LOGICAL MEDIATION STRUCTURES FOR TOYOTA'S DRIVER SUPPORT SYSTEMS

Kazushi Kuroda
Iwao Izumikawa
Osamu Kouketsu
Toyota Motor Corporation
Japan
Paper Number 09-0120

ABSTRACT

The driver support system (DSS) computer is an important part of systems such as adaptive cruise control (ACC), pre-collision system (PCS), and lane-keeping assist (LKA).
The DSS computer receives information from peripheral sensors such as the forward radar, forward camera, and driver-monitoring camera, and transmits requests to controllers such as the engine, brakes, steering computer, and combination meter.
DSS such as those listed above use the peripheral sensors in common and are also activated simultaneously, which makes it necessary to consider coordination among the systems.
For example, if a part becomes inoperable, each system that uses the part reverts to a default condition and the condition of each system is shown on the combination meter.
In such a case, the combination meter must not flash or show other such undesirable conditions.
Therefore the behavior of these systems must be fully taken into consideration and guidelines for mediation constructed in terms of ergonomics.
As a result, three aspects of design for mediation must be reviewed: diagnostic design, control design, and human-machine interface (HMI) design. These are all important for effective coordination among these systems.

INTRODUCTION

Various advanced systems that further enhance the driving experience have been developed over the years.
Adaptive cruise control (ACC) systems that use laser radar to control the vehicle-vehicle distance for driving speeds over 40 km/h were introduced in 1997 to reduce driver pedal operation workload (these systems are referred to as AC- below). Subsequently, in 2004, an ACC system was released capable of control in lower speed ranges below 30 km/h. This was further developed and released in 2006 as ACC with a full-speed range (AC+) capable of control from higher speed cruising to start/stop driving in congestion.
In Europe, cruise control systems with speed limiters (CSL) have been on the market since 2006 to meet the requirements imposed by speed limit regulations.
The first pre-collision system (PCS) was commercialized in February 2003. This system used forward millimeter wave radar (F-MMW) to help detect vehicles or obstacles in front of the vehicle and controlled the pre-collision seat belt (PSB) and pre-collision brake assist (PBA) system just prior to a collision to reduce damage.
In August 2003, the pre-collision brake (PB) and adaptive variable suspension (AVS) were added to the PCS. AVS switches to sport mode to reduce nosedive caused by emergency braking.
In 2004, an improved PB system was introduced that fuses the detection results of F-MMW and a forward camera (F-CAM) (fusion processing).
In 2005, the pre-collision alert brake (PAB) system that uses a driver-monitoring camera (DMC) was added. This system warns the driver of an imminent collision and regulates brake operation when the driver is judged not to be looking straight ahead.
Moreover, an advanced PCS was introduced in 2006 with additional variable gear ratio suspension (VGRS) and rear PCS. This vehicle has a forward stereo camera that detects pedestrians and the positions of objects in more detail. In rear PCS, the pre-collision hazard lights (PHL) are flashed to warn the driver of a vehicle approaching from behind, and the pre-collision headrests (PHR) are automatically moved forward to reduce the risk of whiplash injury.
In 2008, PAB was further developed by the introduction of a function capable of detecting the driver's eye opening angle that indicates drowsiness.
In 2009, two forward millimeter wave radars (L/R-F-MMW) were added to detect vehicles approaching from the front diagonally. This system quickens the response to the side airbags (PSA).
Figure 1 shows the functions of the PCS described above.
The lane keeping assist (LKA) system was commercialized in 2004 to reduce the driver's steering workload. When it detects the possibility of lane departure, the LKA system warns the driver and controls the electric power steering (EPS) actuators to produce inward steering torque for a short period of time (this is referred to as lane departure alert (LDA)).
When ACC is in operation, the LKA system controls the EPS actuators to assist the driver to keep the vehicle in the center of the lane (lane keeping (LK)).

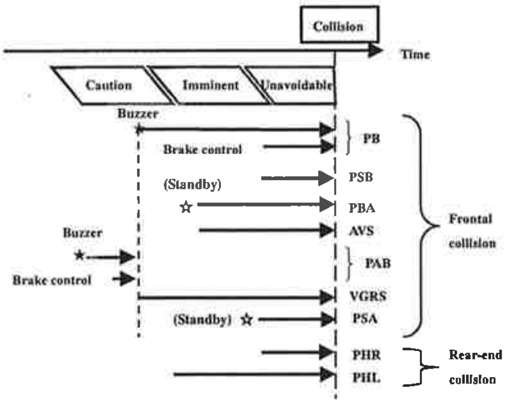

Figure 1. PCS operation timing.

