THE XK8 HIGH SPEED POWERTRAIN SERIAL COMMUNICATIONS SYSTEM

By

Andrew Croft BSc, MSc, CEng. MIEE

Electrical Engineering, Jaguar Cars Ltd

ABSTRACT

Serial Communications within vehicles has emerged as the enabling technology for the next generation of electrical vehicle architecture. Currently, many of the major automotive companies are evaluating serial communications as a solution for delivering real-time control powertrain system functions. Amongst the front runners is Jaguar.

This paper highlights how Jaguar has successfully implemented high speed serial communications technology, Controller Area Network (CAN), to enable communications between powertrain sub-systems entailing Anti-Lock Braking System (ABS), Engine Control Module (ECM), Transmission Control Module (TCM) and Instrument Pack. This high speed network is the core of the vehicle electrical system which enables enhanced feature and refinement of vehicle functions and service bay diagnostics, allowing the XK8 to meet all current emissions legislation, whilst maintaining best in class drivability.

1. INTRODUCTION

The vehicle of today is no longer perceived by customers solely as a means of getting from A to B. Modern customers pay particular attention to a vehicle having the right feature at the right price and of the right quality.

As customer demands have increased, the complexity of the vehicle electrical system has mushroomed to such a degree that practically every feature within the vehicle has become dependent upon some form of electrical interface. Technology is now perceived as a competitive weapon due to its ability to increase feature level, and applications achieved via the use of technology in the luxury market undoubtedly provide a competitive edge, which is a critical factor in any business environment, since a company's success is likely to depend upon it.

In order to remain competitive within the luxury car market it is the responsibility of engineers to find ways of achieving the upwards pressure on functionality for the customer, at higher quality and with more reliability while at the same time handling the downward pressure on cost, weight and time to market.

2. A TECHNICAL OVERVIEW OF CAN SERIAL COMMUNICATIONS

Powertrain and chassis control place demands on a vehicle's electronic systems. These systems/modules must be able to handle the rapid responses that are necessary to make them perform properly in a real-time environment.

Serial communications enables this process as it provides a means for the interchange of inter-module data and control information at high speeds on a single bus. Its role is to ensure that any communication between these systems is fast enough to cope with the demands made upon them.

Serial communications is the technique by which many functions, normally carried by numerous wires, is passed along a single medium - a twisted wire pair in Jaguar's case. The information is converted to digital form (i.e data) and transmitted as a series of binary digits, 0 and 1, along the twisted wire pair. The speed at which the numbers can be transmitted allows the sequential nature of the information to be hidden i.e the faster the better. The numbers are coded by allocating voltage pulses to time slots and using the pulses to represent the binary digits, 0 and 1. A single message consists of a series of numbers, the first one is special and is called the identifier which informs the system what it is. Following the identifier is the information itself and additional numbers at the end form part of the error checking mechanism.

2.1 Considerations for Jaguar's Application

The automotive environment is known to be both physically harsh and electrically noisy, and as such, any communication protocol chosen must be capable of performing under these conditions as well as meeting the requirements of the application. When determining the network architecture for Jaguar's high speed powertrain application, which involves real-time control, the following factors were taken into account :

- *Latency Time* : This is defined as the time a transmitting node is ready to send information up until the time the transmission has been completed. Short latency times are essential in real-time control applications.

- *EMC and EMI* : The radiated emissions and susceptibility should not effect system performance and be capable of meeting legislative requirements.

- *Error Handling and Fault recovery* : Less than one undetected error rate in the lifetime of the vehicle is considered reasonable [ref 1]. The ability to handle and recover quickly from faults was also considered an important factor.

- *Data Consistency* : The protocol must ensure consistency of data across the network particularly when sharing sensor information having eliminated duplication of sensors.

- *Flexibility* : Because vehicle configuration requirements may differ across model variants and model years, it is necessary that ECU's on the network can be interconnected at different locations within the vehicle without the need to redesign or requalify the system or sub-system.

- *Expandability* : Existing systems may need to be upgraded or added to over time. This should be possible without modification of the original system if the additional ECUs are listening nodes, i.e. to data already in existence within the core system. Modification of a sub-system is acceptable to accommodate additional ECU's if it is restricted to software changes only.

The CAN protocol was chosen to meet the demands of the Jaguar powertrain system as it was the only available technology that could realise the requirements of the system specification.

To appreciate the other benefits CAN offers, the following overview is given.

- Expansion and conversion to different configurations are simple
- A multi-master broadcast communications system. That is, every control unit has the same right to access the network
- The CAN arbitration mechanism is entirely independent of system configuration
- No extra provision for start-up is required
- It can take upto 2032 identifiers
- Error recovery is fast
- Upto 1 Mbps (variable) over 40 metres of twisted pair cable
- The arbitration procedure is deterministic in the sense that its outcome can be predicted for any given contention situation
- Latency time is short for high priority messages
- Contention based with no data loss. Simultaneous transmissions are resolved via non-destructive bitwise arbitration. This also provides the message prioritisation. It operates because a dominant bit (logic 0) always overwrites a recessive bit (logic 1), hence if a node transmits a recessive but receives a dominant at the same instant, it knows another higher priority message is also on the bus and therefore stops transmitting. This scenario is shown in Figure 1 below.

