DISCLAIMER: This file presents information in a potential area of automotive advanced safety system technology. The information presented in this file is in no way intended to be, either directly or indirectly, representative of completely formulated and organized aspects of the respective technology, and should not be assumed to be such unless it is expressly indicated to the contrary by the inventor via a formal notification method of his choosing. It is not intended to take the place of laws, regulations, safe driving habits or common sense. ALWAYS DRIVE SAFELY! This proviso may apply to any other works by the inventor.

A New Systems Engineering Approach to Multi-Sensor based Collision Warning and Avoidance Systems

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Abstract

This systems engineering approach towards designing and developing requirements for a portion of a collision warning and avoidance system (CWAS) is based upon experience gained while assigned to Ford Motor Company's Research and Advanced Engineering group. As a design engineer, I participated in the design and development of a forward sensing system specification for a multi-sensor based collision warning and avoidance system including (but not limited to) frequency modulated continuous wave radar, monocular vision, and yaw rate sensing modalities. The primary suppliers for this project were Delphi Corporation and Mobile Eye Vision Systems. One intent of this project was to design and develop a set of systems requirements leading to a forward sensing system appropriate for commercial automotive applications with the goal of a production safety system towards the end of this decade.

The systems engineering approach towards requirements design and development applied by Ford Motor Company was to let the supplier(s) come up with a prototype collision warning and avoidance system and then to extensively test and evaluate the system under a wide range of operating conditions, letting the failure modes of the prototype system drive future requirements and systems development.

This paper starts with a proposed conceptual system architecture for a CWAS. It then covers functional and performance requirements for CWAS tasks including (but not limited to) detection, tracking, and classification along Precrash sensing scenarios as a means to support requirements development and facilitate system testing and verification. A brief look is then taken at testing and verification methodologies (both static and dynamic). From there, an overview of the radar and vision systems is covered as well as how sensor and data fusion might be performed.

The last major portion of this paper includes a more elaborate description of the systems interfacing with the forward sensing system including the sensor management system and the threat assessment unit. A more detailed look is then taken at the subsystems within the Threat Assessment Unit including the Collision Estimator and the Path Prediction subsystem as well as how it may interface to the Active and Passive Safety subsystems. Finally, potential subsystems and control signals are added to the conceptual system architecture for the CWAS.

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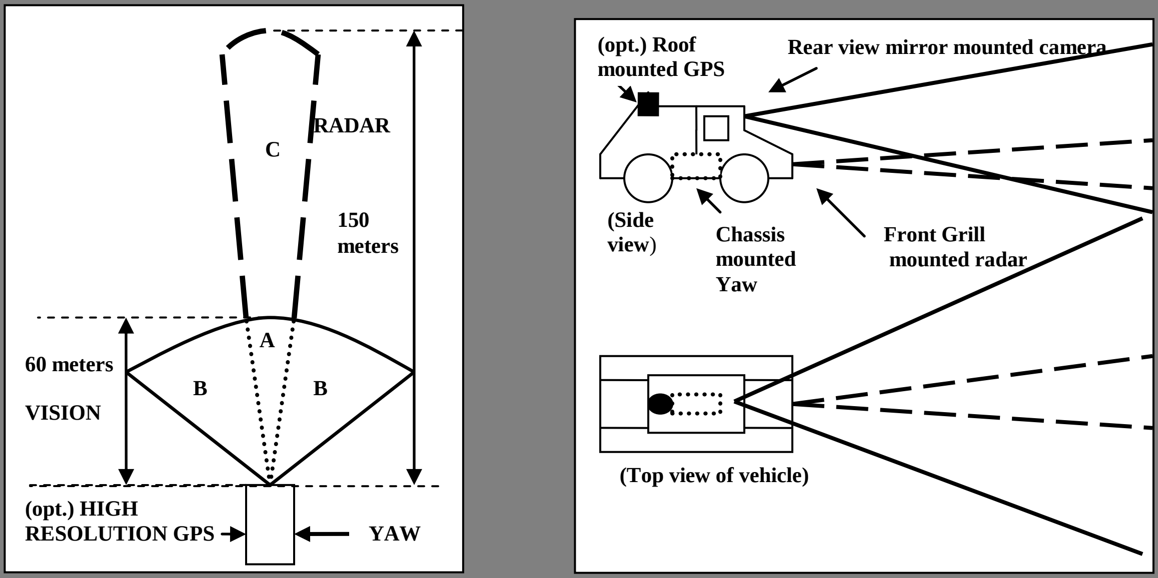


Figure 1: Three (with optional fourth) primary sensing modalities in FSS of vehicle and their regions of interest

1 Introduction

The purpose of a collision warning and avoidance system is to assist in the maintenance of a safe state of vehicle operation under all circumstances, and if an unsafe operating condition does arise, to notify the vehicle operator of the condition. If it turns out that this unsafe state has lead to a situation where a collision is imminent, the goal is to minimize the severity of the collision. This field has been investigated heavily in the last fifteen to twenty years, finding a portion of its original commercial popularity with the addition of radar systems to large trucks who's drivers usually spent large periods of time on the road driving and were susceptible to 'driver drowsiness'. The military has also been investigating this area of technology for a substantial period of time and various government agencies have also taken an interest in this field. However, it has been primarily in the last ten to fifteen years that the automotive industry has realized the enormous potential in collision warning and avoidance systems pertaining to vehicular safety. It has also been during this period of time that the industry has realized the incredibly high level of technology required for implementing this level of safety along with the potentially colossal pitfalls associated with problems arising in these systems. Back in the 1995, Ford Motor Company and General Motors formed the Crash Avoidance Metrics Partnership (CAMP) aimed at improving traffic safety by accelerating the development of technologies associated with crash avoidance countermeasures [1]. This partnership has spawned many new partnerships for projects over the last nine years amongst various companies within the automotive field. Some of them include the Forward Crash Warning Requirements, Driver Workload Metrics, Enhanced Digital Maps for Safety, and Vehicle Safety Communications [1].

The development of well-written, clear, concise, accurate, and thorough requirements in an area of technology that has so much being discovered about it on a day-to-day basis can be a daunting task. When you also consider the fact that suppliers nowadays are performing a major portion of the design and development tasks from a set of specifications, along with the fact that it should generally be the intent of the company outsourcing the engineering work to mandate 'what' the system should do but not 'how' it should be done (specific to the case of systems requirements), the undertaking becomes even more challenging. Of course, there are always exceptions to the rule of imposing design constraints. Take for example the scenario of having to set up specific bus messages for information communication within a vehicle. Nonetheless, it is for this reason that the development of requirements for collision warning and avoidance systems is such a major undertaking. A well written set of systems requirements can generally be broken up into the following categories:

1) Introduction and assumptions.
2) Organization.
3) Definitions and relevant figures.
4) Functional requirements.
5) Performance requirements.
6) Testing and verification.
7) Features and bus messaging.
8) Sensor specifications.
9) Mechanical specifications.
10) Electrical specifications.

A proposed abstract preliminary system architecture for a collision warning and avoidance system (including the forward sensing system) is shown in figure two below.

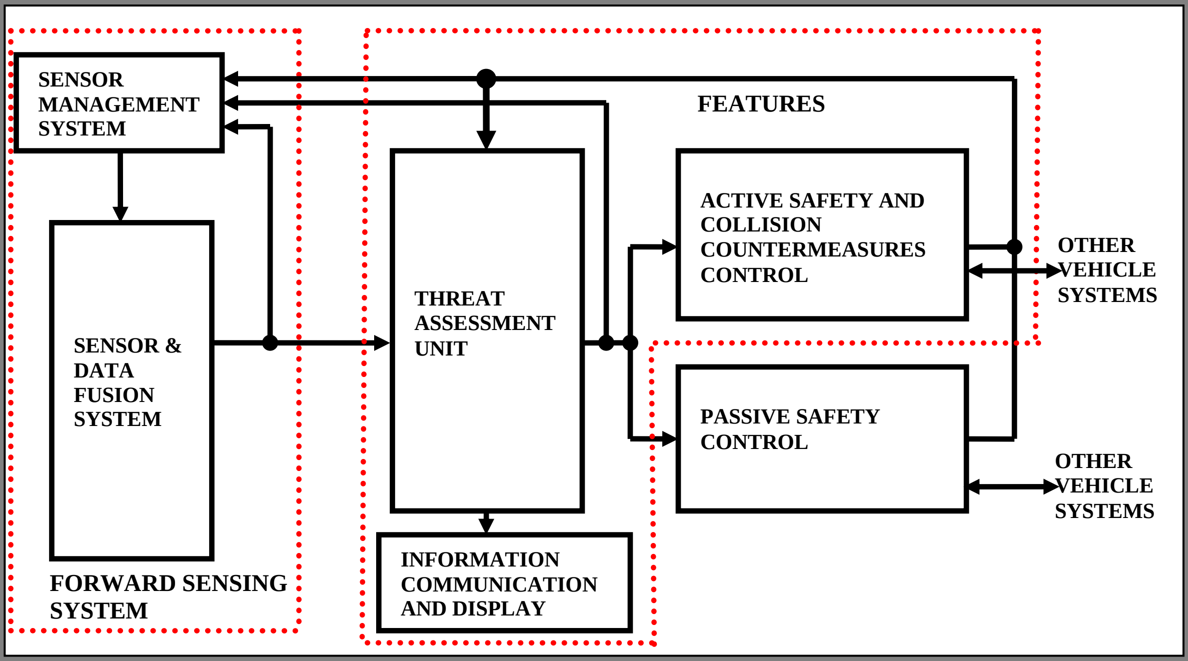


Figure 2: Potential Preliminary System architecture of CWAS including FSS

The sensor management system, forward sensing system, and threat assessment unit will each have portions of this paper dedicated to them. Some general information will also be included on the Active Safety and collision countermeasures system and Passive Safety systems. However, the initial focus will be on the Forward Sensing System's functional and performance requirements as they relate to detection, tracking, and classification.

