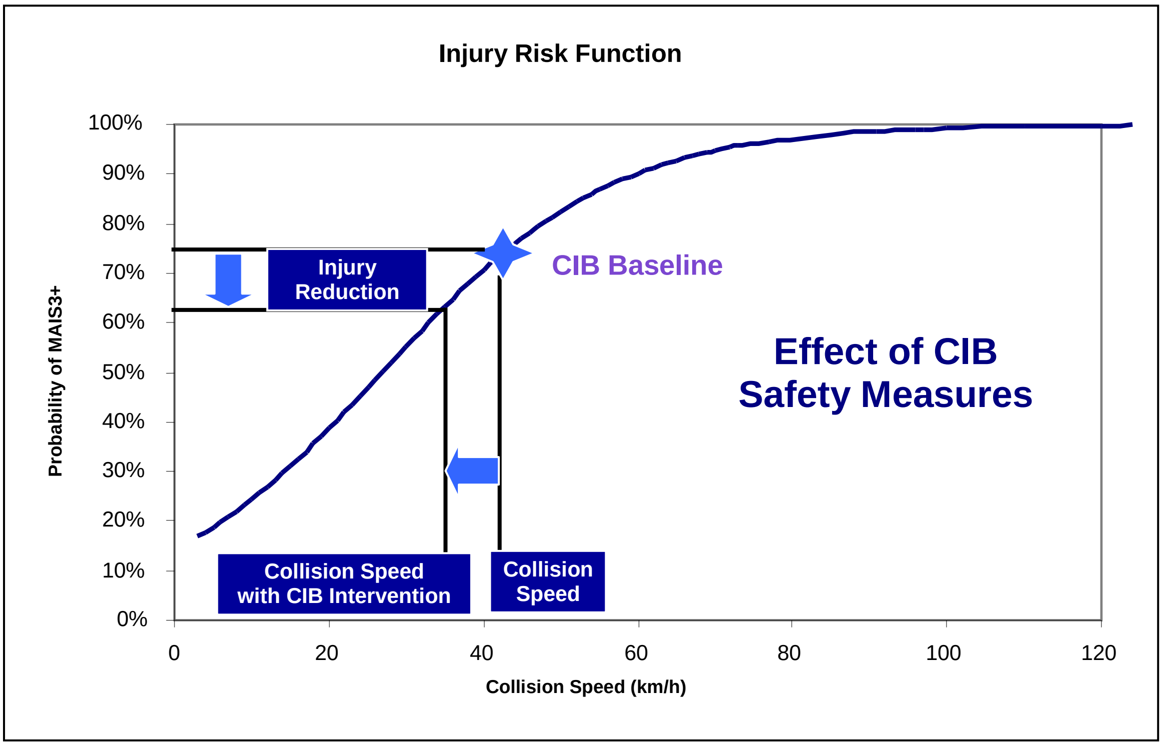

Figure 2: Benefits of PCS-CIB Systems

The PBA feature requires the driver to initiate a crash intervention action before the PCS system will provide any crash-severity reduction assistance. When the PCS system has predicted an imminent crash event, the PBA feature will automatically activate a pre-charge of the brake system in order to shorten the brake response time in anticipation of a driver initiated braking action. When the driver initiates the braking action, then the PBA feature will apply additional brake pressure to improve further the driver's braking response and, thereby, further reducing the crash speed. Given the driver initiated brake action 500 ms before impact, the PBA feature is able to provide an additional crash speed reduction of 6.5 km/h (4 mph),; while 16 km/h (10mph) crash speed reduction action can be achieved if the driver initiated a brake action 1000 ms before impact. Unfortunately, based on 2003 GES data, only 50% of drivers initiate a braking action prior to the crash, while only 30% initiate a braking action prior to a fatal crash event. Thus, the PCS-PBA system is unable to be totally effective in achieving crash energy reduction for all crash events.