Figure 1

NON-DESTRUCTIVE PRIORITISED BITWISE ARBITRATION (EXAMPLE)

NODE 1 : (ID 162)	0	0	0	1	0	1	1	0	0	0	1	0	(ENGINE SPEED)
NODE 2 : (ID 65A)	0	*1	1	0	0	1	0	1	1	0	1	0	(COOLANT TEMP)
NODE 3 : (ID 1B4)	0	0	0	1	*1	0	1	1	0	1	0	0	(VEHICLE SPEED)
BUS :	0	0	0	1	0	1	1	0	0	0	1	0	

* NODE DETECTS LOST ARBITRATION, STOPS TRANSMITTING, AND CONTINUES TO RECEIVE MESSAGE

- Error handling techniques (Cyclic Rdundancy Checking and bit stuffing) for reliable operation in an automotive environment
- Variable data length, 0 - 8 bytes

2.2 Technical Highlights of CAN

CAN was developed by BOSCH in the early 1980's and the first working silicon became available in 1987 after INTEL signed a licensing agreement in 1985. It achieved full ISO standard in 1984[ref 2] and was already approved by the American Society of Automotive Engineers as the standard for the truck and bus industry.

CAN uses a linear bus topology (see Figure 2) which means that every control unit has the same right to access the network, i.e. it is a multi-master broadcast system. Expansion and conversion to different configurations are very simple. However, the constraining factor of this structure lies with the cable length since the maximum length of cable for an application is directly related to, and hence determined by, the rate of data transfer.

CAN is capable of running at 1 Mbps (million bits per second) which enables data transfer to be carried out in a few milliseconds, meeting the needs of the control modules which will use this data. The transfer of data takes place within a CAN message frame (see Figure 2).

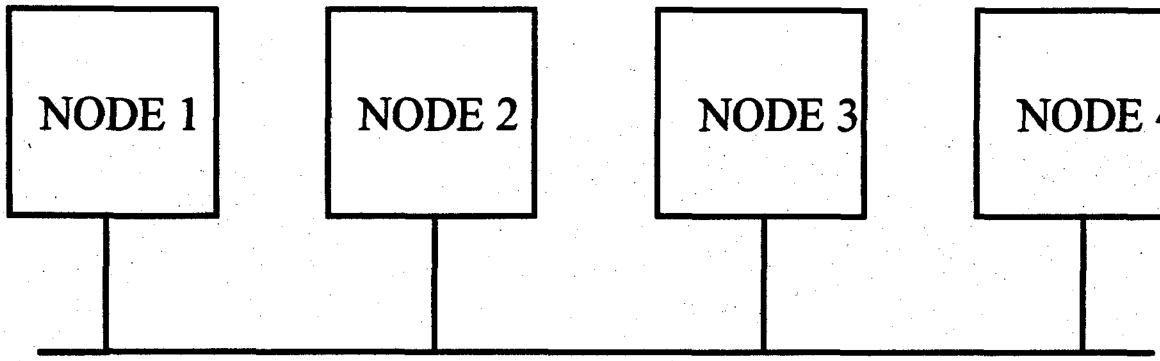
2.3 CAN Message Frames

Communication within a CAN network takes place through a Data Frame. A Data Frame is used to transfer data between nodes. The first field is special and is called the identifier which assigns meaning to the message by defining what it is. The Data Length Code (DLC) indicates the length of the data field. What follows this is the data itself and an error checking mechanism (CRC). The acknowledge (ACK) bit ensures error free transmission has taken place since the assertion of the ACK bit informs the transmitting node that at least one receiver has received the data correctly. If not, an ERROR FRAME is generated and the message is rejected by all nodes. An Error Frame is transmitted if any node on the network detects an error condition during or after a message transmission.

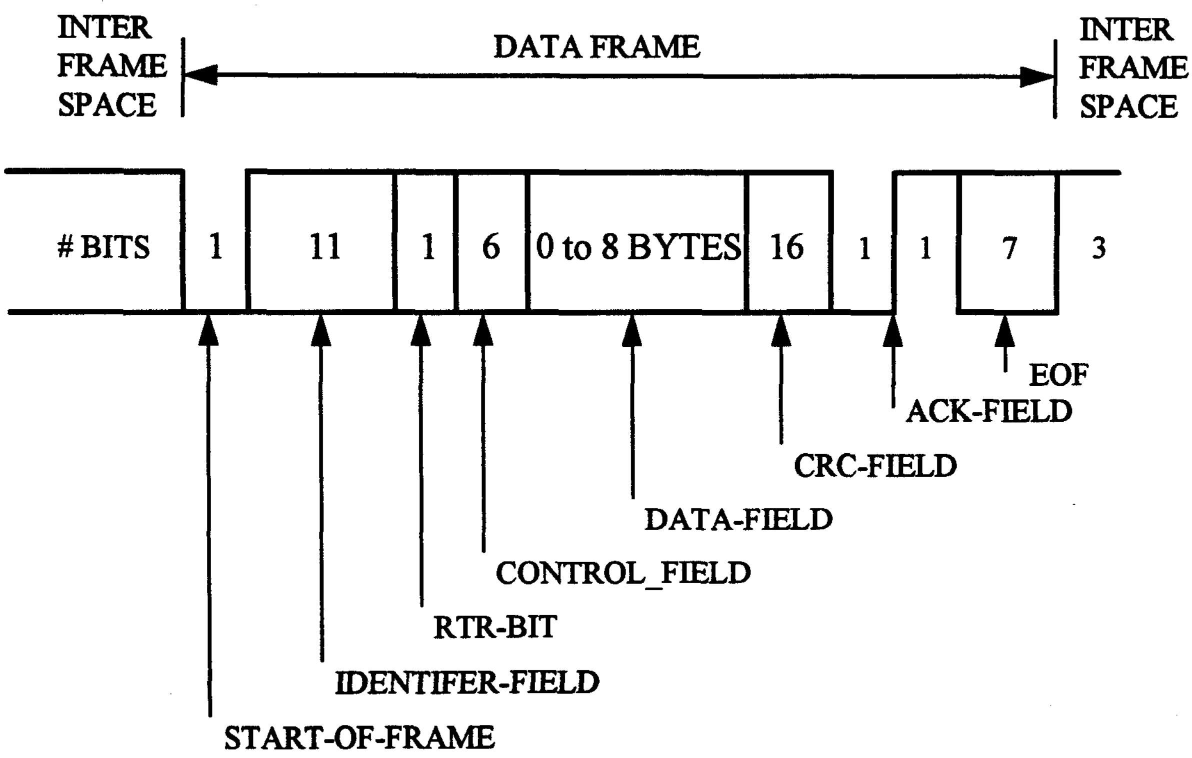
The strength of all this is that it is transparent to the host processor which minimises host processing time. All the host has to do is read and write data into memory slots inside the CAN chip and everything else is performed by the CAN chip. This enables higher level system design to take place without worrying about the details.

