

AN INTRODUCTION TO THE ZF 5HP24 TRANSMISSION CONTROL SYSTEM FITTED TO THE NEW JAGUAR XK8

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Abstract

The launch of the Jaguar XK8 (codenamed X100), also sees the launch of a brand new powertrain into Jaguar Vehicles. The new powertrain consists of the Jaguar designed AJ26 V8 engine and the ZF fully automatic five speed 5HP24 transmission.

The aim of this paper is to give the reader an introduction to the new features of the 5HP24 transmission control system and an understanding of why a new transmission system was needed.

Introduction

The ZF 5HP24 is the first five speed automatic transmission to be fitted to a Jaguar vehicle and represents a significant step in automatic transmission technology. The importance of this new transmission is reflected in the fact that for the first time a Jaguar vehicle will not be offered with a manual gearbox.

Some of the forces driving the need for an all new transmission are listed below:

1. XK8 would have a brand new engine. A transmission was required to complement the performance parameters of this engine. In particular the transmission must be able to cope with low idle speeds and very high gearshift speeds (in excess of 7000rpm) under high torque.
2. Customer expectations of shift quality and transmission feature content have changed. Customers expect improvement. A quantum leap was required.
3. Fuel economy targets drive the need for five gears and low transmission power losses.

Jaguar has had a long relationship with ZF automatic transmission systems. This new transmission has been developed jointly between ZF and their customers to meet the changing requirements of the luxury vehicle sector.

The 5HP24 also features a brand new control system and shift control strategy which is significantly different to conventional four speed systems. New features include:

1. Full closed loop control of shift energy management, in real time.
2. Overlap gearshifts.
3. Driving situation recognition.
4. New 32-bit TCM with C.A.N. (Controller Area Network) on board.

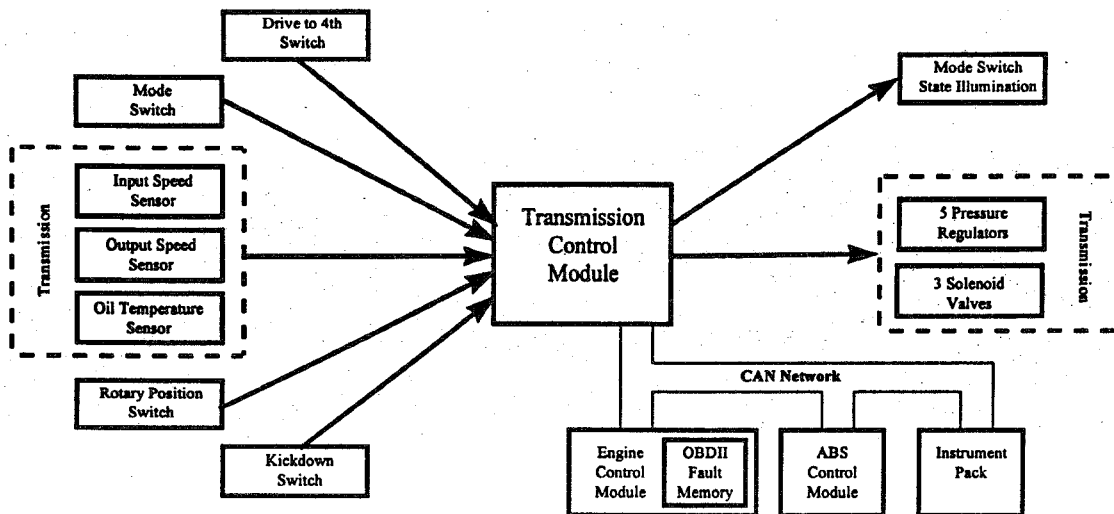
These new features will be discussed in the following sections.

Control System Overview

The Transmission Control Module (TCM) controls the operation of the transmission. The TCM receives information in both analogue and digital form and uses this information to select the most appropriate gear for the current conditions. Figure 1 shows an overview of the transmission control system.

The TCM also monitors the transmission system for correct operation and is able to diagnose faults and take appropriate action when needed.

Figure 1



The TCM controls the transmission by operating the solenoid valves and pressure regulators which control the flow of transmission fluid to the various clutches.