As mentioned above, the functions of the ACC, PCS, and LKA systems have developed through the use of radars and cameras.
The main computer used to control these systems is called the driver support system (DSS) computer.
This paper describes the configuration of the electronic control unit (ECU) and the logical structures for mediation control of Toyota's DSS.

1. DSS Configuration

As shown in Figure 2, the main categories of parts in these systems are sensors, computers, and actuators.
ACC can be classified as either AC- or AC+.
AC- uses a forward radar and maintains an appropriate vehicle-to-vehicle headway time at a selected cruising speed over 40 km/h. In contrast, AC+ uses a forward radar and a forward camera to control the vehicle from higher speed cruising to stop/start driving.
There are two types of PCS system: one for frontal collisions and one for rear-end collisions.
The former system uses F-MMW, F-CAM, and DMC. It controls the PSB system, engine, brakes, AVS system, a warning buzzer, VGRS system, and the PAS system in accordance with the possibility of collision.
The latter system uses the rear millimeter wave radar (R-MMW). It controls the PHL system, the PHR system and PAS system.
The LKA system also uses the forward camera. It controls the EPS to assist the driver keep the vehicle in the center of the lane.

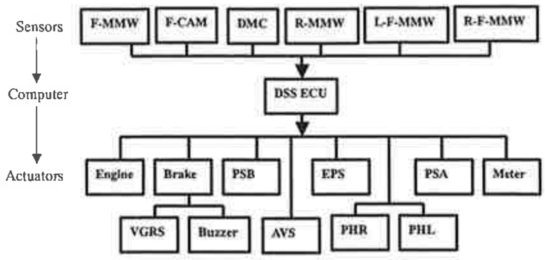

Figure 2. Information flow of DSS.

Figure 3 shows the configuration of the parts used for these DSS.

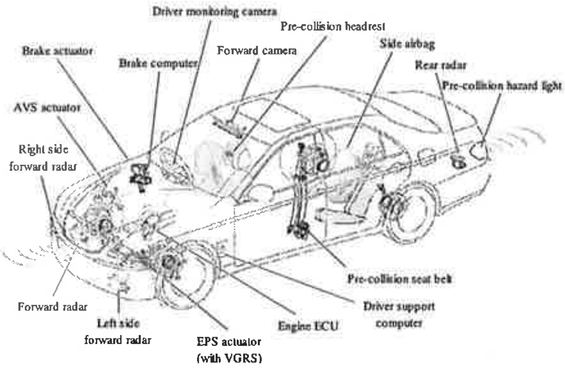

Figure 3. Configuration of parts.

2. DSS ECU Configuration

As computerized control technology has improved greatly in recent years, the number of computers and the scale of software have also multiplied rapidly.
In response, it is necessary to efficiently integrate these computers. The trend also applies to the DSS ECU.
Figure 4 shows the trend for volume. The present volume of the ECU is about 60% of the distance control computer that was introduced for the first time in 1997 for AC-.

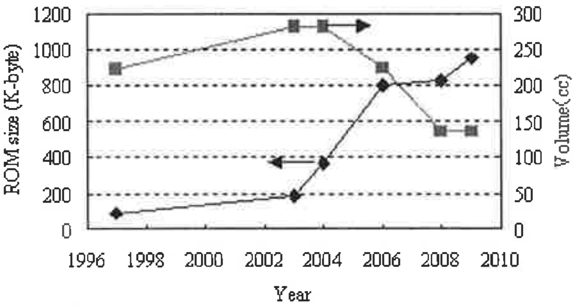

Figure 4. Trends for ECU volume and ROM.

Figure 4 also shows the trend for the software scale. The software scale has increased due to the addition of the PCS and LKA systems. The present scale is about eight times larger than the initial ECU.

Therefore, by a simple calculation, the software density has grown by about 13 times (=8/0.6). Figure 5 shows the present DSS ECU.