Figure 2

LINEAR BUS TOPOLOGY



MESSAGE FRAME

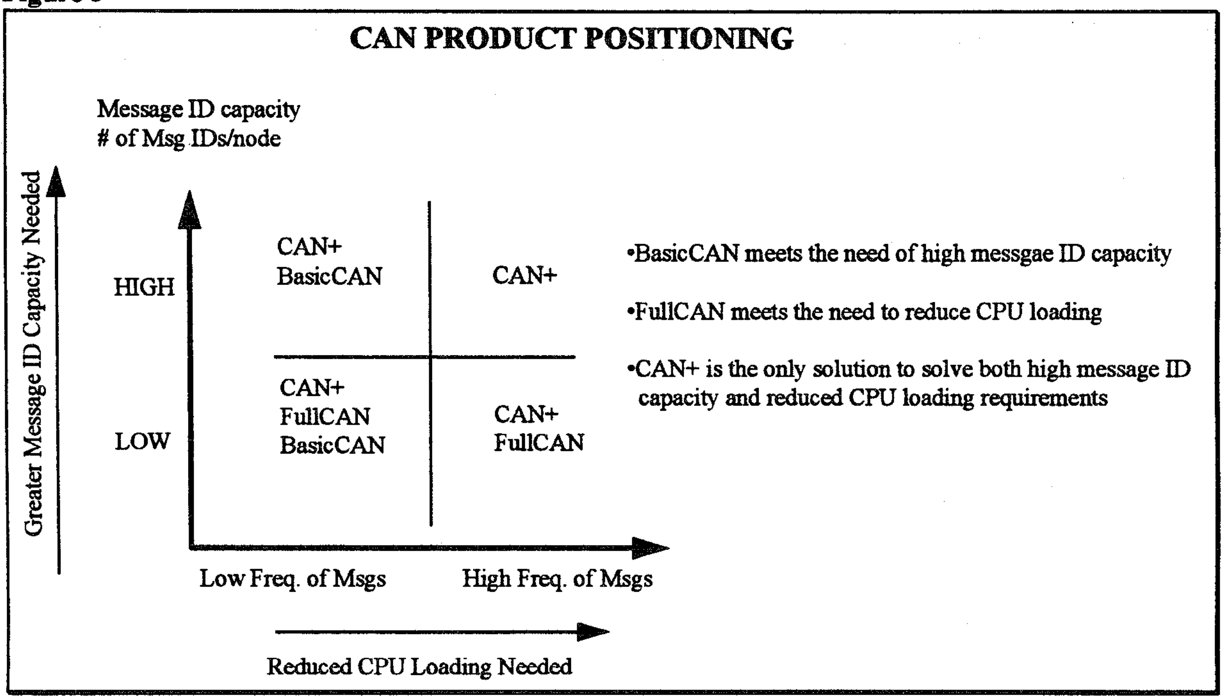


2.4 Implementation of the CAN protocol

A CAN 'chip' can be designed into the electronic circuit of a control module and allow data to be passed in and out of the module via a twisted pair cable linking all the modules on the network together. Chips are available from a number of semiconductor suppliers in a range of forms such that the complexity (and hence cost) of the device can be matched to the application.

There are currently three recognised implementations of the CAN protocol supported by silicon manufacturers known as BasicCAN, FullCAN and CAN+. These are functionally identical with respect to their interface to the bus, but differ in the way the data is buffered inside the chip. BasicCAN is useful where many message identifiers are used, but it incurs a greater host processor overhead by relying on interrupts to service each individual message reception and is therefore suited to non-time critical applications with many message identifiers, for example body system applications. FullCAN does not rely solely on interrupts, but has limited dedicated buffer capacity and hence is useful in applications with few time-critical messages. CAN+ combines the best features of both, allowing some time critical and many non-time critical messages. Figure 3 illustrates how these are positioned in terms of message capacity and the frequency of messages. Jaguar's implementation uses the CAN+ device with the 11 bit identifiers giving 2032 available messages which is commonly known as CAN 2.0A. CAN 2.0B is known as extended CAN and has 29 bit identifiers.

Figure 3



The attractiveness of CAN+ to Jaguar is its capability to handle high performance CAN systems and ability to cater for future requirements. Its memory configuration of 256 bytes has allowed Jaguar's powertrain application to develop in a flexible manner without the memory constraints which would have been imposed with the FullCAN implementation (64 bytes of DPRAM).