The ABA feature is an improvement over the PBA feature in that when the PCS system has assessed an imminent crash event, the ABA feature automatically activates a braking action. Thereby, each pre-crash equipped vehicle can derive the crash severity reduction benefit in the event of a crash. The crash speed can be reduced by approximately 5 km/h (3mph) given a 500 ms pre-crash activation timing, while 17 km/h (10.5 mph) crash speed reduction action can be achieved with a pre-crash trigger activation timing of 1000 ms.

Of course, with the complexity of the "real world" environment (e.g.: poles, trees, signs), the opportunities for false triggering of autonomous brake actions on out-of-path objects that are incorrectly assessed as in the host vehicle's path becomes an issue. Additionally, there is also a risk of false triggering on in-path non-threatening objects such as embedded road objects (e.g.: man-hole covers, gratings), and blowing low-mass objects (e.g.: aluminum cans, boxes, etc.). As such, an autonomous brake activation action will require a PCS-ABA system implementation that provides high reliability and robust operation (e.g.: low tolerance of false activations and minimal missed activations) under a variety of driver, roadway and environmental conditions. This type of autonomous system operation will require a sensor fusion feature implementation between radar and vision systems. Sensor fusion provides the real opportunity needed to predict the crash severity. Through sensor fusion, the system utilizes the best attributes of both radar and vision detection sensors. The radar sensor provides superior performance capability for range and range rate; while the vision sensor provides the complimentary capability of improved angle performance (relative angle, object width, etc), with the additional ability of object classification.

Pre-Crash Enhanced Frontal Crash Sensing System

The wealth of additional data about the crash object (e.g.: speed, direction, impact point, time-to-collision, object width, object classification, etc.) that a pre-crash system is able to offer will provide new opportunities to further extend passive safety restraint system effectiveness. For instance, a simple pre-crash system implementation that provides only the relative range rate parameter information of the impending crash object can improve the logic decision process of the crash sensing operation for post-contact airbag deployment. Preliminary results performed by Delphi, have shown the following performance improvements: (i) Improved immunity for low-speed, no-deploy barrier events, (ii) Offset Deformable Barrier (ODB) deploy time decreased by 50%, (iii) High speed pole/ 0-degree barrier/ NCAP deploy time decreased by 20%, and (iv) Eliminate the need for frontal satellite accelerometers. With the possible elimination of the frontal satellite sensors provides the added benefit of both cost reduction and vehicle integration issues.

Side Pre-Crash System Implementation and Operation

The sensing conditions and decision logic associated with a Side Pre-Crash System will be necessarily different than for a Frontal Pre-Crash System.

Frontal pre-crash systems attempt to achieve crash reduction severity by both reducing crash energy through brake activations and enhancing the safety benefits of passive safety restraint system activation. Thus, in order to enable the brake activation feature, the ability of the pre-crash sensor to detect/track the hazardous object will necessarily require the sensor to provide medium range capability. For example, if the closing velocity of the imminent crash object is 72kph (45mph), and the brake activation event is initiated at 1000ms, then the sensor must be able to detect objects in excess of 20m. Additionally, the integration of active safety and passive safety can provide opportunities for enabling adaptive crash sensing thresholds to further enhance passive safety restraint deployments, along with pre-crash capable frontal airbag concepts. In the immediate future, it is unlikely that frontal pre-crash systems will be utilized to enable pre-contact frontal airbag activation, due to the inherent dangers of the occupants being exposed to a frontal airbag deployment as a result of a false pre-crash trigger deployment event.

Alternatively, side pre-crash systems will not require the pre-crash sensor to detect/track crash imminent objects at long ranges, since a brake activation countermeasure will not be effective. As such, the pre-crash detection sensor will only need to have short range capability. However, a recent Delphi analysis study has shown promising results that a side pre-crash activated side air-bag deployment 20ms prior to impact can provide significant injury reducing benefit to the occupants.