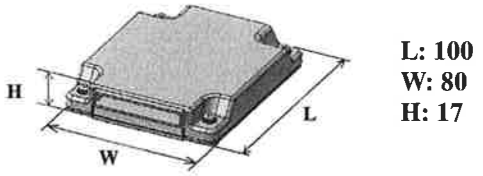

Figure 5. DSS ECU.

As the scale of software increases, a recent trend has been to standardize software to improve quality and reduce development costs.
In Japan, the non-profit organization Japan Automotive Software Platform and Architecture (JASPAR) was set up in 2004. This group cooperates with Europe's standardizing group, Automotive Open System Architecture (AUTOSAR).
Following this trend, the DSS ECU adopted the same standardized software platform as that for brake and engine computers.
Figure 6 shows the software structure of the DSS ECU. Data is transmitted between among the modules by the distribution component (DIS). The order of operation is as follows.
Input transaction (SCOM, IOD) → Pre-transaction (Pre-T) (AFW) → Main transaction (APL, AFW) → Post-transaction (Post-T) (AFW) → Output transaction (SCOM)
Pre-T consists of input Pre-T, diagnostic Pre-T, sensor fusion. Post-T indicates output mediation.
The order of the APL transactions is as follows, in accordance with the priority order of control.
PCS→ACC→LKA
ACC/PCS/LKA and output mediation, which are classified as either control or diagnostics, and the order of each transaction is as follows.
Diagnostic → Control

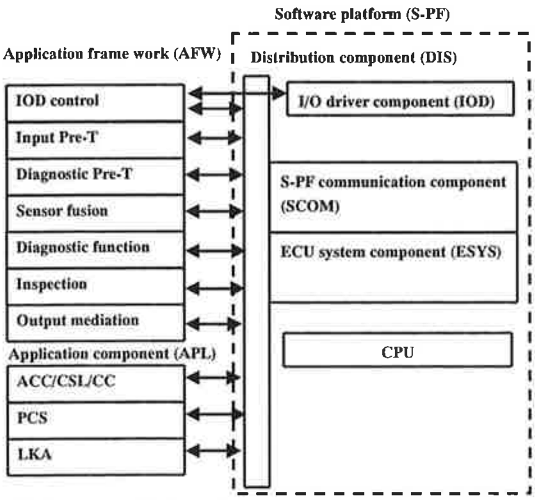

Figure 6. Software structure of DSS ECU

3. Guideline of Coordination
Figure 7 shows the correlation among DSS.

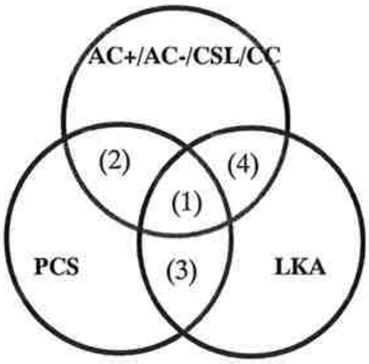

Figure 7. Coordination among DSS.

If a part used by these systems in common becomes inoperative, each system that uses the part reverts to a default condition and the condition of each system is shown on the combination meter for the driver.
In this case, it is more appropriate to inform the driver of this information considering the priority order of the systems. On the other hand, when there are no parts used in common, only the system using the inoperative part transits to the above-mentioned condition. For example, as the parts used in the rear PCS and PAB systems are not associated with ACC or LKA, there is little need to consider their coordination.
This guideline also applies to the control of these systems.
When the PB system is activated in a situation where the DSS judges that a collision is unavoidable, ACC and LKA are automatically canceled and the driver is informed of this state via the combination meter.
Therefore, the behavior of these systems has to be fully taken into consideration and guidelines for mediation must be constructed in terms of ergonomics.
The three types of coordination (fail-safe, control, and HMI) among these systems are reviewed as follows.

(1) Fail-Safe - The ACC, PCS, and LKA systems share sensors and actuators. If a part becomes inoperative or a system judges that control is inappropriate, the concerned system stops the control and reverts the vehicle to a normal driving state.
The following terms need to be considered in this case.

a) The concerned system has two types of behavior: whether its diagnostic state is displayed on the combination meter or not
b) There are four combinations of coordination among these systems, as shown in Figure 7.
c) Cruise control systems (AC+, AC-, CSL, and CC) are controlled separately and not simultaneously.

Therefore, 32 variations (=2×4×4) must be fully taken into consideration.