3. JAGUAR'S APPLICATION

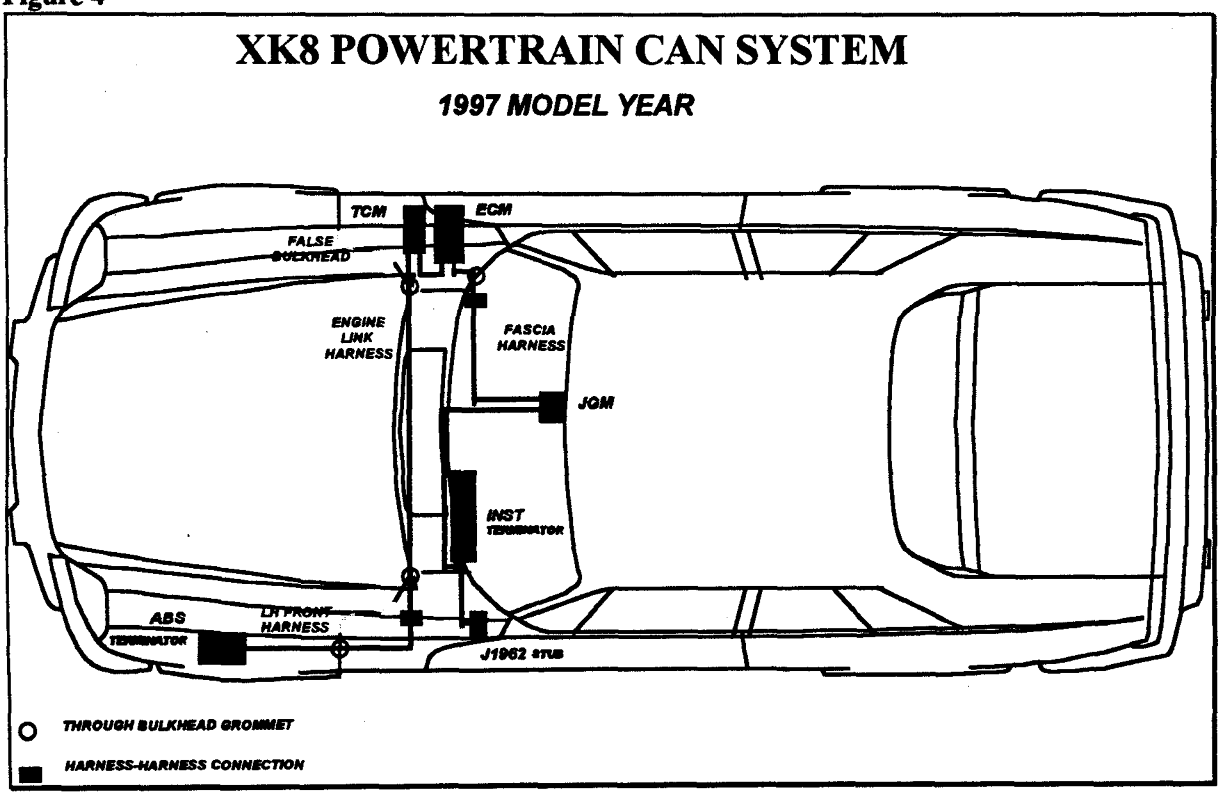
Jaguar's new sports car, the XK8, features the all new AJV8 engine. AJV8 is an advanced 4-litre V8 incorporating sophisticated electronic management and throttle control systems. A CAN communications network is used on this vehicle which links the following systems :

- ECM - Engine Control Module (Denso Japan)
- TCM - Transmission Control Module (ZF Germany)
- ABS - Anti-lock Brakes (Teves Germany)
- INST - Instruments and driver information (FORD ELD USA)
- JGM- J-Gate Illumination Module (AB) : 'listening node only'

3.1 Powertrain Electronics Architecture

The network runs at 500Kbps over a twisted wire pair which facilitates the interchange of information between these ECU's such that they can perform their functions in an integrated manner. This information comprises sensor data, switch data and real time control data. Figure 4 shows the configuration of the system for XK8 as well as the approximate locations of the ECU's and the routing of the CAN bus within the vehicle wiring harness.

Figure 4



The ECU's designated as 'terminators', i.e. those modules at the end of the bus have a 120 Ohm resistor fitted to match the impedance of the twisted wire pair, this reduces reflections which may occur on long bus lengths and at high bit rates.

The object of the system design is to allow the addition or omission of nodes in a modular open system fashion. The network is referred to as 'high speed' to reflect the real-time nature of the information it carries and the bit rate required to meet the response times.