It should be noted that the main output of the forward sensing system is a target report including (but not limited to) range, range rate, azimuth, road and lane information, environmental conditions, and sensor confidence levels. This information is fed into the threat assessment unit and is converted to primary target and secondary target specific information (as well as other specifics). A primary target may be defined as the closest in-path valid target. A secondary target may be defined as any currently tracked target other than the primary target. All of this target report information is available to the features, that is, the specific functional units within the collision warning and avoidance system which will operate on these target reports and produce their own specifically tailored functionality. The features for this particular system include (but are not limited to) Forward Collision Warning, Heading Control, Adaptive Cruise Control (including Urban adaptive cruise control), Situation Awareness, Lane Keeping and Lane Departure Warning, and Collision Mitigation By Braking.

It should also be noted that while future safety system technologies (ex: X-by-wire) will require fault-operational hardware and software designs inherent in distributed redundant systems with fail-operational architectures, this particular facet will not be covered in this paper.

2 CWAS Systems Functionality & Performance

A major portion of the FSS specification will be geared towards what specifically the system is supposed to do and how well it is required to do it. These requirements primarily revolved around the tasks of detection, tracking, and classification. Specifically, detection is the ability to observe the presence of an object [2]. However, the system must be able to not only detect an object's presence but to discriminate between meaningful and superfluous information (clutter, weather or other obscurants, etc.) that a vehicle operator might encounter during his or her journeys. This discrimination must be performed under any and all environmental conditions, during steady-state, transitional , and emergency maneuvers, and on every type of thoroughfare that an operator may encounter. Of course, at the beginning of the specification is a section which dictates what specifically the reasonable assumptions are under which the forward sensing system is supposed to operate. A major undertaking during the process of detection is that of determining precisely what should and shouldn't be regarded as relevant. A relevant object should be considered as any object whose direct interaction with the current (or future) path of travel of the vehicle may require either operator or safety system interaction. As can be inferred from this statement, the possibilities are endless, and are a source of constant debate.

Tracking is the ability of a system to estimate the state of a target both at the current time (filtering) and at any point in the future (prediction) [3]. The process of tracking a single object can be difficult, but consider the task of tracking twenty targets while driving on a busy expressway during rush-hour traffic. Tracking includes (but is not limited to) new track initiation, track management, and track removal, and can be centralized, distributed, or a combination of the two. There are many factors which influence the ability of a system to track targets including system processing speed, system information throughput, sensor resolution, sensor performance, sensor accuracy, algorithm efficiency, tracking system architecture, and the effectiveness of the sensor management system, just to name a few.

Classification is the ability to recognize an object as belonging to a certain class of objects while identification is the next further progressive step in analysis and involves the differentiation within the particular class type. For example, an object on the road may be classified as vehicle or non-vehicle and then a vehicle can be further identified as car, truck, van, bus, semi, etc. Classification can be performed in a number of different ways: from template matching to complex algorithms solely dedicated for pattern recognition. The ability of a system to classify objects in a real-time environment is incredibly complex (as is tracking) and is dependent on everything from the resolution of hardware, processing speed and information throughput in hardware and software, algorithm efficiency, architectural choice, environmental conditions, and range, number, and type of objects being monitored, just to name a few. Figure three below shows a context diagram for the forward sensing portion of the collision warning and avoidance system.

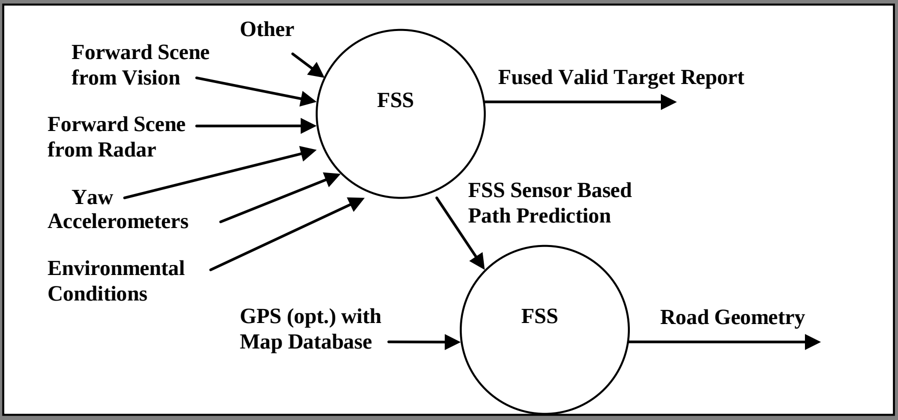


Figure 3: Context diagram of Forward Sensing System portion of Collision Warning & Avoidance System

The list of functional requirements for a system of this complexity are too numerous to list in their entirety. For the sake of brevity, I will include a very brief sampling of some of the more obvious ones. Note that numerous documents have been previously written in this area and can be viewed on the National Highway Transportation Association (NHTSA) website listed in the references for this paper. Several other links to informational sites are listed on this NHTSA website as well. With that being said, the forward sensing system must be able to extract target and other information from a fused version of the forward scene incorporating vision, radar, yaw rate, environmental conditions, and (optionally) global positioning system (GPS) as shown in figure three above. Information extracted from the environmental conditions will contribute to a confidence factor for each of the sensor readings while information in the forward scene will be used to predict the path of travel based on yaw, lane markers, road edge, traffic patterns and possibly GPS. Information on the road (coming from optional GPS with map data), combined with the sensor based path prediction, will aid in predicting road geometry which will be supplied as information to the features. The target report that is produced by the FSS will be combined with the predicted path of travel to provide an estimate of the collision conditions. Additionally, the FSS will accurately and robustly detect objects in the forward scene, track those objects, and classify them according to vehicle or non-vehicle, small, medium, or large, moving, stationary, or stationary with previous movement, etc. Additionally, the FSS should be able to discriminate bridges at a range of XX meters or less.

Specific to the tasks of detection, tracking, and classification, a set of standard metrics can be used to identify the primary processes within each task. These common metrics are input, processing, control, output, and performance. Again note that the list is not comprehensive but gives a general idea as to some potential subtasks within each task.

Detection produces the decision on an object as being a valid or invalid target.

1) Input: The inputs to the detection task will consist of the forward Scene form the vision system, the forward scene from radar system, yaw rate, environmental conditions, possibly GPS, and the remainder of the sensing modalities.
2) Processing: The processing will be divided up into two sections since it is performed in fundamentally different fashions for radar and vision . The first section is for the radar system and the second is for the vision system.
   a) For *radar* based target identification in noise (and clutter), one goal is to maximize the effective target signal-to-noise (and signal-to-clutter) ratios, thus maximizing the detection probability of a target. This process involves analyzing objects (potential targets) for features and signal strengths that are related to those of the actual target. The spectral features of targets identified in advance can be compared to spectral features of objects (potential targets) and used in the identification algorithms. This process may be precluded by median or other types of filtering to remove spike type clutter. Once a target has been detected, range and range rate (velocity) information may be calculated as a function of wavelength, the speed of light, total round-trip wave propagation time, up-beat and down-beat frequencies, frequency change, etc.
   b) For *vision* based target identification in noise, a goal may be to match a predefined template model of an object (actual target) to a related template model of an object (potential target) in one frame of a scene and then find a corresponding match in a subsequent frame. This requires that the template models be known a-priori so they can be tracked. The degree of matching can be determined in different manners potentially including correlative methods, sum of squared difference, or simpler methods based on tokens or images. These methods produce optic flow or image-point correspondences. Preprocessing operations are usually performed as a precursor to template matching techniques and may including edge detection or other forms of filtering or smoothing. Upon detecting a target, range information may be calculated by exploiting models of the road geometry, the cameras perspective projection and camera lens specifics, knowledge of target sizes at specific ranges, etc. Accuracy in range rate calculations is heavily dependent on the accuracy in range data.
3) Control: *TBD*
4) Output: Valid target(s) report
5) Performance: *TBD (will partially be based on false negatives, false positives, etc. related to total system usage.)*

Tracking produces a variety of kinematic quantities pertaining to a set of valid targets within the field of view.

1) Input: Valid target(s) report with additional sensor information including time, position, and variance.
2) Processing [3]: a) Initialize a tentative track
   b) Process subsequent tracks as they are introduced, maintained, and removed from the system
   c) Handle divergent track conditions (multiple tracks emerging from single track)
   d) Handle track swaps (tracks of targets that switch due to inability to differentiate for finite time)
   e) Handle track to track associations (multiple tracks from same target)
   f) Remove track from system once all sensors are no longer producing readings for a particular target.
3) Control: *TBD*
4) Output: Estimate of the kinematic state of valid targets at present and future time including
   a) Track number
   b) Tracked target location (range, range rate, etc.)
5) Performance: *TBD (will partially be based on false tracks assignments, misassociations, etc. relative to total usage)*

Classification produces the assignment of a valid target to a class of targets:

1) Input: Valid target(s) report
2) Processing: The processing is again to be divided up into sections for the radar and vision subsystems
   a) For radar, classification is primarily dependent on vertical (elevation) and horizontal (azimuth) resolution cell size as well as proximity of potential targets to the host vehicle. As target proximity becomes nearer, additional features can be extracted, adding increasing spectral detail to be used in comparison to previously identified spectral features of the actual targets. In addition, target classification via inference based on target features may be used by comparing statistical knowledge of a potential target to that of a known target.

b) For vision, classification is primarily dependent on the resolution, sensitivity, and dynamic range of the vision system hardware as well as proximity of the potential target to the host vehicle. Efficiency of the classification algorithms as well as the processing speed of the vision hardware and software are paramount to successful real-time classification of targets.