(2) Control - Similarly, the priority order of control among these systems must be decided in advance.

This priority order is defined as PCS>ACC>LKA. Examples of this prioritization are as follows.

When the brake control of PB is activated, ACC and LKA are automatically canceled.

If ACC is canceled due to the forward radar detecting that the grille is obscured by snow, LK is also automatically canceled.

Moreover, system behavior must be decided when systems other than DSS are activated.

For example, when vehicle stability control (VSC) is activated in the event of skidding, ACC and LKA are automatically canceled.

(3) HMI - HMI coordination is related to the combination meter, head up display (HUD), and buzzer.

The most important consideration for HMI coordination is the design of the display on the combination meter since a flashing display may annoy the driver.

As the HUD display includes items that are also shown on the meter, this section describes only meter coordination.

HMI coordination design for the combination meter is reviewed as follows.

DSS-related meters generally have a multi-information area. This area conveys messages to the driver in accordance with the priority order. The messages are largely divided into those related to diagnostics and those related to the vehicle's condition.

The former basically has the priority over the latter. The former types of message pop up in the area the instant that a problem with the system occurs, and are displayed cyclically instead of other messages when the display request continues. Warnings for the PB system have a high priority and are included in this group.

The latter types of message pop up in the area the instant that the vehicle condition changes but are not shown again without manual operation or a further change in condition. Displays related to the outside temperature, fuel-efficiency, and the DSS are included in this group.

The DSS is indicated in the display and the design for each system generally overlaps those of other systems.

The display guidelines are as follows when multiple systems are designed to be displayed in the same area.

1. DSS must be classified into three categories: cruise control systems, the steering support system (LKA), and the collision mitigation system (PCS). Cruise control systems consist of AC+, AC-, CSL and CC systems, which are exclusive of each other.
2. The combinations of these three categories that need to be displayed must be listed.
3. If the systems are designed so that overlap occurs, the priority order must be decided. First, the mediation within the DSS ECU must be considered. Once that is completed, the mediation within the combination meter must also be considered.
   An example of mediation within the DSS ECU is as follows.
   When a vehicle with active ACC is too close to a vehicle ahead, the ACC display will blink to alert the driver.
   On the other hand, if there is an imminent risk of collision, the PCS display will blink.
   Therefore the overlapping alert of ACC and PCS are designed carefully and the priority order is set to ACC alert > PCS alert and the output request of for a PCS alert from the DSS ECU to the meter must be OFF when the ACC alert is ON.
   An example of mediation within the combination meter is as follows.
   When a vehicle with an active CSL system is cruising over the selected speed limit, the CSL alert display will revert to black and white.
   In this case, when a PCS alert is issued, the priority order of the combination meter is set to PCS alert > CSL alert.
   This is because Toyota has two kinds of drive power control systems, and the CSL output computer may be different from the PCS output computer.
   Therefore the combination meter needs to perform mediation in terms of the difficulty of mediation within the DSS ECU and the shared software of the meter.
4. When blinking requests overlap each other, synchronization must be performed within the combination meter.
5. There are two kinds of meter display: monochromatic and color. Therefore, suitable designs for each display must be reviewed as means of notifying the driver.

HMI coordination design for the buzzer is reviewed as follows.

DSS share the buzzer of the brake computer. The computer that requests an ACC alert to the brake computer differs depending on the two kinds of drive power control systems. The VSC and hill assist control (HAC) systems also share this buzzer. Therefore the brake computer must mediate requests from the ACC, PCS, LKA, VSC, and HAC systems.

4. Fail-Safe Design

The ACC, PCS, and LKA systems share the forward radar and camera as sensors and the buzzer as an actuator.

Therefore, the behavior of inoperative sensors or the actuator is divided into four cases, as shown in Tables

1a to d.
When the forward radar is inoperative, system behavior is as follows.
The ACC and PCS systems revert to the default condition and their diagnostic state is displayed because the forward radar is used as a major sensor in these systems (a). In contrast, the diagnostic state of the LKA system is not displayed and only LK is automatically cancelled because LKA uses the forward radar as an auxiliary sensor (c).
When the forward camera is inoperative, system behavior is as follows.
Although AC+ uses the forward camera, AC-, CC, and CSL do not. The diagnostic state of AC+ is displayed and the system is automatically cancelled (a). No display is made for AC-, CC, or CSL and these systems remain activated (d).
The diagnostic state of the PCS system is displayed as it uses the forward camera to provide auxiliary data. However, it remains activated by using the forward radar only (b).
The diagnostic state of the LKA system is displayed, and it reverts to the default condition as it uses the forward camera as a major sensor (a).