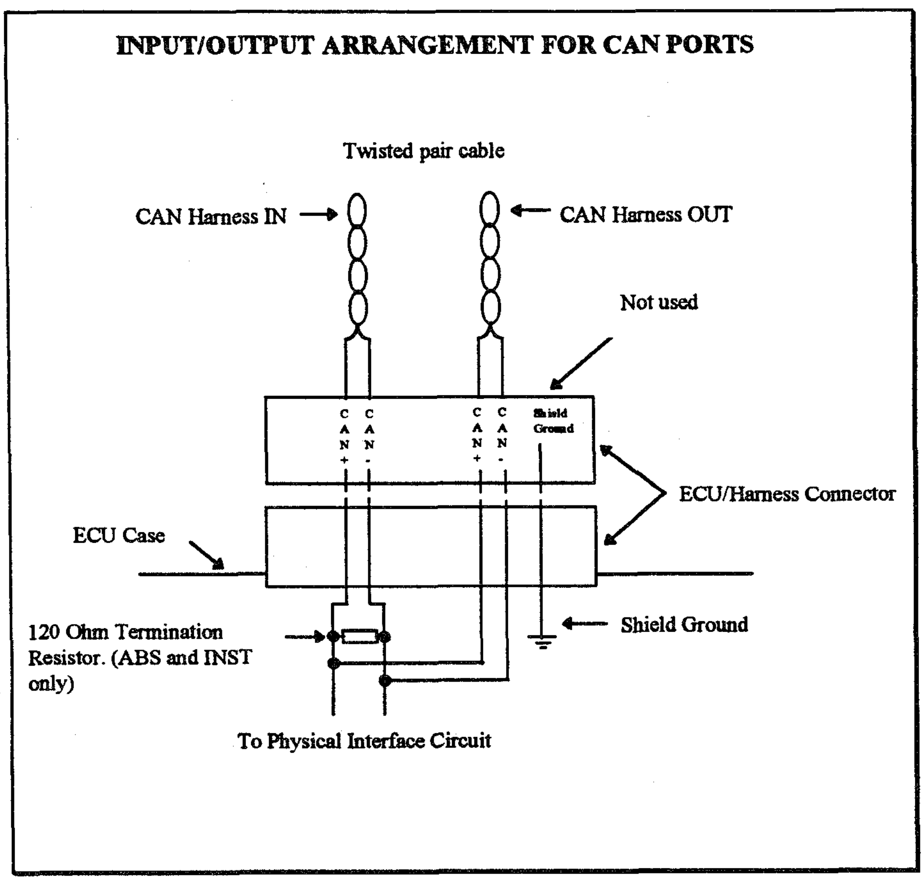
3.2 The Transmission Medium

The CAN wiring harness is a standard 0.5mm unshielded copper twisted wire pair cable. It is configured such that the bus enters and leaves each communicating module via separate input and output terminals.

The connection to the CAN bus is via the normal module block connector. Four pins are allocated on each module which are CAN+ IN, CAN- IN, CAN+ OUT and CAN- OUT.

CAN IN and CAN OUT are joined together inside the ECU via PCB tracks, with the facility for a 120 Ohm termination resistor (see Figure 5 below for a detailed illustration).

Figure 5



3.3 System Design

It cannot be stressed enough that to design a sophisticated and reliable in-vehicle network system it is essential that the requirements of the whole system are considered and fully defined up front. After this has been completed, the requirements of the in-vehicle network system can be described. It is from this philosophy that Jaguar has proceeded.

It follows that the protocol is simply the raw medium for communication which forms the platform upon which the system will operate and perform. Once the protocol has been established and proven to be capable of meeting system requirements, the real challenge lies with the system design. This is by far a more important issue than the choice of protocol.

3.4 Message Infra-Structure

Once the requirements of the system have been determined the network infra-structure can be defined. This involves message packaging, assigning priorities and cycle times.

The packaging of information into messages (up to 8 bytes of data) has several benefits. In terms of the system it allows multiple data to be received at the same time, for example, all four wheelspeeds (each of 2 bytes) can be placed into a single message. This enables related data to be presented at the same time. In terms of the network, message packaging alleviates the traffic on the network which in turn reduces the bus loading. It also utilises the hardware in an efficient and economical manner since the 82527 CAN chip is limited to a total of 15 messages in a system configuration before software management, and hence overhead, becomes necessary.

Once the grouping of information was accomplished, prioritisation was assigned to the messages in accordance with overall system performance timing requirements. Simulations of network traffic were then run to confirm that the timing requirements would be met.

4. NETWORK MANAGEMENT AND FAULT TOLERANCE

4.1 Network Monitor

The network monitor is a novel design solution which has been patented by Jaguar. It is a feature of the system design that has several functions. Its primary role is to determine that the system is functioning normally, i.e. that all the nodes are on the network and the bus is intact.

The reason for having such a feature is so the driver can be warned if a fault exists and other nodes on the network can be made aware of a problem and use appropriate default values. It was considered necessary since there is no inherent way of detecting if a node is disconnected unless each individual message is monitored; this is difficult, inflexible and wasteful.

Jaguar's approach to this problem was to introduce the concept of one special message that is monitored by all nodes. This message would then be realised by a higher level of system software known as the network monitor. The profile of the network monitor is as follows :

Musts

- Capable of detecting an incomplete network
- Recognise incompatibility of electronic modules (wrong part fitted)
- Detect and log intermittent faults

Key Requirements

- Common functionality on all nodes
- Consume minimal processor overhead
- Use minimal traffic overhead
- Respond in under a second
- Inform driver of any problem (if required)
- Locate position of fault
- Allow the use of default values
- Diagnostics

The way in which the network monitor works is that each node has a special message, known as a network monitor "token", which it transmits approximately every 200 milliseconds. The network monitor token contains one byte and is structured such that the upper nibble reflects the vehicle model for which the node is intended, for example:

- '1' - represents XK8

The lower nibble represents the level of system the node is intended for. For example, each time the vehicle progresses to the next development phase the value within the lower nibble will be increased by 1. Checks are performed on the tokens to determine the status of the network.

4.2 Status of Nodes

Each node in the system determines the status of the network approximately once every 500 milliseconds. To do this it checks that it has received the network manager tokens from every other node in the system. Therefore, if a node is functioning then its token (transmitted every 200 milliseconds) should have been received at least twice in this time. If the token from one or more nodes has not been received in the 500 millisecond window, then the network monitor software authorises the default values to be used for the information that is normally received from these 'missing nodes'. If a node is detected as 'missing', but then recovers during the same journey, i.e. the token reappears, it is logged by the detecting node as an intermittent fault.