The most obvious differences between this and a typical system diagram of an older transmission system are the larger number of pressure regulators/solenoid valves and the addition of the C.A.N. high speed serial communications network.

Gearshift Control

Electronically controlled overlap gearshifts are used on all shifts except First to Second. First is the only gear with a freewheel clutch, since at the low speeds the first to second change occurs, the accuracy of the data from the input/output speed sensors is limited. All the shifts are completely closed loop controlled so that a consistently high shift quality can be guaranteed through the service life and production tolerances.

Conventional 4-speed transmissions use just two solenoid valves (on or off valves) for gear selection, with the old clutch pack being disengaged before the new clutch is engaged. A simple truth table of the solenoid valves state would immediately indicate the gear selected. This transmission uses five pressure regulators and three solenoid valves and a simple truth table would not indicate which gear is selected. This is because the pressure regulators are not simply “on or off”, but allow the pressure to the clutch packs to be balanced to give the appropriate gear.

Overlap shifts mean that neutral is not selected between gears. Pressure is applied to the “next gear” clutches as pressure is reduced on the “old gear” clutch packs. This requires a high TCM processor overhead as the two clutch pressures must be balanced throughout the gearshift to give a high shift quality and protect the transmission from damage. The advantage of this system is that drive is not interrupted, torque is always applied to the wheels throughout the gearshift and greater shift quality is possible.

Since there is no neutral between gears, the gearshifts are no longer hydraulically protected. Hence, the TCM monitors the change characteristic for anomalies. If the shift does not match the specified characteristic (rate of change of input and output speeds etc.) then the gearshift is aborted to prevent transmission damage.

Overlap shifting is only possible using a high speed communications link to the engine management system so that shift energy management can be closed loop controlled in real time. Shift energy management allows the transmission to control the engine output torque during a gearshift, so that excess power is not dissipated in the transmission friction elements during the shift. The functions of shift energy management are:

1. Increasing the transmission life by shortening the slipping time.
2. Improving the shift comfort by reducing the step change in torque caused by the gearshift.
3. Limiting the maximum engine power transferred into the transmission.

There are four basic control strategies for overlap shifts, depending on the type of gearshift, these are discussed below:

1. Upshift Under load

Figure 2

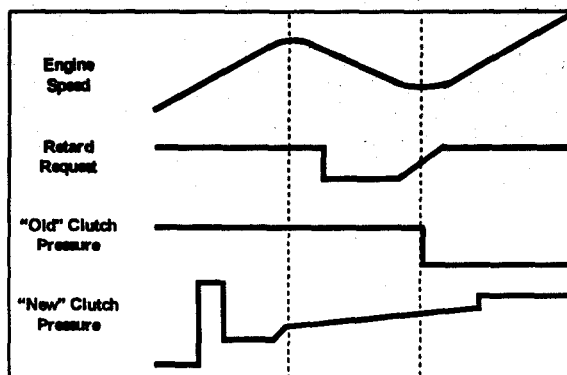
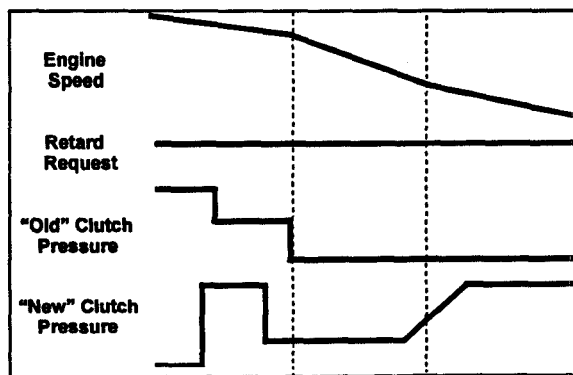


Figure 2 shows an example of an upshift under load. The first vertical dotted line indicates the start of the actual shift, the second the “synchronisation point” almost at the end of the shift. Prior to the shift beginning the TCM applies a high pressure pulse to the “new” clutch set. This quickly pre-fills the new clutch with transmission fluid and brings the clutch to an almost engaged state. As the change begins the pressure applied to the new clutch is increased, gradually engaging. At the same time ignition retard is applied to help reduce the engine speed, increasing clutch life. During this period the pressure on the old clutch is maintained. The pressure on the old clutch set is reduced once the synchronisation point is reached and the ignition retard is ramped off. Once the pressure on the new clutch reaches the desired level the shift is complete.