3) Control: *TBD*
4) Output: Target classification according to:
   a) type (vehicle, non-vehicle, pedestrian, etc.)
   b) size (height, width, as it relates to small, medium, or large objects, etc.)
5) Performance: ***TBD (will partially be based on misclassifications, etc. related to total system usage)***

The features (as previously noted) are the specific functional units within the CWAS which will operate on the target reports (along with road specifics) and generate specific outcomes. The Forward Collision Warning (FCW) system focuses on the different characteristics of alert signals including visual and audible cues of different numbers, repetition rates, and other visual and audible properties. Visual cues are typically shown on a heads-up-display (HUD) or specially designed dashboard mounted display unit to notify the vehicle operator of a driving situation that needs to be addressed. A common method used to analyze potentially hazardous driving situations and a driver's response to them is the 'surrogate target' methodology [5].

Collision Mitigation by Braking (CMBB) is a feature that focuses on reducing the amount of time that elapses between the instant a driver presses on the brakes and the instant the vehicle begins to decelerate. It also addresses the assurance of generating full decelerative capability of a vehicle. It turns out that a very small amount of time saved can translate into a significant reduction in stopping distance. The three primary tasks involved in CMBB include pre-charge apply, actual application of the brakes, and panic brake assist.

Lane keeping and lane departure warning are related features and are focused on maintaining the position of a vehicle within its lane. The primary inputs to this feature are the camera system, steering wheel angle transducer, and steering wheel torque transducers. The short range camera field of view is monitored for lane markers to identify where the vehicle is supposed to be traveling and any deviations to this path. The system also monitors the current driving conditions experienced by the vehicle and performs an estimation of the vehicle state. This is then combined with the steering wheel angle and steering wheel torque to perform the required actuation for maintaining the vehicles position within the lane. The lane departure warning system feature notifies the driver of any deviation from the acceptable position within a lane that has not been intentionally initiated by the driver.

Urban adaptive cruise control (UACC) is different than the adaptive cruise control systems currently in production for vehicles operating in non-urban environments. It is sometimes also called Stop-and-Go Adaptive Cruise Control (SAGACC). This form of cruise control has specially designed hardware, software, and algorithms dedicated for travel in environments where there is frequent braking at low vehicle velocities or braking to a complete stop, such as during rush hour traffic. Another feature of UACC is for cruise control operation when approaching traffic lights or stop signs, which is a very significant task. This is partially due to the current technological limitations of existing inertial navigation systems.

Situation awareness is an 'idealized' situation in which all possible sensing modalities that could be included in a collision warning and avoidance system (radar, vision, yaw and other inertial, infrared, etc.) are fused to extract a thorough picture of the current environment. Consider the scenario of driving a host vehicle in a suburban neighborhood and approaching a school crossing. The GPS system or other navigation system combined with stored road maps might provide information as to the fact that a school is nearby. The vision system might be used to extract school crossing sign information from the side of the road or the white stripes on the ground for designated crossing areas. Rain sensors, the use of wipers, or the vision or radar systems might be used to alert the driver of hazardous road conditions. The vision and infrared might detect the presence of youngsters crossing the street and alert the driver to the fact. The radar and vision system might be used to detect when the crosswalk is not being used. Thus each of the modalities is combined to extract an overall understanding of the current state of the environment that the driver is experiencing.

Heading control is a feature that monitors the distance to vehicles in the forward scene. It takes into account target range, target range rate, and vehicle speed (to name a few) and can produce an audible or visual warning if the proximity to a 'lead' vehicle becomes too close. The warnings are generated via the FCW system and will generally range from low threat level to imminent collision.

Figure four on the following page gives a general idea as to how the features interact with the forward sensing system.

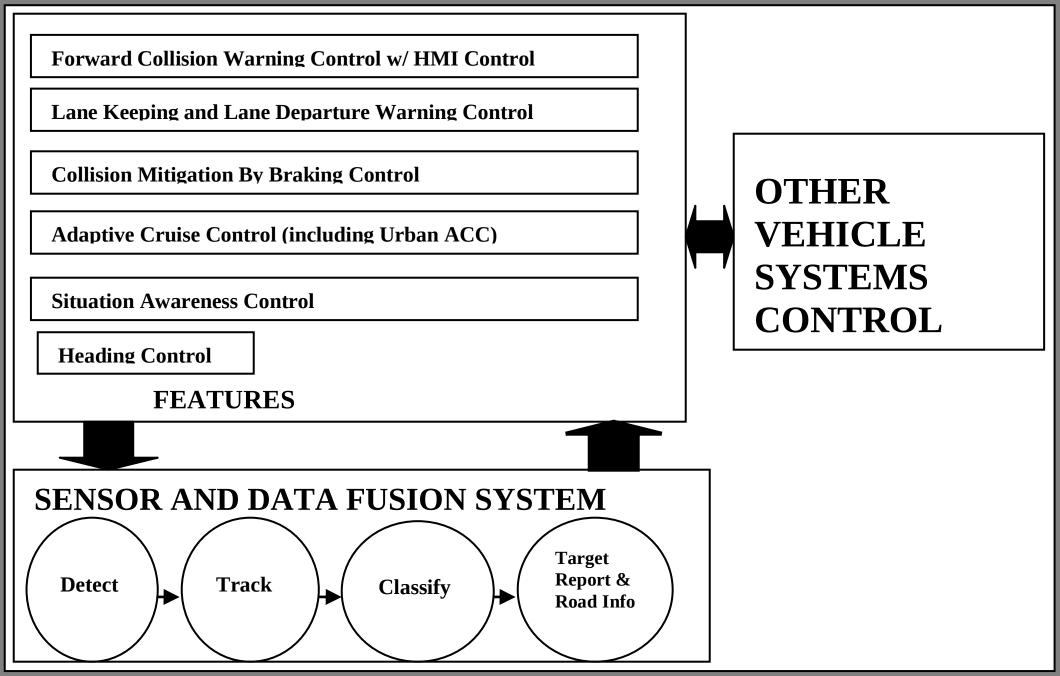


Figure 4: Interaction of features with Forward Sensing System and Vehicle subsystems control

As can be seen from figure four, the sensor and data fusion system will produce target reports and road information to be used by the features. The features will then directly interface with other vehicle systems which require safety system specific information for actuation and control. These subsystems may include those designated for inter-vehicle dynamics (IVD), suspension, and powertrain, to name a few. Note also that these subsystems may produce information that could be returned to the features for processing and control.

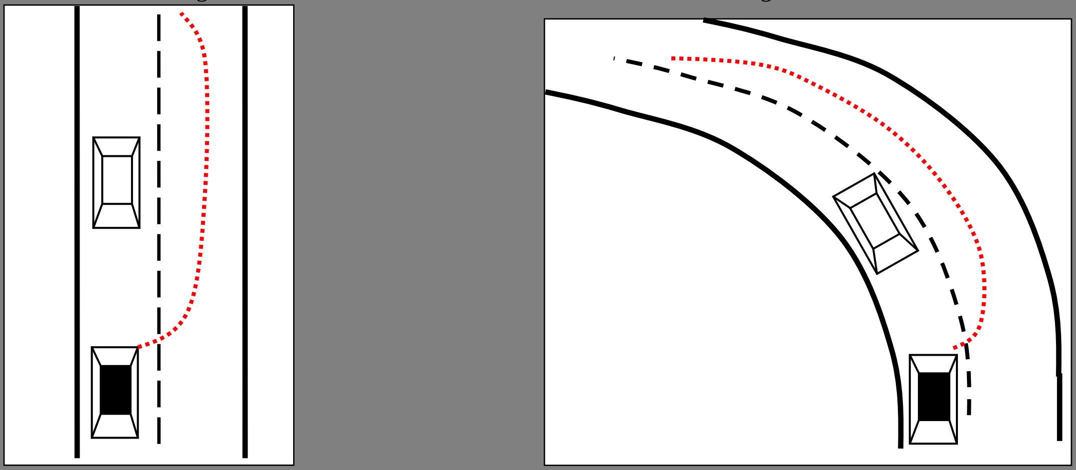
Thus, the functions of detection, tracking, and classification play a very important role when specifying the operational requirements for a safety system from the systems point of view. Both functional and performance requirements must be considered to not only ensure that a system does specifically what it is supposed to do, but also that it does it as well as it is supposed to do. This is one of the primary documents that the supplier and original equipment manufacturer (OEM) will use to ensure that the system is engineered in the proper fashion. While this document does serve to cover functional and performance requirements for a system, along with metrics for static and dynamic testing, it cannot comprehensively cover the vast number of scenarios that a driver of a CWAS equipped vehicle may have to deal with during his or her everyday travels.

3 CWAS PreCrash Sensing Scenarios

The PreCrash Sensing scenarios must contain the full range of scenarios that a driver might encounter during everyday travels with various types of vehicles on assorted types of roads under different environmental conditions with a mixture of types of vehicular and non-vehicular objects you find on roads. Some of the many types of objects that need to be considered are automobiles, trucks, busses, semi-tractor trailers, sport utility vehicles, motorcycles, pedestrians, and various forms of non-target clutter. Scenarios may range from having only two vehicles (one host and one target) to many vehicles (single host, multiple targets) as well as considering the effects of having multiple host vehicles (that is, multiple vehicles with forward sensing systems). These serve to establish one form of detailed scenarios and procedures that need to be followed during evaluation of a collision warning and avoidance system. A much more comprehensive look at the very many scenarios that need to be considered for evaluation of a collision warning and avoidance system is given in [9]. However, several of the very many scenarios might include the four in figure five below. Please note that these are only very general drawings with minimal detail included where the red dotted line designates the path of travel of a particular vehicle and the vehicle with black roof is host.