In order to prevent data inconsistency in the system all four tokens must be of the same value. If one or more tokens received are not equal to the transmitted token then default values are used for the data normally received from these 'inconsistent' nodes. Additionally, the Instrument Pack displays a 'Wrong Part Fitted' message. This also applies to the upper nibble which represents the vehicle model. From production and thereafter such events are only likely to occur during manufacture or service replacement action. However, during the development stages it served to be an excellent control for maintaining system consistency.

5. DEPENDABILITY

Dependability can be described as the ability to tolerate all levels of network errors/faults without ever preventing the vehicle from starting or operating which was a major factor in the overall powertrain system design. Dependability is an important attribute of a real-time control system [ref 3], and any communications which operate in such an environment must also be dependable. Dependability is a feature of the overall system design and attaining it is over and above what the CAN protocol can inherently offer.

The normal approach to communications system design is to use the 7 layered ISO-OSI model [ref 4]. However, this a theoretical model and in a real-time system such as CAN for powertrain control, it does not help to think of services at all levels of this 7 layer model. Therefore, for this reason the model is simplified to 3 layers: Physical, Transfer and Application as shown in Figure 6.

The application layer contains information used by the ECUs on the network. It is the layer where the data becomes meaningful and its use within the system becomes relevant.

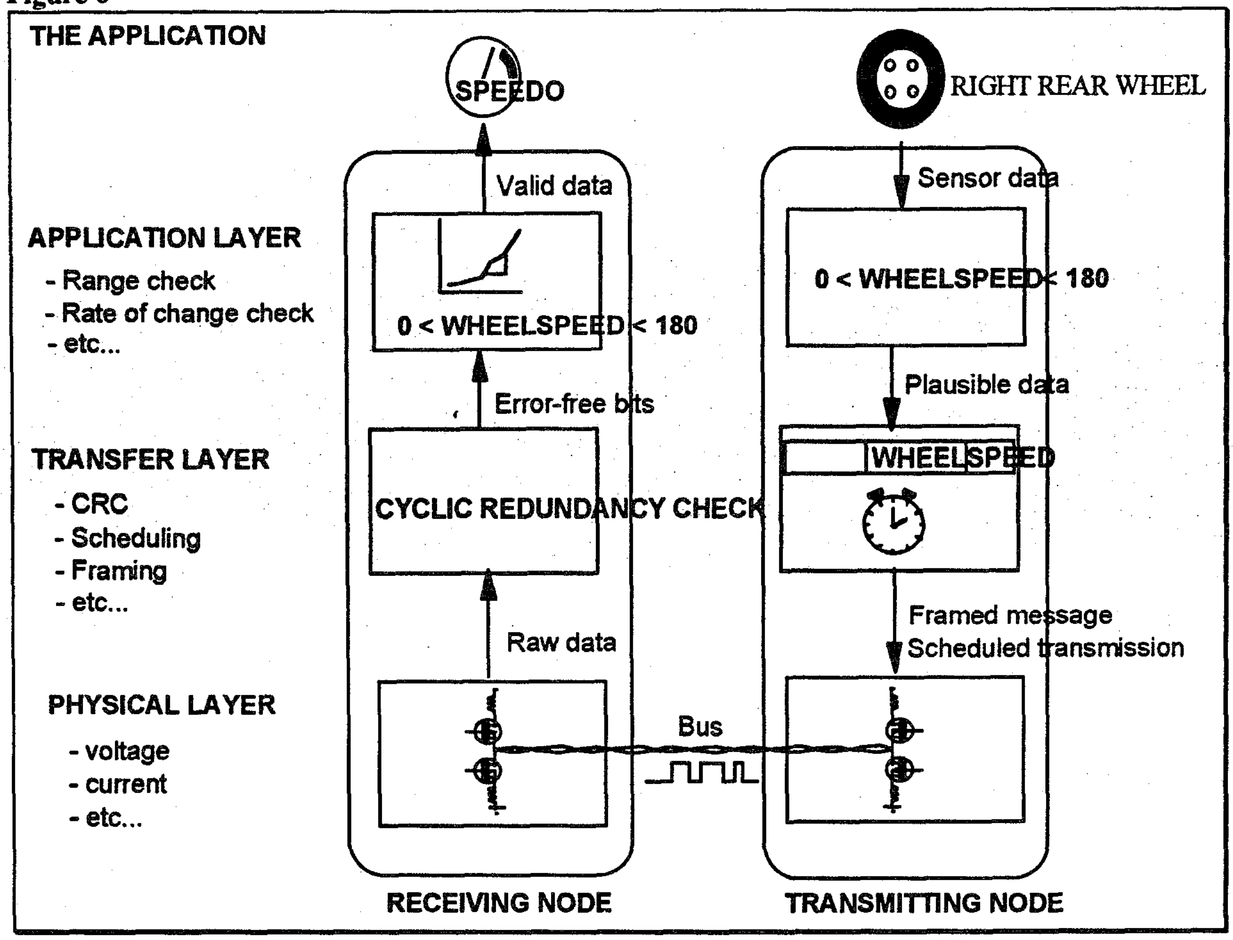
The transfer layer is the part of the system where the techniques for managing the integrity of the network are located. The requirements of the transfer layer are mainly met by software. The requirements are divided according to whether they apply to message level (received and transmitted) or system level (see Figure 7 for further details).