Table 1.
Display combinations of diagnostics and control

		Control of system	
		Cancellation	Continuation
Diagnostics display	With	(a)	(b)
	Without	(c)	(d)

Coordination among the DSS has four combinations, as shown in Figure 7.
Of these DSS, the AC+, AC-, CC, and CSL cruise control systems all use different parts.
As an example, AC+ and AC- use the buzzer and yaw rate sensor, but CC and CSL do not. AC+ uses the forward camera, but AC- does not.
Therefore cases (1), (2), and (4) in Figure 7 must be divided between the four kinds of cruise control systems.
Table 2 shows the result of behavior (a) and (c) above as examples.
The priority order for notifying the driver of system cancellation due to behavior (a) only is

ACC>LKA>PCS. (4-1)

As the state of the PCS system is not displayed on the meter during normal driving conditions, the priority of PCS is lower relative to the other systems.
The time used to determine whether these systems are inoperative is set to a common fixed time. When the buzzer used by these systems becomes inoperative as shown in "Fail BUZZ" in Table 2, the output mediation for DSS diagnostics determines the priority order and the DSS ECU sends diagnostic messages in sequence to the meter with a time lag by CAN communication. Therefore, the meter displays each message in turn in the order of priority.

Table 2.
Fail-safe matrix (excerpt)

	(1)	(2)	(3)	(4)
(a) only	AC+ AC- CC Ncom B-ECU Ncom Y-SEN Fail BUZZ Ncom F-CAM Fail F-CAM	AC+/AC- CC Ncom E-ECU Fail E-ECU Ncom S-SEN	AC+/AC- Fail Y-SEN	AC+/AC-/CC Fail STP Ncom B-ECU
(a)+(c)	AC+ AC- Ncom F-MMW Fail F-MMW F-CAM overheat	None	None	AC+/AC- Dirty F-MMW Wiper operation

Note 1) Forward radar (F-MMW), Forward camera (F-CAM), Brake ECU (B-ECU), Engine ECU (E-ECU) Yaw rate sensor (Y-SEN), Steering sensor (S-SEN), Buzzer circuit (BUZZ), Stop switch (STP)
Note2) Ncom A means lost communication with A
Note 3) Fail B means B malfunction

Figures 8 and 9 show system behavior when this condition occurs.
Figure 8 (a) shows the displays for ACC under normal cruising. The vehicle-to-vehicle distance can be set in three ways: long, medium, short. A vehicle ahead of you will be displayed to indicate the presence of the vehicle if a vehicle is cruising ahead of you. Set speed is displayed in the upper-right position. Figure 8 (b) shows the displays for LDA. Thick white lines indicate the condition under LDA control. The overlapping display of (a) and (b) shows in Figure8 (c).
If the buzzer suddenly becomes inoperative in "Fail BUZZ" in Table 2, the display changes in sequence in accordance with (4-1), as shown in Figure 9.
In particular, when behavior (a) + (c) occur, the control changes conditions almost simultaneously. However, the control and diagnostic displays must be shown without flashing.
When the windshield wipers start operating at high speed as shown in "wiper operation" in Table 2, the display changes in sequence at intervals of at least 2 seconds, as shown in Figure 10.

(a) ACC normal cruising (b) LDA control (c) Simultaneous display

Figure 8. ACC and LDA displays.

Figure 9. Displays for behavior (a) only.

Figure 10. Displays for behavior (a) + (c).

Mediation for the above-mentioned behavior is performed within the DSS ECU.
Moreover, as a diagnostic function of the DSS ECU, unified diagnostic trouble codes (DTC) among DSS are set for the DSS to improve the ease of repair services.

5. Control Design

There are also four combinations of control coordination, as shown in Figure 7, and the four types of cruise control systems must be considered. DSS behavior when other systems are activated must be considered in terms of control coordination. VSC using brake control is part of this consideration.
The priority order involving VSC control is VSC>PB/PAB (brake control) >ACC>LKA.
This correlation shows in Figure 11. The arrows indicate the cancel request of control against other systems. The priority order of VSC>PB/PAB is performed within the brake ECU.
Control coordination including switch operation is shown in Table 3.