Rollover Pre-Crash System Implementation and Operation

Occupant safety can also be improved for rollover crashes using pre-crash information. The most common type of rollover event, with an occurrence rate of over 50%, is a trip over [7]. A required precursor to a trip over is a loss of vehicle control resulting in the vehicle sliding sideways. Electronic Stability Control (ESC) systems have long been available on vehicles to reduce the likelihood of losing control and, therefore, prevent a vehicle from rolling over. ESC is an example of an Avoidance Zone technology, but data from the ESC sensors can be use in the Mitigation Zone as well.

There are four primary inputs for ESC: yaw rate, low g range lateral acceleration, hand wheel angle, and vehicle speed. The yaw rate and lateral acceleration sensors are packaged in a single module often referred to as an Inertial Measurement Unit (IMU). The IMU is usually located on the vehicle tunnel near the vehicle center of gravity. This is also the typical location of the Airbag

Control Unit (ACU). The ESC feature is performed by the braking system. The IMU and hand wheel sensor traditionally interface with the brake ECU either via direct wiring or a dedicated high speed CAN bus.

Various architectures have been studied to find the optimum solution to allow the IMU, brake ECU, and the ACU to interface. The recommended solution is to integrate the IMU into the ACU and use high speed CAN between the hand wheel sensor, brake ECU, and IMU/ACU [8]. The primary enabler to this solution is government initiatives which greatly increase the application rate of ESC. After September, 2011, ESC is a required feature on passenger vehicles with Gross Vehicle Weight less than 4526 Kg in the US [9]. The European Commission is also drafting a proposal requiring ESC. In addition, this architecture provides lower component costs, increased packaging flexibility due to eliminating a separate module, higher reliability due to fewer parts, reduced wiring, and fewer parts to assemble into the vehicle.

It has been documented by Cooperrider, et. al. that lateral velocity is a key indicator of whether a vehicle will roll or not during soil trip events [10]. The ESC sensor set provides the ability to determine the velocity vector of the vehicle. This information is extremely helpful in providing robust, early discrimination during trip over events while maintaining a high level of immunity to abuse and misuse conditions.

Typical rollover detection systems use roll rate and acceleration to detect the onset of a rollover event. These systems deploy window curtains and seat belt pretensioners to reduce occupant injuries and ejections. Deployment decision times for rollover events are usually defined by the time required for an occupant to enter the window curtain deployment zone.

Soil trips pose a challenge in that the lateral forces generated by the vehicle's wheels furrowing while sliding sideways also cause the occupant to move towards the curtain deployment zone. As a result, the desired deployment time is at a very low roll angle. Figure 3 shows two soil trip tests for the same vehicle: 16 km/h lateral velocity, no-rollover and 30 km/h lateral velocity, rollover. For the 30 km/h event, the desired time to fire (TTF) is 194 ms. The roll rate, roll angle, and lateral acceleration for these events are virtually indistinguishable before the TTF. Clearly there is not enough information in these signals to reliably separate the events and reliably deploy countermeasures. The additional information provided by the ESC sensors does allow them to be separated.