2. Upshift Without Load (Coast)

Figure 3

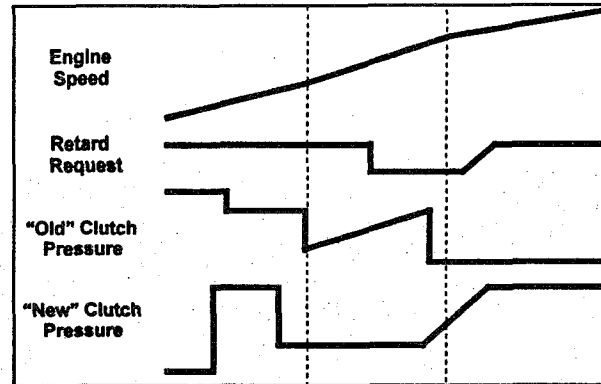


The control strategy for a gearshift without load is significantly different (see Figure 3). The most obvious difference is that no torque reduction is required as the engine speed drops on its own. The shift sequence

starts with the “normal” pre-fill of the new clutch, to bring it to the just disengaged state. The old clutch is then completely disengaged during the shift. The new clutch is engaged gradually just before the synchronisation point. It can be seen that the control strategy for an upshift without load is much simpler than an upshift under load.

3. Downshift Under Load

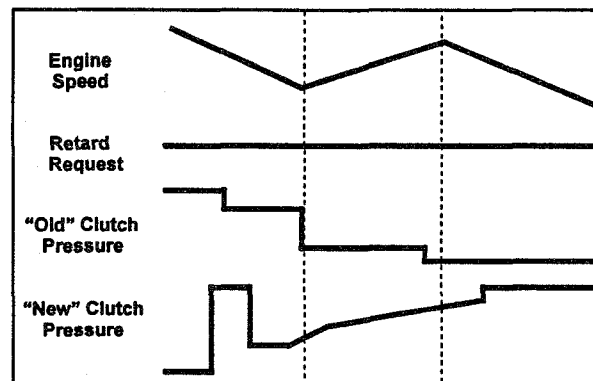
Figure 4



A typical trace for a downshift under load is shown in Figure 4. The new clutch is pre-filled as before. The graph shows the old clutch pressure ramping upwards during the gearshift, this is because the engine torque is changing during the gearshift and the TCM compensates to keep the old clutch just engaged. Ignition retard is used to control the engine torque. The old clutch is disengaged just prior to the synchronisation point, as the new clutch is engaged. The retard request is then ramped off to give a smooth transition, otherwise there would be a shock as the new clutch set is engaged.

4. Downshift Without Load (Coast)

Figure 5



The last class of shift is a downshift without load (Figure 5). Like all shifts, it begins with a pre-fill of the new clutch. The old clutch is kept just engaged to ensure the engine speed does not change too quickly, so giving a smooth shift. The new clutch is ramped on, causing the engine speed to rise. The time between the new clutch beginning to engage and the synchronisation point is critical. If this is too short the shift will be uncomfortable, if too long the vehicle will slow down. The old clutch is disengaged just prior to the synchronisation point.

Driving Situation Recognition

Special shift maps are available, which are designed to enhance the operation of the vehicle, under very specific operating conditions. The shift maps are as follows:

Table 1 "Specific" Condition Shift Maps

| Priority (1=Highest) | Program Name | Operating Condition |
|-------------------------|--------------|---|
| 4 | Cruise | During cruise control. |
| 1 | Traction | When traction intervention is active. |
| 3 | Gradient | Under specific speeds and load. |
| 2 | Hot Mode | Extreme Engine/Transmission temperatures. |

The "specific condition" maps have higher priority than the basic sport/normal shift maps, i.e. whenever the specific entry conditions for each of the three maps arise the TCM will enter the appropriate traction/cruise/gradient map.

The Traction map is intended to compliment the traction control system. The TCM will implement the Traction map whenever traction control intervention (either engine or brake) is taking place. The aim of the map is to maximise stability under wheel slipping conditions. This is achieved by minimising gearshifts and shifting and the smoothest point in the engine speed range.