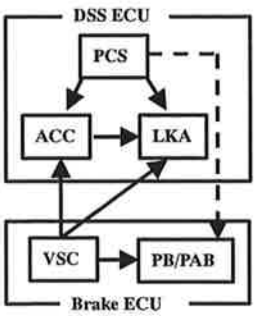

Figure 11. Information flow of control cancel request

**Table 3.
Control coordination matrix**

No	Coordination item	AC+	AC-	CC	CSL	LK	LDA
(1)	Fusion processing PB/PAB	r	r	r	o	r	r
	Switch operation	r	r	p	o	r	p
(2)	PB/PAB	r	r	r	o	-	-
(3)	Fusion processing PB/PAB	-	-	-	-	-	r
(4)	Switch operation	r	r	p	o	r	p
Other	VSC	r	r	r	o	r	r

Note 1; r: removal of the function, o: normal,
p: depends on Switch operation, -: irrespective
Note 2; Switch operation: cruise main switch, cruise cancel switch, brake switch, Wiper switch, snow mode switch

6. HMI Design

(1) Combination Meter - DSS are controlled individually and their control states are displayed on the combination meter.
When one system requests the blinking of the display on the combination meter, a request from another system might be transmitted at the same time.
If the blinking request timing of two systems does not match, the meter display may flash or show another undesirable condition.
In particular, display coordination between the ACC and LDA systems can be described as an example. Figure 12 (a) shows the display for an ACC alert. When LDA is being controlled simultaneously, thick white lines are overlaid on the display, which reverts to black and white as shown in Figure 12 (b).

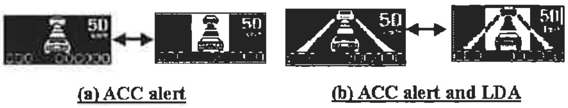

Figure 12. Overlapping display of ACC and LDA.

Similarly, Figure 13 shows the blinking of systems other than ACC.
The blinking frequency of these systems is set to 1 Hz on a common basis. On the other hand, CSL alert reverts to black and white without blinking.

Figure 13. LDA/LK/PCS/CSL displays.

Moreover, the non-control states of ACC and LDA are displayed as shown in Figure 14.

Figure 14. ACC/LDA non-control displays

Combinations of HMI coordination are the same as those for fail-safe or control coordination as shown in Figure 7. As an example, Region (4) covers the display shown in Figure 12.

Display mediation is performed by the following procedure.
1. Mediation within the DSS ECU (6-1)
2. Mediation within the meter

2-1 Simultaneous display (6-2-1)
2-2 Priority order of display (6-2-2)
2-3 Blinking synchronization (6-2-3)

(6-1): When a request for an ACC alert occurs simultaneously with a PCS alert, the output request for the PCS alert from the DSS ECU is set to OFF. As another example, inspection displays such as for the DSS and sensor adjustment are mediated within the DSS ECU.

(6-2-1): The simultaneous display shown in Figure 8(c) is an example. Combinations of these designs should not overlap.

(6-2-2): The priority order of these systems is set as follows, and the overlapping part of lower priority systems is not displayed.

PCS alert > ACC non-control (1) and (2)/CSL control/CSL alert

(6-2-3): When the blinking of one system overlaps one of another, the blinking is synchronized. For example, when an LDA alert overlaps an ACC alert, the design delays the simultaneous display in accordance with the blinking cycle shown in Figure 15 to prevent the display from flashing.

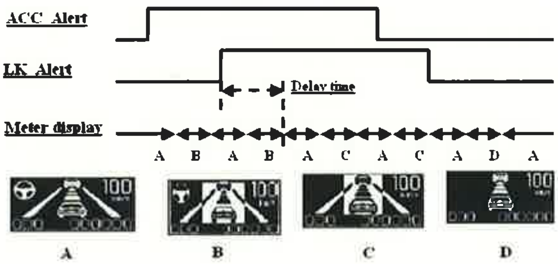

Figure 15. Blinking synchronization.

Table 4 shows an excerpt from DSS behavior. All combinations of these systems must be listed and the mediation decided in advance.