1) The host vehicle approaches a slower moving target vehicle in the same lane, passes it to the right, and then enters its original lane.

2) The host vehicle approaches a slower moving vehicle in the same lane on a curve, passes it to the right, and then enters its original lane.



3) The host vehicle approaches a slower moving target vehicle in the adjacent lane and attempts a cut-in.

4) A motorcyclist approaches the slower moving host vehicle in the adjacent lane and attempts a cut-in.

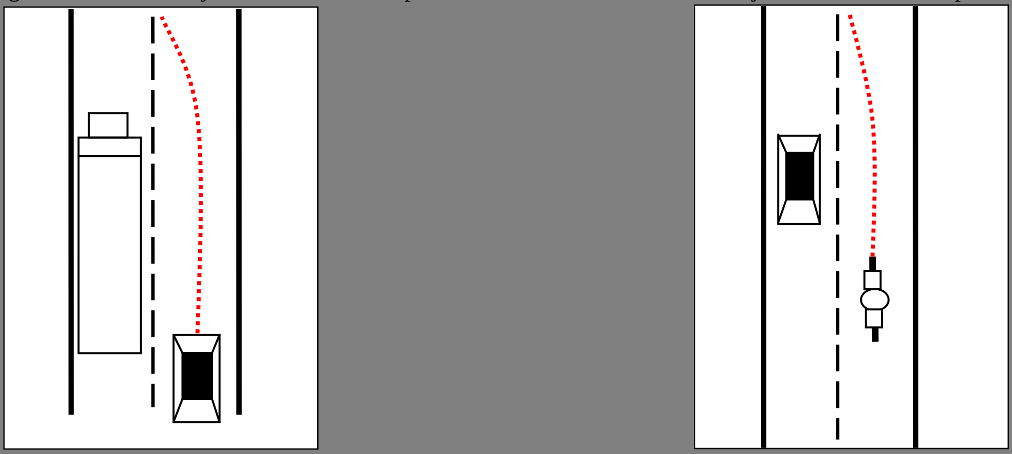


Figure 5: Four PreCrash sensing scenarios that a driver might encounter during everyday travels

The top eleven PreCrash scenarios from the year two thousand for light vehicles are: lead vehicle stopped, straight crossing paths, control loss, left turn across path/opposite direction, drifting (going straight), lead vehicle decelerating, left turn across path/lateral direction, vehicle changing lanes, vehicle going straight/animal in roadway, drifting (in curve), and lead vehicle moving at constant speed [6]. These however are only scenarios and don't specify the metrics under which the testing and verification may be validated.

4 CWAS Systems Testing and Verification

There are two primary portions of collision warning and avoidance system testing and verification including static testing and verification (and its performance metrics) and dynamic testing and verification (and its performance metrics). The dynamic performance metrics are typically based on driven mileage or vehicle usage (hours spent driving vehicle) while both are heavily dependent on human factors engineering. Human factors engineering involves detail beyond the scope of this paper and thus negligible attention will be paid to it. Note that there are entire documents written on this particular facet of engineering and can be found on the NHTSA website.

The static testing and performance evaluation portion of the requirements is the far simpler of the two testing portions and involves the evaluation of the system under static conditions. This may include evaluation of both the systems and their subsystems according to a predefined test metric under static operating conditions using a surrogate target (or set of targets) in a controlled environment. This procedure will need to cover a full-range of environmental conditions as well as detailed steps involved in the execution of the testing.

The dynamic testing and performance evaluation portion of the requirements is the far more complex of the two testing portions and may be comprised of one or two portions. The first may include evaluation of both the systems and their subsystems according to a predefined set of test metrics under dynamic operating conditions using surrogate target(s) on a closed-course or during on-road evaluation. The second method involves the establishment of a set of minimum vehicle-level performance requirements for system evaluation [9]. Field operational tests are typically performed with drivers evaluating system performance in a wide range of environments under varying conditions, using data loggers to monitor and record drive-time events in real-time. These tests will also assist in identifying two major characteristics that a driver will exhibit when posed with a potential collision situation. The first is the amount of time that it will take for a driver to respond to a potential collision situation and the second is the actual brake force that the driver will use to generate decelerative forces [9]. The data loggers serve a number of important purposes during these tests. One of the primary purposes is that a failure in system functionality can be recorded and analyzed as to its root cause. These root causes can be tabulated and used to develop more accurate requirements leading to better designs. However, another lesser known purpose is the fact that the logged information can be ‘replayed’ with updated algorithms to monitor improvements in system performance. This has the important benefit of saving many hours of road testing when analyzing the performance of say, the sensor fusion algorithms.

Many different classes of roads will need to be traveled on during the testing and evaluation process. These will include interstates, freeways and expressways, minor and principal arterials, collectors, and local roads and streets. This assortment of roads will need to be representative of roads and driving situations that might occur in any part of the world where a CWAS equipped vehicle may be driven. On these various classes of roads, the differentiating features for a particular road will need to be traveled by a range of drivers, under an assortment of environmental conditions, being exposed to a wide range of vehicle operating conditions.

5 CWAS Subsystems within the FSS system

The forward sensing system has four primary transducers that are used to extract information from the environment. The first is the frequency modulated continuous wave radar system. This type of radar is generally chosen because of the fact that it provides better range resolution for ‘closer’ proximity targets than other types of radar, as well as the fact that it can be used to determine range rate information. A yaw rate sensor is currently used to aid in determining the predicted path of travel for the vehicle. Note that this methodology works well while the vehicle is traveling in a straight line or in a curve of constant radius, but has serious deficiencies when considering its response to predicting path during transitional maneuvers or while traveling in curves without constant radius. It uses the relationship between vehicle velocity and yaw rate to establish the radius of curvature for the path being traveled. The third sensing modality is the monocular vision system. A monocular vision system does not provide the depth perception of a stereo camera based vision system, but is substantially more cost effective than stereo based systems. The vision system, whether used as an individual sensing system or used in conjunction with radar and yaw contributing to a fused output, has a wide range of applications. These include forward collision warning, lane departure warning, headway-distance keeping, and cut-in warning [8]. The fourth (optional) sensing mode is Global Positioning System. Further detailed information will now be included on the radar and vision subsystems.

5.1 Radar Subsystem

In these early prototypes, there was no brake actuation or throttle actuation control. However, a later version used audible/visual indicators produced on a laptop computer to indicate a pending collision to the vehicle operator. Table one below shows some basic information. For detailed product specifications, contact the manufacturer in the appropriate fashion.

Table 1: Basic operating characteristics of radar system

Transmitted Signal Waveform		**PORTION OF TABLE INTENTIONALLY REMOVED**
Carrier Frequency	(GHz)	
Reflector Type		
Switching methodology		
Azimuth Field of View	(degrees)	
Vertical Field of View	(degrees)	
Range	(meters)	
Range rate discrimination	(meters/sec.)	
Vertical Resolution	(degrees)	
Azimuth Resolution	(degrees)	
Radar target information representation		
Maximum number of targets for tracking		

Benefits of the radar system (over the vision processing system) are it’s accuracy in longitudinal target identification and the ability to perform measurements in environmental conditions that would typically produce problems for the vision system.

In general, the radar antenna will transmit the FMCW into the field of view in an attempt to find a target. After being reflected by a target in the radars field of view the energy returns and then undergoes a frequency transformation where it is converted into an intermediate frequency (IF). From there, it generally undergoes various types of filtering and amplification to prepare it for digital signal processing (DSP). A general description of various aspects of radar DSP has been given previously and now a brief description will be given on the use of Fault Tree Analysis as a tool for analyzing the operation of the radar portion of the sensor fusion system.

Fault tree analysis is the identification of an undesired state of a system and then the system is analyzed in the context of the environment and operation to find all credible ways in which the undesired event can occur [7]. It is a deductive methodology that finds the relationships between the events that lead up to the undesired event. The first few layers of a generalized preliminary fault tree for the radar portion of the fusion system are shown in figure six on the following page. Notice that this tree has the standard structure of a fault tree but does not have the geometric shapes indicative of the gates and transfers which allow or prohibit the channel of logic for a fault up the tree. The initial event at the root of the tree typically corresponds to a radar system failure. Finally, note that the section on algorithms has been left blank. Nonetheless, it gives a general idea as to how a conceptual fault tree for a radar system might be structured architecturally.

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Figure 6: Portion of preliminary fault tree for radar component of sensor fusion system

As can be seen from figure six above, all radar system failures will stem from either kinematic, algorithm, or target faults. Target faults will arise from either closest target designations, in-path target designations, or valid target designation. These designations can continue to be broken down further until it is no longer useful to do so.

5.2 Vision Subsystem

Vision systems have only recently (within about the last ten years) become a major sensing modality in real-time automotive collision warning and avoidance systems. There are several reasons for this. The first is the fact that the hardware associated with acquiring frames of a scene has gone through significant improvements in technology and the price has come down considerably. Another reason is that the resolution and dynamic range of the hardware has improved drastically. A third is that the fact that increased demand (due to a greater number of potential commercial applications) has lead to a wider range of tools and products that can be used in the development of vision systems. The fourth (and perhaps, most importantly) is the fact that processing power in microprocessors and digital signal processors has improved significantly.