The Cruise map is intended to reduce unwanted gearshifts and "hunting" during cruise control operation. The map is activated when cruise control is resuming or cruising near the set speed. This shift map contains extra hysteresis about the shift points.

The Gradient maps are intended to enhance the driveability of the vehicle when climbing a gradient. The maps are implemented when increased driving resistance is detected by the TCM. The TCM monitors acceleration and vehicle torque and compares the actual acceleration against its internal vehicle model. If the acceleration is below the calculated threshold then gradient mode is enabled. This map is calibrated to give increased vehicle performance, enhanced driveability and improved cooling performance under gradient conditions.

Under extreme high temperature conditions, when either the engine coolant or transmission oil temperature exceed set thresholds, the TCM enters Hot mode. In this mode the TCM adopts a shift and torque converter lock-up strategy to minimise the heat introduced into the vehicle cooling system by the transmission. The torque converter is kept locked whenever possible and lower gears are selected.

Legislated Diagnostics

An attractive feature of the OBDII diagnostic system on the XK8 is that it is an entirely integrated system rather than each ECU diagnosing its own components in isolation.

All OBDII fault information is passed immediately to the Engine Management Control Module (ECM). The ECM holds the legislated fault memory for the entire system and controls the Malfunction Indicator Light (MIL). All information is transferred over the CAN network.

The TCM passes the fault code to the ECM, with the following information (flags):

1. Fault Temporary or Permanent Flag (i.e. First or second fault cycle).
2. Emission effect flag (i.e. Does fault effect emissions by > 15%?).

The TCM also monitors the fault cycle logic for each of its emission failures so that MIL illumination can be controlled by the ECM. This is required since legislation states that the MIL need not be illuminated until the second drive cycle in which the diagnostic test has been completed and failed. The legislation also requires

the MIL to stay illuminated for a further three drive cycles, in which the diagnostic is completed and passed. The TCM, therefore, continues to transmit the fault code to the ECM for the required additional time.

The reason each ECU monitors its own fault cycle logic, and not the ECM, is as follows: Each individual fault will have a different fault cycle. For instance, to complete a torque converter diagnostic it may be necessary to test in the locked state. Only the TCM can tell when the test conditions are met, so only the TCM can monitor the fault logic.

The flags transmitted above allow the ECM to pass to the OBDII scantool all the information required by legislation.

Additional Diagnostics

In addition to meeting all the OBDII diagnostic requirements for fault storage and freeze frame data, the TCM also has its own fault memory and diagnostic functionality for non-emissions related failures.

For each and every fault the TCM stores freeze frame data which is tailored to the specific failure. For instance, for electrical failures the supply voltage at the time of failure would be recorded. Three items of freeze frame data are stored for each fault.

The TCM also stores the following information for each fault (and keeps up to date):

1. How many times the failure has so far occurred.
2. Is the fault present now?
3. Is the fault intermittent?
4. Has the diagnostic test for this fault been completed in this drive cycle?
5. Fault type (short circuit high/low, open circuit, rationality check etc.)

This information is designed to aid quick and efficient rectification of the failure.

All the fault information is kept in EEPROM memory so that, even if the TCM is removed from the vehicle, fault information is not lost.

Safety Functions

The safety functions are designed to safeguard against maloperation by the driver as well as against system malfunctions. The maloperation system prevents reverse gear from being engaged at high forward speeds and prevents manual downshifting at excessive engine speeds. These functions are not operational in mechanical limp-home mode.

Great attention must always be paid to safeguarding against, and detecting, malfunctions in the electronic control system. Consequently, the mechanical connection between the selector lever and transmission is retained. Hence, it is not possible as a result of any fault in the electrical system, for reverse or any forward gear to be selected whilst the selector is in the neutral position. The design of the electrical and diagnostic system must be such that system integrity is protected at all times, the safety concept being based on the following three points:

1. The hydraulics system has "fail-safe" characteristics regarding its electrical energisation, i.e. as a result of the power supply being lost to the electro-hydraulic actuators the transmission moves into a reliable emergency limp-home mode.
2. Recognition of critical shift operation by monitoring the last element in the signal path, i.e. the solenoid valve, and checking by means of redundant measured variables, i.e. engine speed, input speed and output speed.
3. Measures which guarantee a high degree of availability of safeguard functions, i.e. monitored safety circuits. For this purpose each time the vehicle is started there is a check on the entire safety hardware and the associated program parts and signal paths. A malfunction in this part of the system, or triggering of the safety circuit, is communicated to the driver through the illumination of the transmission warning lamp.