The physical layer is the wires, connectors, transmit/receive interface circuits, and all the associated voltages, currents, resistances and capacitances.

Dependability is achieved by using a number of techniques. To increase the dependability of the physical layer, which is effectively the communication hardware, would be to use redundancy. It was not considered either appropriate or necessary in Jaguar's application to have a dual operational bus, however, by introducing other methods in the transfer layer the appropriate level of overall system dependability can be achieved.

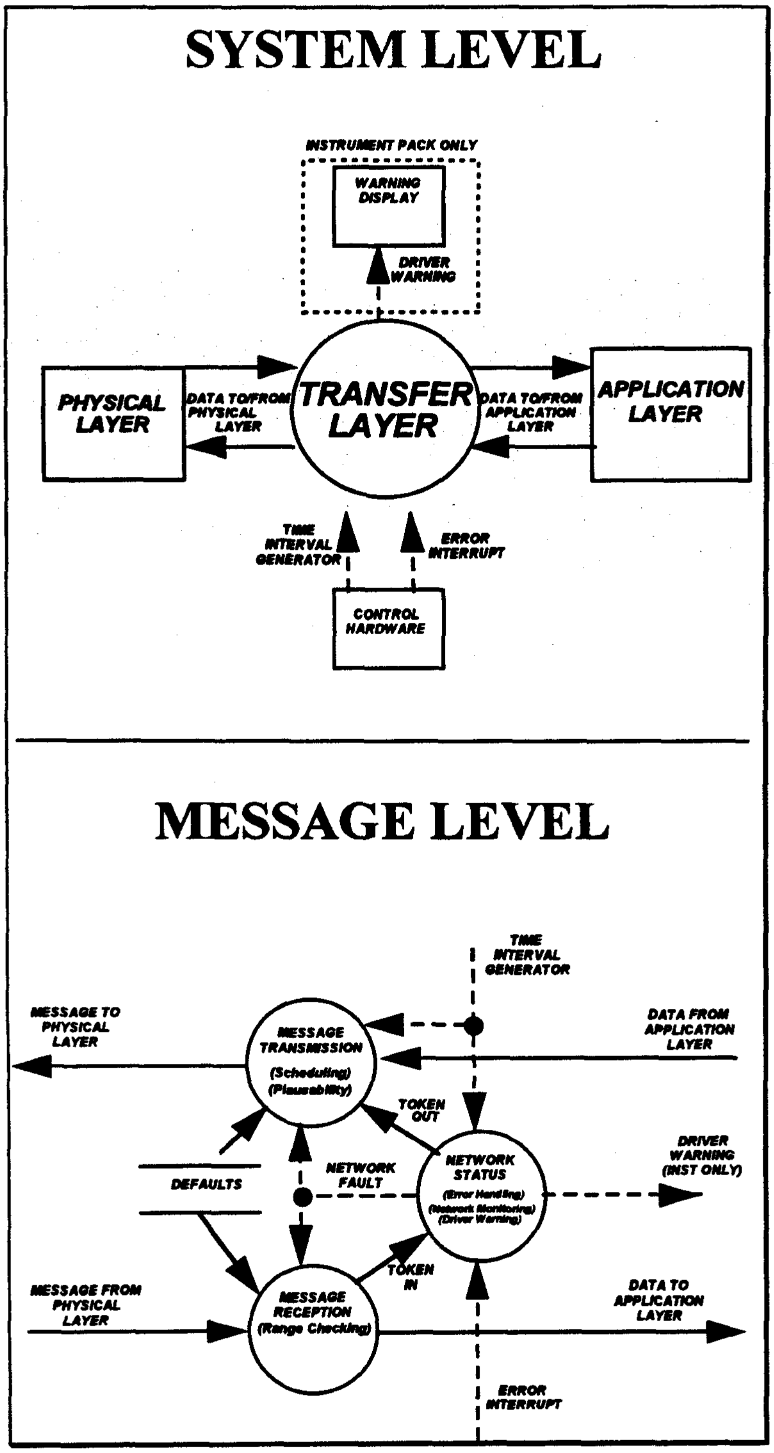
Jaguar's system contains a number of methods aimed at dependability, some of which are supplied by the CAN chip itself, and others which are implemented in software. The techniques used are as follows:

Figure 6



THE APPLICATION
SPEEDO
RIGHT REAR WHEEL
Valid data
Sensor data
APPLICATION LAYER
- Range check
- Rate of change check
- etc...
0 < WHEELSPEED < 180
0 < WHEELSPEED < 180
Plausible data
Error-free bits
TRANSFER LAYER
- CRC
- Scheduling
- Framing
- etc...
WHEELSPEED
CYCLIC REDUNDANCY CHECK
Framed message
Scheduled transmission
Raw data
PHYSICAL LAYER
- voltage
- current
- etc...
Bus
RECEIVING NODE
TRANSMITTING NODE

Figure 7


SYSTEM LEVEL
INSTRUMENT PACK ONLY
WARNING DISPLAY
DRIVER WARNING
PHYSICAL LAYER
DATA TO/FROM PHYSICAL LAYER
TRANSFER LAYER
DATA TO/FROM APPLICATION LAYER
APPLICATION LAYER
TIME INTERVAL GENERATOR
ERROR INTERRUPT
CONTROL HARDWARE
MESSAGE LEVEL
TIME INTERVAL GENERATOR
MESSAGE TO PHYSICAL LAYER
MESSAGE TRANSMISSION (Scheduling) (Plausability)
DATA FROM APPLICATION LAYER
TOKEN OUT
NETWORK FAULT
DEFAULTS
NETWORK STATUS (Error Handling) (Network Monitoring) (Driver Warning)
DRIVER WARNING (INST ONLY)
TOKEN IN
MESSAGE FROM PHYSICAL LAYER
MESSAGE RECEPTION (Range Checking)
DATA TO APPLICATION LAYER
ERROR INTERRUPT