Vision systems for automotive applications will generally be monocular vision (single perspective) or stereoscopic. In stereoscopic vision, two perspective projection images are taken from the same scene from slightly different positions [10]. Although stereo vision has several benefits over monocular vision (including depth perception), the additional costs associated with the hardware and software required make it currently unfeasible for commercial automotive applications. Monocular vision systems, on the other hand, provide a cost effective means for extracting meaningful information (including targets and path prediction) from the forward scene. The Mobile Eye Vision system is based on a dual-RISC processor based system on a chip with four different vision processing engines performing the tasks of process, window and filtering, tracking, classifying, and lane detection. These four engines operate in parallel and greatly increase throughput of the computationally burdensome vision processing algorithms. Various memory architectures are available and interfacing to a wide range of peripherals is provided. Also available are multiple direct memory access (DMA) channels as well as interfacing to high dynamic range cameras (HDRC).

The vision processing application software runs within an open source operating system and boots automatically after running the appropriate executable. Target proximity is indicated by a unique visual cueing method that is based on colors. Depending on the proximity of the target to the host vehicle, the color of the visual cue identifying the particular target changes. This visual cue is a rectangular box that borders the particular target. An object that is determined to be the primary target will be bordered in one color, while other targets, based on their proximity to the host vehicle, will have border boxes represented by different colors. Similarly, the indicators used for lane markings and road geometry are different colors. The future road scene is generated by a complex model incorporating lateral position, slope, and curvature [8]. Benefits of the vision system (over the radar sensing system) are it's wide field of view, it's ability to perform target classification, and it's ability to provide accurate lateral target measurements. Even though the system design exploits parallel architectures for efficient image processing, the systems data acquisition rate of 30 frames/second still causes it to lag behind the processing speed of the radar's digital signal processor (which performs detection, tracking, and other functions in 100 ms). Still, the radar and vision system complement each other when contributing to a fused output of the forward scene.

6 CWAS Sensor and Data Fusion System

Figure seven below adds another layer of detail to a portion of that shown in figure two for a potential architecture including a sensor management system, forward sensing system, threat assessment unit, and active and passive safety units. The dSPACE Autobox system was chosen for the data fusion environment for a number of reasons including (but not limited to) high processing speed and data throughput, rapid prototyping, hardware-in-the-loop capabilities along with a wide range of supported analog I/O boards, digital I/O boards, and communication boards (including CAN). Further information can be obtained for the Autobox system from the dSPACE website listed in [16].

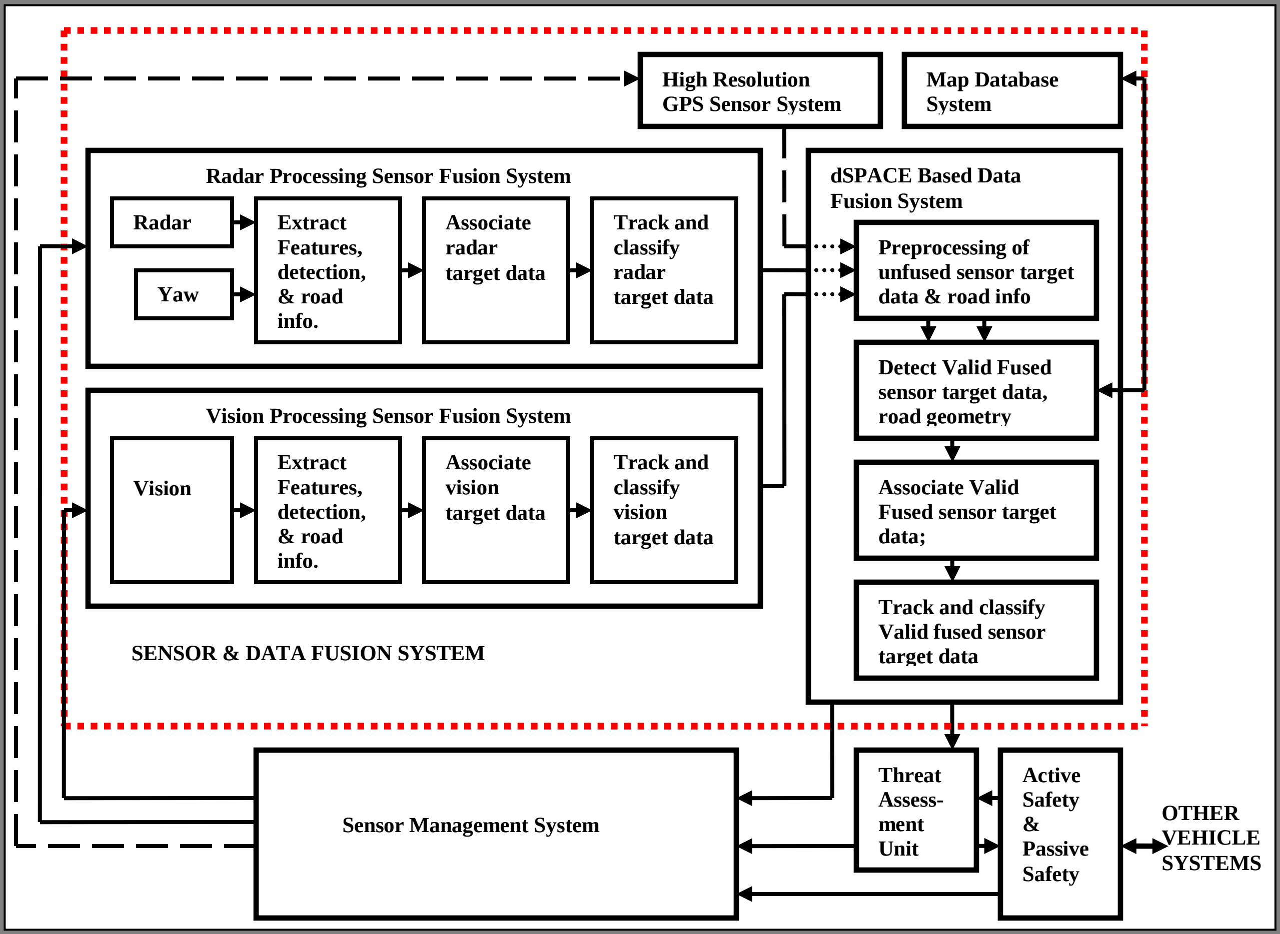

Figure 7: Added layer of detail to portion of CWAS (shown with optional GPS as long dashes)

Figure seven shows the potential interaction amongst several of the systems. As can be seen from the figure above, both the radar and vision systems will initially extract features and perform target detection on images (radar and vision, respectively) from the forward scene. Road scene information is also determined. Association may then be performed on the respective target data to determine which target specific information will be included for tracking and classification. Some of the potential outputs from the radar and vision processing sensor fusion systems are shown in table two below.

Table 2: Some potential outputs from the radar and vision processing sensor fusion systems

Output number	**Output of Radar system**	**Output of Vision System**
1	Radar target information	Vision target information
2	Radar confidence levels	Vision confidence levels
3	Radar accuracy levels	Vision accuracy levels
4	Radar road geometry	Vision road geometry
5	Radar lane information	Vision lane information
6	Radar environmental conditions	Vision Environmental Conditions

Target specific information might include (but not be limited to) target range, target range rate, target azimuth, target azimuth rate, target height, target width, target classification, along with information about the path of travel including road geometry, lane specifics, and confidence levels.

The outputs from the radar and vision processing sensor fusion systems will serve as inputs to the data fusion system. These two sets of inputs will typically first be preprocessed in such a way as to establish a common orientation standpoint so that the respective target information can be compared and correlated. Five processes that may be included in the preprocessing include common formatting, time propagation, coordinate conversion, misalignment compensation, and evidential conditioning [11]. Once the two unfused individual segments of sensor information have been sufficiently preprocessed, a detected valid fused target data list can be generated via fusion of the two. Similarly, the two road geometry predictions may be fused to form a single estimate (assuming that the radar system is being used to generate predicted paths as part of the target tracking). If GPS is included in the sensor fusion system, this may also be used to contribute to a fused version of the road geometry when combined with the map database system.

The detection of a valid fused target list is created from a combination of the radar and vision systems target lists. This valid fused target list is a function of the individual sensors' target lists, confidence levels, accuracy levels, and environmental conditions, just to name a few. The final two portions of the data fusion system are comparable to those of the sensor fusion systems. First, a valid fused target is associated; next, tracking and classification may be performed. Some of the potential outputs from the data fusion system are shown in table three below.

Table 3: Some potential outputs from the data fusion system

Output number	**Data Fusion System Output**	**Serves as input to (Sub)System**
1	Fused target information	Threat Assessment Unit
2	Fused confidence levels	Threat Assessment Unit
3	Fused accuracy levels	Threat Assessment Unit
4	Fused road geometry	Threat Assessment Unit
5	Fused lane information	Threat Assessment Unit
6	Fused environmental conditions	Threat Assessment Unit
7	Fused target report identification errors	Sensor Management System
8	Fused target report tracking errors	Sensor Management System
9	Fused target report classification errors	Sensor Management System
10	Fused target report priority threat & errors	Sensor Management System

7 CWAS Sensor Management System

The sensor management system (SMS) typically performs control and coordination of multiple sensor readings under various environmental conditions during various states of vehicle operation. One of the keys is to balance system performance with system resources and is heavily dependent on fusion system architecture. The type of fusion discussed in the previous section is a hybrid version based on sensor (or feature level) fusion.

Inputs to the sensor management system will typically come from the threat assessment unit, the data fusion portion of the forward sensing system, and the active and passive safety system. The threat assessment unit is composed of two primary subsystems, the collision estimator and the path prediction estimator and is discussed in the next section of this paper. Note that special attention needs to be paid to the inputs and outputs of the sensor management system as they play a crucial role in the operation of the system. One potential input to the SMS may include errors in threat assessment information originating from the threat assessment unit. Another possible set of inputs to the SMS consists of any tracking and classification errors that were discovered and quantified by the data fusion system. These quantities, along with any other required sensor specific information, allow the sensor management system to generate accurate cueing, error correction, and other pieces of information for both the vision and radar processing sensor fusion systems. One potential usage of cueing is to provide ‘hints’ to the radar and vision processing systems as to particularly high areas of interest that should be focused on within the particular sensors field of view. Another use of cueing is that of indicating to a particular sensor that a specific piece of information that is currently being processed contains anomalies and needs to be addressed.