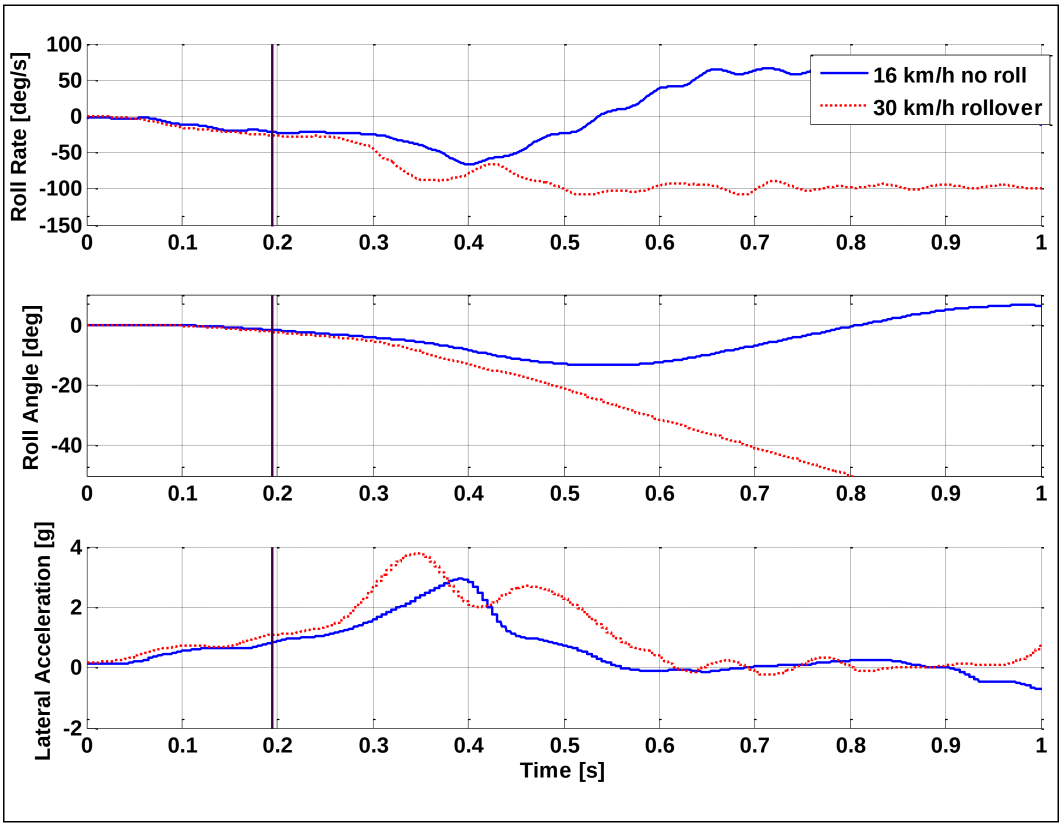

Figure 3: Comparison of Roll and No roll Soil Trip Events

A new rollover discrimination algorithm, ALGO-R2, has been developed to make use of the ESC sensors and is shown in Figure 4. Although the discussion above has focused on soil trip events, the same concepts can also be applied to curb trip events. ALGO-R2 has been calibrated across different vehicle types to demonstrate its performance capabilities. The results are shown in Table 4. These results have been achieved while still maintaining high level of immunity to various abuse, misuse, and driving conditions.