5.1 Scheduling

Each ECU schedules the messages it is required to transmit on a regular and predictable cycle time. This involves a timer and queuing mechanism which allows the highest priority and lowest cycle time messages to be correctly scheduled for transmission. It should be noted at this point that the CAN chip manages the waiting for the 'bus idle' condition before the transmission commences, which is an entirely separate item.

5.2 Bit Level Error Handling

The majority of this is implemented within the CAN chip itself (error detection and correction by retransmission).

5.3 Data Range Checks

Each sensor message has a specified range of valid data; all information that is transmitted and received within the CAN system is checked for a valid data range and is ignored if out of range.

5.4 Plausibility Checks

These are only applied to certain critical signals, and are carried out at source prior to transmission. Hence if the data passes the range check on reception then the data can be considered plausible. The advent of OBDII has now brought greater attention to this area.

5.5 Network Monitor

The network monitor continually assesses the network and decides what state it is in. It has the ability to quickly detect a fault with the CAN network and once a fault has been detected the appropriate default strategy is assumed. It also has another function of indicating the vehicle model and system level thus preventing the fitment of any wrong parts, as discussed previously.

6. CAN AND DIAGNOSTICS

Demanding emission regulations, continually improved quality and increasing customer satisfaction now mean that on-board and off-board diagnostics play a key role in the success of the vehicle and hence the company. Sophisticated diagnostics are managed to full effect to serve both the environment and the customer.

On-board diagnostics provide the self monitoring capability for fault logging, fault reporting and driver information, whereas the role of off-board diagnostics can be visualised as ECU interrogation to establish any identified problems. Off-board diagnostics are used within the manufacturing and service environment.

The majority of component on-board diagnostics, within a powertrain environment, are of an OBDII nature. These diagnostics are governed by legislation issued by the California Air Resources Board

(CARB) - whose mission is to reduce emission and smog in the state of California - to ensure that drivers of vehicles are made aware and then repair their vehicles, when a failure occurs in their emission control system (45% of Jaguar's Federal sales are in California).

6.1 External Diagnostic Session

The Jaguar specific diagnostic methodology is achieved across CAN for the powertrain system and does not qualify as one of the two bus communication techniques which conform to the requirements of the CARB legislation.

The transactions that take place between the powertrain ECU's and the Jaguar Diagnostic System (JDS) follow a master/slave procedure. The master initiates all transactions and slaves never initiate transactions. In all cases the diagnosed ECU is the slave and the diagnosing unit is the master. Diagnostics of the control modules themselves are catered for by allocating two special CAN messages to each node, this enables communication with the external diagnostics tool.

7. BRIEF SCOPE OF BENEFITS

The introduction of an integrated vehicle system using serial communications introduces a series of new opportunities which include harness standardisation and wire reduction, improved system visibility, less operator intervention in the diagnostics process, reduced diagnostic times and improved on-board diagnostics capability.

Harness standardisation and wire reduction improve diagnostics by reducing the number of variant harnesses to be diagnosed around the world, therefore saving on software and development time. In addition, the fault finding algorithms are simplified because of the reduced harness size. Benefits of improved quality from the reduction in harness size and connectors are also realised.

Improved system visibility is a major advantage in diagnostics, particularly in diagnosing systems which interact with other systems on the vehicle. This gives the capability to perform system diagnostic checks by accessing the communications bus and monitoring the inter-system communication in addition to direct connection to the individual ECUs. This reduces the use of previous techniques such a harness probing, T-piece monitoring which can themselves cause damage to vehicles.

In a similar way to diagnostics, an integrated system offers new opportunities to manufacturing. The harness wire reduction improves vehicle assembly and the harness standardisation reduces the parts count. The integration of vehicle systems offers improvements to vehicle electrical tests by allowing single point testing and ECU configuration for the whole vehicle, this makes the vehicle testing time considerably shorter which reduces lead time of the vehicle on the production line.

Furthermore, flexibility is enhanced as the nature of the CAN approach implies that the feature addition can begin at the software phase, thus significantly reducing the lead time to the market place for new features. Competitive edge can therefore be maintained and opportunities of conquest sales can be exploited.

8. CONCLUSION

Feature growth, electronic sophistication and aggressive competition over recent years have made it necessary to provide system integration with high levels of inter-system communication within luxury vehicles to satisfy customer demand. Conventional methods could no longer fulfil this requirement and hence a new technology was needed. Serial communications has proved a suitable technology to take on this role and, although several protocols exist under this heading, the most capable for Jaguar's powertrain system is CAN.

REFERENCES

1. Jan Unrah, Hans-Jorg Mathony and Karl-Heinz Kaiser.: 'Error Detection Analysis of Automotive Communication Protocols'. SAE paper 900699, Feb. 1990

2. SAE Implementation of CAN for Heavy Duty Truck and Bus Market, Specification J1939

3. The Motor Industry Software Reliability (MISRA).: 'Development Guidelines for Vehicle Based Software', Nov.1994

4. ISO Open System Interconnect (OSI) Model, ISO 7498