The effective management of the sensor system is highly dependent on the relationships between the current environmental conditions, current threat assessment level, and the current chassis state estimate. Table four below lists some of the environmental conditions that must be considered when analyzing both the individual operation and joint interactions between the three aforementioned systems.

Table 4: Some environmental conditions affecting collision warning and avoidance system operation

Subjective Description of Environmental Condition or Obscurant	**Unit of typical measurement**
Light, moderate, heavy fog	g/m^3
Light, moderate, heavy rain	mm/hr
Light, moderate, heavy snow	mm/hr
Light, moderate, heavy haze	g/ m^3
Night, tunnel driving, sunrise, daytime, sunset	
Dust, smoke	Obscurant dependent

The data acquisition rate for a system is typically fixed but the priority for which data is considered for processing is an important control factor in the SMS. Take for example the situation of driving on an expressway in a heavy fog. Since the confidence level for the vision system’s sensor readings will be very low in comparison to the confidence level of the radar sensors readings, greater priority may be dedicated to the processing of radar system information. This may be performed by transmitting higher priority messages on the bus (which is allowed in time triggered CAN and will be covered very briefly in the section on vehicle multiplexing and bus messaging). Consider however the case of driving on a tight curve where the radar’s narrow latitudinal field of view will severely limit the usefulness of its readings. In this case, much greater priority may be dedicated to the (computationally intensive) processing of vision system information.

Note that the radar subsystem of the forward sensing system will generally yield high confidence levels in most weather conditions and at all times of day but with limited resolution, narrow lateral field of view, and susceptibility to clutter and noise. The vision system will yield lower confidence levels during inclement environmental conditions or high levels of obscurants but will provide higher resolution and wider lateral field of view. Note also that the chassis estimator, particularly related to brakes and steering, will be immensely affected by the current environmental conditions. Thus, calculation of a brake threat number and steering threat number (as part of the threat assessment unit) will have to take into account all of these relevant factors.

8 CWAS Subsystems within the Threat Assessment Unit

The following figure shows an overall potential architecture for the collision warning and avoidance system along with the two subsystems within the threat assessment unit, namely, the collision estimator and the path predictor.

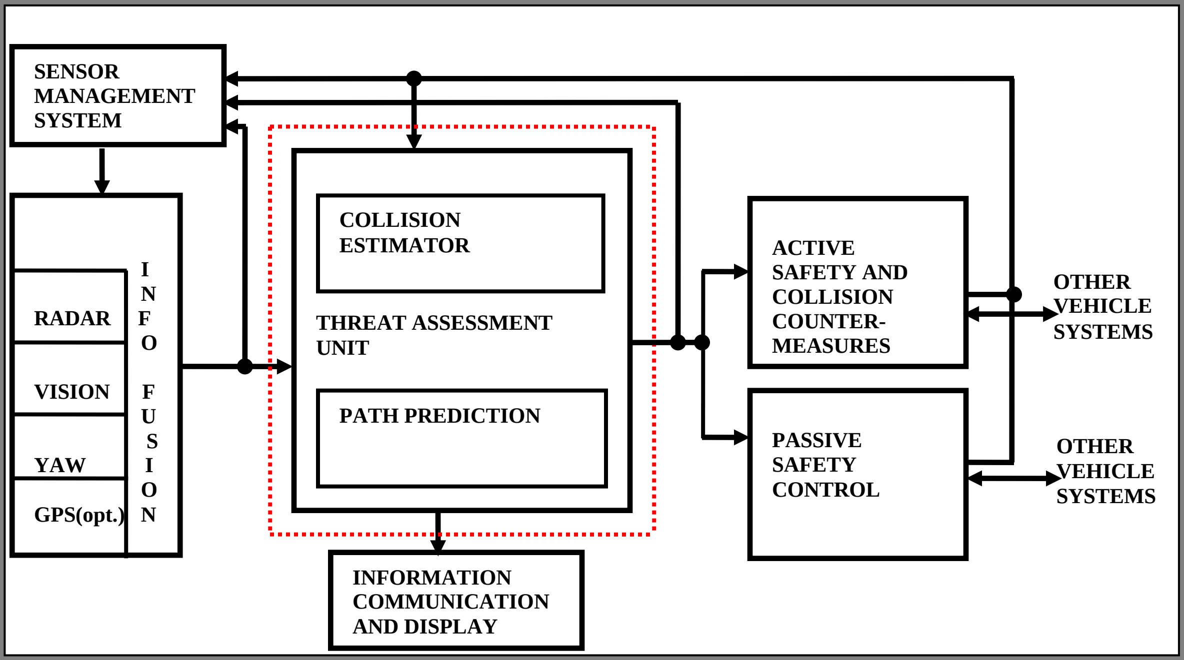

Figure 8: Subsystems within threat assessment portion of CWAS

Several of the inputs to the threat assessment unit are given in table five while the outputs from this unit include target information specific to primary and secondary targets. The primary target will be designated as the highest priority target within the system and will be processed as such. The importance of this stems from the fact that processing resources within each of the units, particularly for the six shown in figure eight above, are highly dependent on factors such as environmental conditions, target kinematic information, and the current state of the Active Safety and Collision Countermeasures system (just to name a few). Consider the scenario of driving in icy conditions at a high rate of speed with a primary target at a moderate distance and multiple secondary targets. Under these conditions, processing of the primary target (and 'potential' primary target) should always be the highest priority as they have the most direct effect on the current state of the collision warning and avoidance system. A potential primary target may be defined as the secondary target that has the greatest likelihood or probability of becoming the primary target.

The threat assessment unit plays a very significant role within the CWAS because there are several important factors that must be considered when analyzing the potential for a crash. The first is to be able to predict which direction you are currently heading in and where you will be in several seconds. Another is to identify where the valid targets are located within the field of view of the forward sensing system. Once you have identified what your path is and what the valid targets are in that particular path, you can determine what the primary target is and what the current kinematic state is for that particular object (as the threat posed by this object is the vehicle operators and safety systems highest priority). A general description is given in figure nine below.

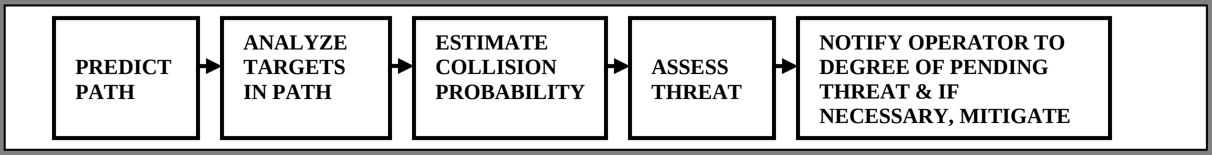

Figure 9: Block diagram for portion of potential processing involving threat assessment unit

The third is to be able to reliably determine how the current environmental conditions are going to affect control of the vehicle. Yet another is to be able to reliably determine how the current environmental conditions are going to affect the accuracy of sensor readings. However, the threat assessment unit must not only be able to assess the potential for a crash with a target, it must be able to assess the potential for any other hazardous situations that may arise during any and all operating conditions experienced by a CWAS equipped vehicle. Several of these possible scenarios are listed in the table five below.

Table 5: Several potential scenarios for hazardous driving situation not directly involving contact with another vehicle

Scenario #	Scenario Description
1	Driver enters exit ramp at velocity much too high for given radius
2	Driver drifts at high speed across road edge onto unpaved surface
3	Driver drifts into adjacent lane startling that lanes vehicle operator causing incident

8.1 Collision Estimation Subsystem

One purpose of the collision estimator is to estimate the effects of the current driving situation as it relates to the likelihood or probability that an adverse outcome (collision) might potentially occur. In other words, it assesses the current driving situation and estimates the potential impact of an incident with regards to all entities involved.

Braking, steering, and a combination of braking and steering are the three primary methods a vehicle operator may use to deal with the threat of a collision. The degree to which braking and/or steering are applied by a driver is largely dependent on his or her perception of the current driving conditions including those for the environment, lead vehicle headway distance, current vehicle speed, and lead vehicle deceleration, just to name a few. Both modeling and data binning techniques may be used to analyze driver response and performance to lead vehicle deceleration from range and range rate information [12]. Thus, one of the quantities that may used to estimate the likelihood of a crash occurring is the brake threat index.

The brake threat index is a numerical quantity that is primarily a function of both the available and required distances for braking to avoid a collision. Available distance is the headway distance (range) to the lead vehicle (primary target) while the required distance is the total amount of stopping distance required under the current vehicle operating conditions and is a function of environmental conditions, range, range rate, and vehicle speed, just to name several. Table six below gives a very general description of the relationships involved in evaluation of the brake threat index.

Table 6: Brake Threat index as related to crash conditions and braking distance variables

Subjective Description of Brake Threat Index	Crash avoidance likelihood	Distance variables
Very low brake threat index	Collision highly avoidable	Available distance >>> Required distance
Low brake threat index	Collision avoidable	Available distance > Required distance
Moderate brake threat index	Collision likely	Available distance = Required distance
High brake threat index	Collision imminent	Available distance < Required distance

Specifics as to the calculation of the brake threat index will not be expounded on as it is beyond the scope of this paper.