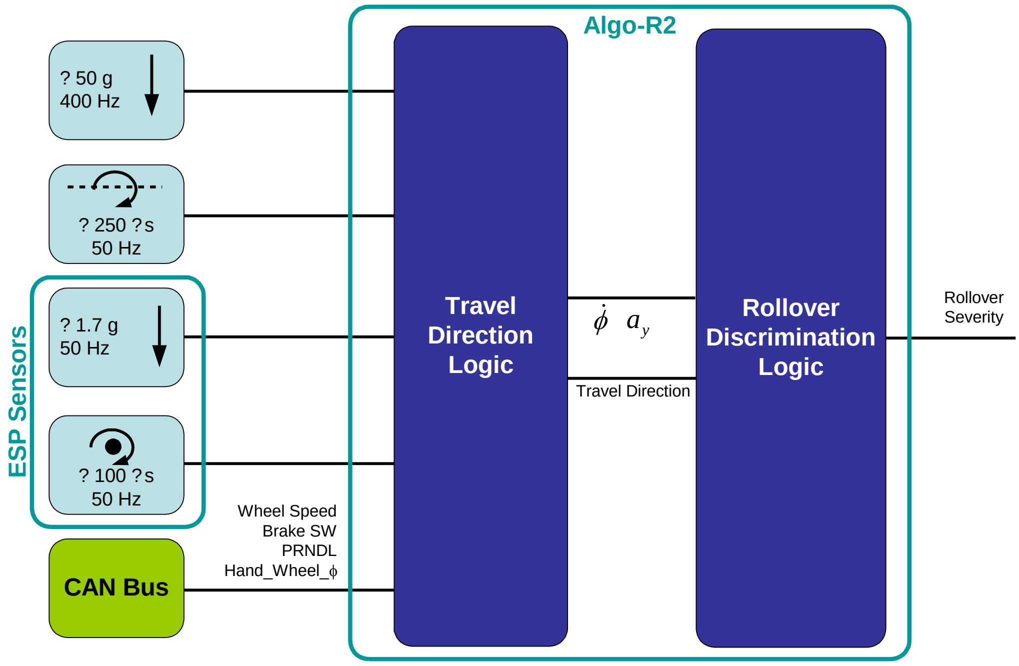

Figure 4: ALGO-R2 Diagram

Table 4: ALGO-R2 Performance Improvements on Tripped Rollover Events

Test	Speed (km/h)	Improvement	Test	Speed (km/h)	Improvement
Curb	17	28%	Soil	25	31%
Curb	18	33%	Soil	25	39%
Curb	18	29%	Soil	25	45%
Curb	19	25%	Soil	25	41%
Curb	19	37%	Soil	25	35%
Curb	19	38%	Soil	25	41%
Curb	19	32%	Soil	25	29%
Curb	19	50%	Soil	28	25%
Curb	19	32%	Soil	29	26%
Curb	20	42%	Soil	29	28%
Curb	22	39%	Soil	29	29%
Curb	23	39%	Soil	30	25%
Curb	24	38%	Soil	30	29%
Curb	24	42%	Soil	30	37%
Curb	24	42%	Soil	30	38%
Curb	24	33%	Soil	30	30%
Curb	24	29%	Soil	30	41%
Curb	24	41%	Soil	30	35%
Curb	24	26%	Soil	30	26%
Curb	24	28%	Soil	31	29%
Curb	24	29%	Soil	31	28%
Curb	24	33%	Soil	31	31%
Curb	24	37%	Soil	32	49%
Curb	25	42%	Soil	32	29%
Curb	28	24%	Soil	33	28%
Curb	28	24%	Soil	36	33%
Curb	28	29%	Soil	36	72%

3 Conclusion

Pre-crash sensing technologies enhance roadway safety by recognizing precursor collision events and then actively assisting the driver to avoid the crash. The assistance may be in the form of an alert intended to make the driver aware of the situation and initiate action or the assistance may be the vehicle acting autonomously, such as brake assistance or electronic stability control, to reduce the likelihood of a collision and reduce the injuries should a collision occur. Further, pre-crash systems can be used to provide significant occupant safety improvements by augmenting the passive safety restraint systems such as activating resettable seat belt pretensionsers or, once a crash becomes unavoidable, enhancing traditional crash sensing algorithms to act based on the specific situation occurring..

The frontal crash sensing can be improved by knowledge that a crash is imminent and where the impact will occur, allowing the ACU to tune the crash sensing algorithm to the situation occurring. Improvements have been found in immunity for low speed no-deploy events, offset deformable barrier collisions, and high speed pole impacts by using pre-crash data with the traditional crash sensors. The pre-crash data may even allow the elimination of some of the traditional remote frontal sensors.

Significant occupant injury reduction results when side airbag deployments can be initiated pre-contact. Having pre-crash side / curtain deployments prior to eminent side impacts greatly reduces the risk of the occupant contacting the interior side of the vehicle prior to full deployment of the airbag in such events.

Rollover sensing can be improved by using the information about the vehicle motion prior to the rollover onset to achieve early deployments for trip events while maintaining high immunity to abuse and misuse events. This performance can be gained without adding new sensors to a vehicle using a traditional rollover sensor, but by only allowing the ESC sensor set to be interfaced with the ACU. In addition, integrating the ESC sensors into the ACU provides cost savings, packaging flexibility, and easier assembly in addition to the crash sensing performance increases.

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