Table 4.
Display coordination matrix (excerpt)

Method		(6-1)	(6-2-1)	(6-2-2)	(6-2-3)
(1)	ACC Non-control (1)(2) + PCS alert + LDA control		X	X	
	CC control + PCS alert + LDA alert		X		X
	CSL alert + PCS alert + LDA control		X	X	
	CSL alert + PCS alert + LDA alert			X	X
(2)	ACC non-control (1)(2) + PCS alert		X	X	
	ACC control + PCS alert		X	X	
	ACC alert + PCS alert	X			
	CSL alert + PCS alert			X	
(3)	PCS alert + LDA control		X		
	PCS alert + LDA alert		X		X
(4)	ACC alert + LDA control		X		
	CSL alert + LDA control		X		
	ACC alert + LDA alert				X
	CSL alert + LDA alert		X		

These displays apply to monochromatic meters, but the guidelines can also be adapted to TFT meters, which can display in color.

Figure 16 shows examples of TFT alert displays from the ACC, PCS, and LDA systems. The blinking frequency of these systems is set to 2Hz to the advantage of the high response of TFT meters.

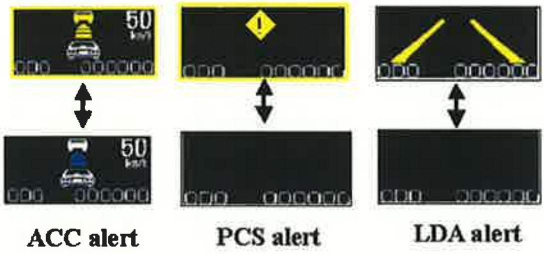

Figure 16. ACC/PCS/LDA alerts on TFT display.

(2) Buzzer - Table 5 shows the intermittent frequency of the buzzer and the priority order of each system.

The higher the frequency is, the more urgent the message to be conveyed to the driver.

The priority order of the controls has already been mentioned in the section on control interference design, and is as follows.

VSC>PB/PAB (brake control) >ACC>LKA

While VSC is automatically controlled, warnings from the PB system convey urgent messages to the driver to prompt avoiding action.

For this reason, the priority order of the buzzer has been decided as PB>VSC.

PCS alert includes PAB buzzer and continues to beep until PB warning in high possibility of collision.

Table 5.
Priority order of buzzer requests

Priority	System	Intermittent frequency
1	PB warning	10 Hz
2	VSC alert	5.2 Hz
3	ACC alert	5 Hz
4	PCS alert	5 Hz
5	LKA alert	5 Hz
6	HAC alert	4 Hz

CONCLUSIONS

Logical mediation structures for Toyota's DSS have been developed.

Mediation design can be largely classified into fail-safe, control, and HMI aspects.

The important procedures of mediation are as follows.

(1) Understanding the behavior of each system
(2) Deciding which part is the most suitable to perform mediation
(3) Consideration in terms of ergonomics

These logic structures are adopted in all Toyota and

Lexus cars containing DSS.
These mediation guidelines are also expected to be considered for possible adoption in future systems.

REFERENCES

[1] Fujita, K. et al. "Development of Pre-crash Safety System." The ESV 18th Conference, Paper No. 544-W, 2003

[2] Tokoro, S. et al. "Pre-crash Sensor for Pre-crash Safety." The ESV 18th Conference, Paper No. 545-W, 2003

[3] Ohue, K. et al. "Development of a New Pre-crash Safety System." SAE Paper 2006-01-1461

[4] Kawahara, S. et al. "Toyota's New Integrated Drive Power Control System." SAE Paper 2007-01-1306

[5] Morita, M. et al. "Introduction to Radar Cruise Control System with Full-Speed Following Function." Toyota Technical Review Vol. 55 No. 1 Mar. 2007

[6] Usami, M et al. "Stereo Vision System for Advanced Vehicle Safety System." SAE Paper 2007-01-0405

[7] Matsubayashi, K. et al. "Development of Rear Pre-Crash Safety System For Rear-End Collision." The ESV 20th Conference, Paper No. 07-0146

[8] Shimizu, M. et al. "Development of Collision Avoidance System." 14th World Congress on Intelligent Transport Systems

[9] Nishina, K. et al. "Development of New Pre-crash Safety System Using Driver-Monitoring Sensor." 15th World Congress on Intelligent Transport Systems, Paper No. 10315, 2008