8.2 Path Prediction Subsystem

Path prediction is the uninterrupted evaluation of the path of travel of a vehicle using an assortment of sensing modalities and the fusion of these individual evaluations to obtain a more comprehensive estimate of the future path of travel. This fused estimate may then be used with supplemental GPS based map data to further identify future potential path of travel along with other characteristics of the driving environment.

Path prediction may be performed in a number of different ways but will tend to produce the best results when a combination of sensing techniques is applied. Two primary sensing modes available that facilitate path prediction are the yaw rate sensor and vision system. A third, inertial navigation systems or high resolution global positioning systems (differential GPS), when combined with map data and fused with the first two methodologies, may lead to a very accurate prediction of the path of travel. Another potential method is to predict path based on the current path of travel of targets being tracked. The inherent limitations with using yaw rate to predict path have previously been mentioned. However, great potential exists with using vision systems for extracting meaningful path information including lane markers, lane position, and road edge from the forward scene.

There are many important factors needing to be considered when evaluating how well road information can be extracted from a captured image of the forward scene. The first that should be mentioned is the dynamic range of the imaging sensor being used. The dynamic range is the ratio of the largest to the smallest dynamic inputs that the imaging system can accurately measure [14] and is a gauge of the span or range of values that will be produced by an imager. Special complimentary metal oxide semiconductor (CMOS) chips have been designed with high dynamic ranges in mind allowing meaningful information to be captured and interpreted under the most challenging illumination conditions. A general characteristic required in automotive imager performance is that the imager must have high enough dynamic range to resolve objects under all driving conditions [13]. High dynamic range cameras will typically have dynamic ranges of at least 100 db. Two other important characteristics of an imager are its resolution and sensitivity.

Assuming that a 'high quality' image has been captured of the forward scene by the various sensing modalities of the FSS, the next step is to use the extracted information to predict a path of travel with a high degree of confidence. Some of the relevant information being transferred from the fusion system to the path predictor includes road geometry, lane markers, lane position, and road edge. A vehicle may be designated as traveling in a lane while at least fifty percent of the vehicle falls within that particular lane. The road geometry information coming from the fusion system will typically be decomposed into short range, medium range, and long range road geometry. This information will all be used to contribute to a 'predicted' path of travel for the vehicle.

The vision system will generally produce lane marker, lane position, and road edge information. Road curvature during non-transitional vehicle states will come from the yaw rate sensor. Host vehicle location data may come from the GPS sensor (if included) when combined with a digital road map, and each may contribute to short range, medium range, and long range road geometry estimate. These road geometry estimates might include straight paths, constant or non-constant curvature paths, and smooth and sharp transitions to and from straight or curved paths, just to name a few. Thus, all sensing modalities contribute to a fused version of the predicted path of travel. However, increased confidence levels in target identification result from a non-transitional vehicle position within a lane where vision data can most accurately differentiate lane boundaries and lane position.

The yaw rate subsystem is primarily used in path prediction during non-transitional vehicle operation. Non-transitional vehicle operation typically occurs while driving in a straight line or a curve of constant radius. Figure ten below shows four curves of constant radius designated as R1, R2, R3, and R4 where R1 > R2 > R3 > R4 corresponding to the constant radius paths in which a vehicle might travel.

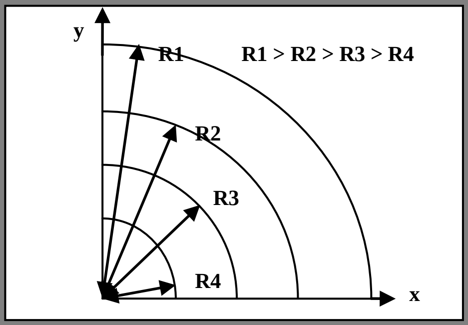

Figure 10: Curves of constant radius for yaw rate analysis of predicted path of travel

The radius of curvature (and thus the predicted path of travel under the aforementioned conditions) is a function of variables including (but not limited to) yaw rate and vehicle speed.

As has been touched on previously, there are a great number of factors contributing to the confidence levels for the various sensor readings. These include environmental conditions, current driving and chassis state, established sensor accuracy levels, the current path of travel, and the efficiency of the sensor management system, to name a few. The number of sensors contributing to a particular forward scene interpretation will also affect the confidence level. From figure one, the forward scene is divided up into three regions, designated A, B, and C. In region A, both vision and radar information may be fused to obtain a higher degree of confidence in target and path prediction than that obtained from the individual sensors acting alone (as in regions B and C). However, region B will yield a relatively high confidence level with regards to the predicted path of travel specific to road edge. Region C is only available to the radar system but will yield lower confidence levels than for fused data from region A or from region A radar data alone.

It should be noted that generalized path prediction is feasible during vehicle lane-change transitions but will yield a much lower confidence level in primary and secondary target identification. On the other hand, path prediction during non-transitional vehicle operation will generally yield high confidence in path prediction and high confidence in the identification of targets as primary or secondary.

The Active Safety and Collision Countermeasures Control system contains the chassis state estimator and the Driver State Estimator. These two subsystems will provide inputs to the threat assessment including (but are not limited to) brakes, steering, throttle, suspension, powertrain, and intervehicle dynamics (IVD) signals along with driver operating patterns. These parameters are fundamental to the processing going on in the threat estimation unit (particularly in the collision estimation unit). The Passive Safety Control system will also contribute to threat assessment unit processing and control. This system includes the Crash Severity Estimator and the Occupant Position Sensing subsystem. In particular, the occupant position sensing subsystem is a camera based system which will monitor the activities of both the driver and the passenger to estimate the a number of factors including driver distraction, driver gaze, driver and passenger bodily positions, to name just a few. These camera readings may also be combined with more traditional occupant position sensing modalities to achieve a higher confidence level. Both of these systems will be covered in further detail in this papers next section.

Thus, figure eleven below adds another layer of detail to that shown previously in figure nine.

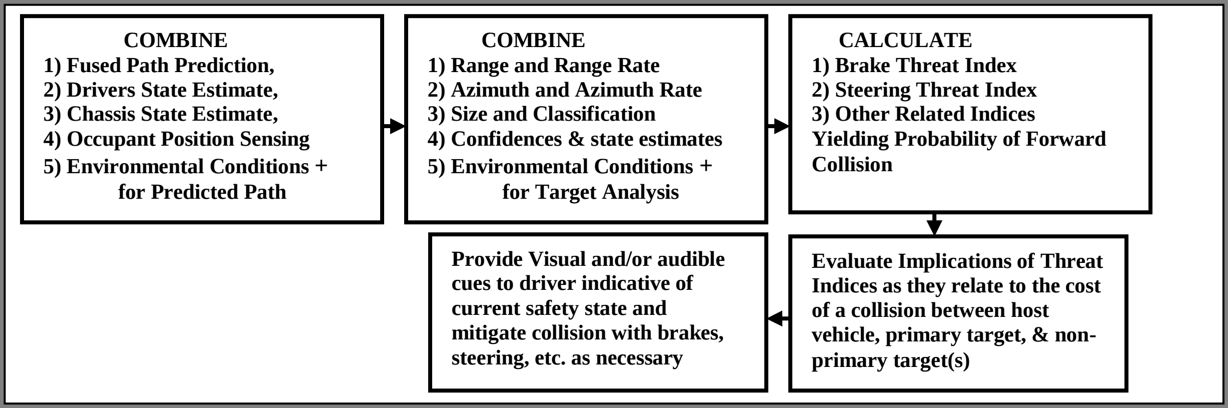

Figure 11: Block diagram for portion of potential processing involving threat assessment unit

9 CWAS Active Safety and Passive Safety control

A diagram incorporating the subsystems within the Active Safety and Collision Countermeasures Unit and Passive Safety Control unit is shown in the figure below:

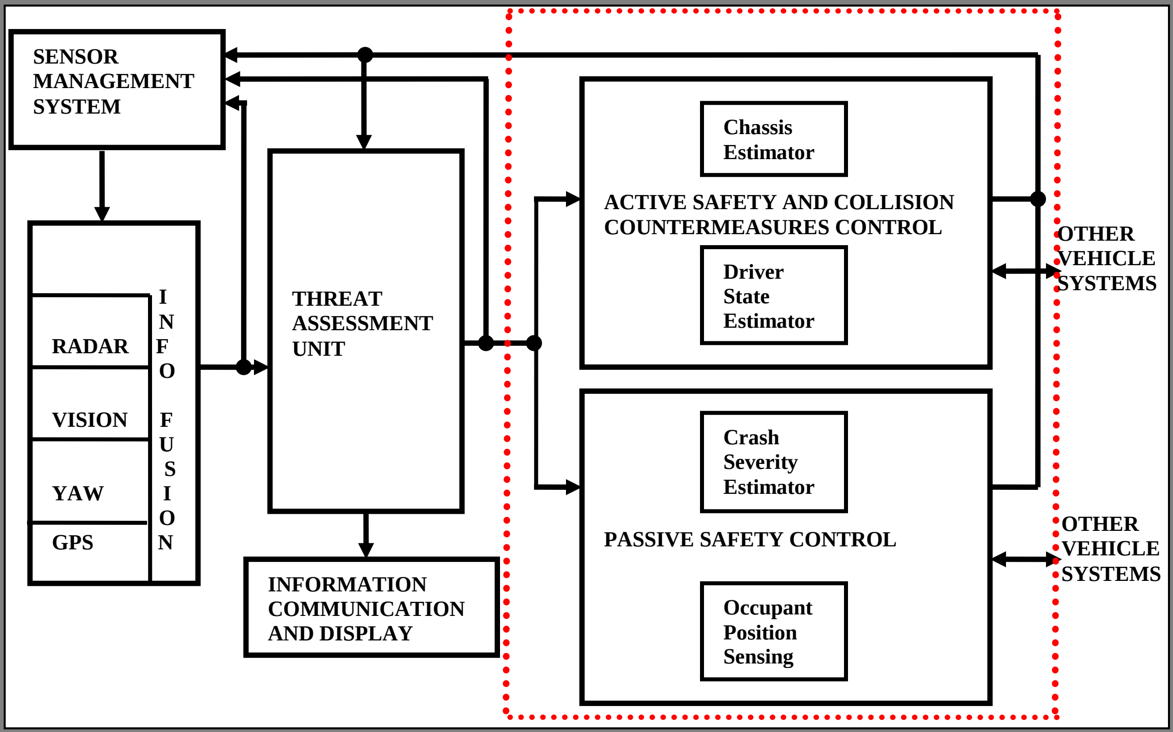

Figure 12: Subsystems within Active and Passive Safety Systems

Active safety involves the automatic activation of warning systems and actuation of vehicle chassis subsystems in response to an unsafe driving event. As was mentioned in the beginning of this paper, one of the original production radar based sensing systems was designed for semi tractor trailer drivers who spent long periods on the road and were susceptible to driver drowsiness. One of the earliest automotive production systems involving braking and throttle actuation is that found in adaptive cruise control systems where the vehicle will perform throttle and brake changes to maintain a desired headway to a lead vehicle. This headway distance is typically monitored with a frequency modulated continuous wave radar system. Current prototype versions of CWAS incorporate vision, radar, GPS, yaw rate, infrared, and lateral-longitudinal-vertical accelerometers along with brake and throttle actuation and other sensors and actuators to facilitate active safety functionality. Although brake and throttle actuation is occurring without being initiated by the driver, the system must be easily overridden via driver intervention.

The outputs from the threat assessment unit serve as inputs to the Active Safety and Collision Countermeasures Controller and the Passive Safety system controller. Some of the outputs from the Chassis State Estimator are given in table seven below.

Table 7: Some characteristics of chassis state variables affecting threat assessment unit

CHASSIS STATE VARIABLE	**COMMON FUNCTIONS OR CHARACTERISTICS**
Brakes	Anti-lock; traction control; Deceleration rate
Throttle	Idle; Open; Wide open; Closed; Acceleration rate
Steering	Under steer; Over steer ; Steering wheel angle; Steering wheel torque
Suspension	Suspension ‘stiffness’; damping level; Active; Semi-active; Variable
Powertrain	Torque; Power
Intervehicle dynamics	Stability control related to brakes, powertrain, etc.

Similarly, some of the outputs for the driver state estimator are given in table eight below.

Table 8: Some characteristics of driver state variables affecting threat assessment unit

DRIVER STATE VARIABLE	**COMMON FUNCTIONS OR CHARACTERISTICS**
Braking patterns/trends	Early braking with uniform decel vs. Late breaking with heavy decel
Throttle patterns/trends	Heavy acceleration vs. uniform velocity increases
Steering patterns/trends	Early steering vs. late steering
Lane position & change patterns/trends	Regular drift vs. maintain position in lane; Frequency of lane changes
Headway distance patterns/trends	Regularly maintain safe headway vs. ‘tailgater’

10 CWAS Information Communication and Display- Vehicle Bus Messaging

Information communication between automobile system control units occurs over a high speed vehicle multiplexing system. For (highly reliable) fault operational distributed safety systems, the scheduling for message transmission and receipt will typically be synchronized (deterministic). This provides an attractive alternative to non-deterministic systems in which bus latency jitter and other factors contribute to less certainty in the transmit-receive process. The name given to the protocols which guarantee message transmission and used fixed determinable time slots for message communication is time triggered [15]. TTCAN and TTP are two popular time triggered protocols which operate in distributed, fault operational environments with a number of topologies including (but not limited to) bus, star, single channel, and multi-channel. In a multi-node, star topology configuration with a central switch transmitting messages to each of the other nodes within the network, highly reliable data transmissions can be guaranteed when redundancy (in both hardware and software) has been correctly applied. The data rates for these systems are typically higher than for non-deterministic systems and have been exploited not only in the automotive industry but in aerospace as well. The specifics of these types of systems will not be elaborated on in this paper but some of the signals that may need to be transmitted are shown in table nine on the following page.

Table 9: Some bus message types that will need to be included in the intercommunication of CWAS systems

Message type	**Information conveyed**
Primary, Secondary, and Potential Primary Target ID	Numerical
Primary, Secondary, and Potential Primary target type	Vehicle, non-vehicle, etc.
Primary, Secondary, and Potential Primary Motion of target	Moving, stationary, stationary w/ past movement, etc.
Primary, Secondary, and Potential Primary Target size	Height, width, etc.,
Primary, Secondary, and Potential Primary Target classification	Vehicle, non-vehicle, etc.
Primary, Secondary, and Potential Primary Target location	Range, range rate, azimuth, etc.,
Predicted path	Radius of curvature, model specific, etc.,
Short, Medium, and Long range road geometry	Model specific
Lane marker information	Relative to position of vehicle
Environmental conditions	Rain, snow, night, etc.,
Sensor confidence level	0.01 to 0.99
Brakes, Throttle, Steering, Suspension, Powertrain, IVD	State Estimate leading to confidence level
Driver State Estimate Parameters	State Estimate leading to confidence level
Collision Severity Estimate	State Estimate leading to confidence level
Occupant Position Sensing	State Estimate leading to confidence level
Sensor Management System	

Note that the information included in table nine is only a tiny portion of the overall information that must be conveyed during operation of this system. However, due to the design constraints inherent in time triggered architectures, it is important (at a very early stage of development) to establish which features will be requiring which signal specifics (as it relates to sub-system intercommunication).

11 Potential overall system architecture

The preliminary Active Safety/Collision Avoidance Architecture along with Passive Safety may be represented as shown in the figure thirteen on the following page.

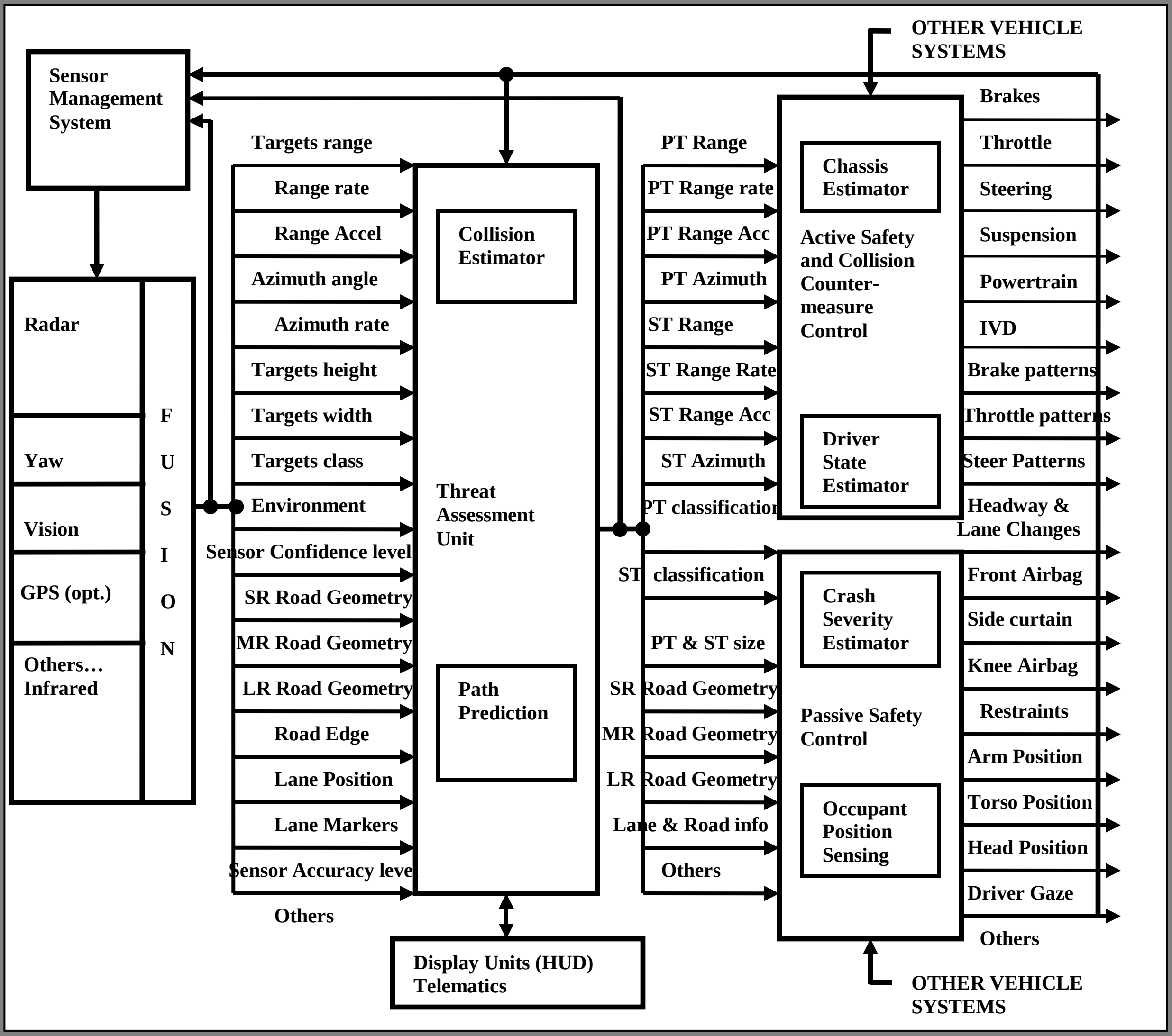

Figure 13: A potential preliminary architecture for a CWAS with portion of control signals

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