CAN Communications System

A very significant improvement over old systems is the introduction of the CAN network onto the vehicle. The new TCM is the first generation of new breed of control module which include the hardware and software to enable it to communicate over the CAN network.

The CAN network is a real time, high speed, communications network. This allows the ECU's connected to the network to exchange real time control and data information. Thus the ECU's can operate more as a single system, rather than separate units and considerable synergies are therefore obtained.

Although the advantages of this system are huge, great care must be taken during development. Once such a network exists, the possibilities for inter-ECU control strategies grow exponentially, and it is important that all the ECU suppliers on the network fully understand the meaning of all the CAN messages and react as expected by the other ECU's. Rigid control must be therefore maintained over the CAN network by a central source, in Jaguar's case this was achieved by a separate CAN team.

The other ECU's on the CAN network are:

Engine management
ABS/Traction Control
Instrument Pack
J-Gate Module (Listening only)

An example of some of the information received and transmitted by the TCM is shown in Table 2

Table 2

| Inputs | Outputs |
|------------------------------|----------------------------------|
| Traction Control Status | Torque Reduction Request |
| ABS Malfunction Flag | Transmission Overload Flag |
| ABS Status | Input Speed |
| Estimated Engine Torque | Output Speed |
| Throttle Position | Torque Converter Slip |
| Pedal Position | Kickdown Status |
| Torque Reduction Acknowledge | Actual Gear Selected |
| Engine Speed | Gear Selection Fault Flag |
| Cruise Control Status | Shift Map Selected |
| Engine Coolant Temperature | Transmission Oil Temperature |
| Engine MIL Status | Transmission Malfunction Message |
| Engine Fault Codes | Transmission Fault Codes |
| All Wheel Speeds | |

Improvements Afforded by CAN

An example of the improvements afforded by the CAN link is shift energy management.

During gearshifts the engine torque is reduced both to improve shift comfort and gearbox durability. The CAN network allows the TCM to request an exact torque reduction value, and then the ECM to respond with exactly the torque reduction it is actually achieving. If the ECM is unable to fully achieve the requested

torque reduction the TCM is able to react to this immediately and change the pressure applied to the clutches in real time. The TCM is also able to modify its torque reduction request through the gearshift. In this way the torque of the engine can be exactly matched to the hydraulic pressure applied to the friction elements all the way through the shift. A significant improvement in shift quality can therefore be obtained. Such real time inter-ECU control is only possible with the introduction of the CAN network.

The CAN network also aids diagnostics. Extra signal redundancy improves the system response to failures or makes failures easier to detect. For instance the TCM is able to use either output speed or rear wheel speed (from the ABS module via CAN) information. In the event of a failure of the output speed sensor, which would previously have resulted in "limp-home" mode, the TCM is now able to switch to rear wheel speed and transmission operation is not affected.

New Transmission Control Module

The introduction of the 5HP24 transmission also sees the introduction of a brand new TCM. The hardware for this TCM was developed by Bosch and the software by ZF and Bosch in accordance with Jaguar's specification.

Hardware

Current generations of TCMs have included 8-bit micro-controllers, which have had sufficient processing power for previous applications. The introduction of many new real-time control strategies, such as overlap shifts, meant that more processing power was required. To meet these requirements a powerful 32-bit TCM was developed.

The specification of the new TCM is shown in Table 3.

Table 3 TCM Specification

| | |
|--------------------------|--------------------------|
| Controller | MC68332 (32-bit) |
| Clock Frequency | 16MHz |
| External Program Storage | 128 or 256 Kword (16bit) |
| Diagnostic Storage | 256 bytes (EEPROM) |
| CAN Controller | 82527 |
| External SRAM | 8 Kbyte |
| External A-D Controller | 10 Analogue Inputs |

Not only is the new TCM quicker and more powerful than previous models, but by using greater integration and new technology it has also been possible to decrease the size of the TCM, whilst increasing the number of features

Figure 6

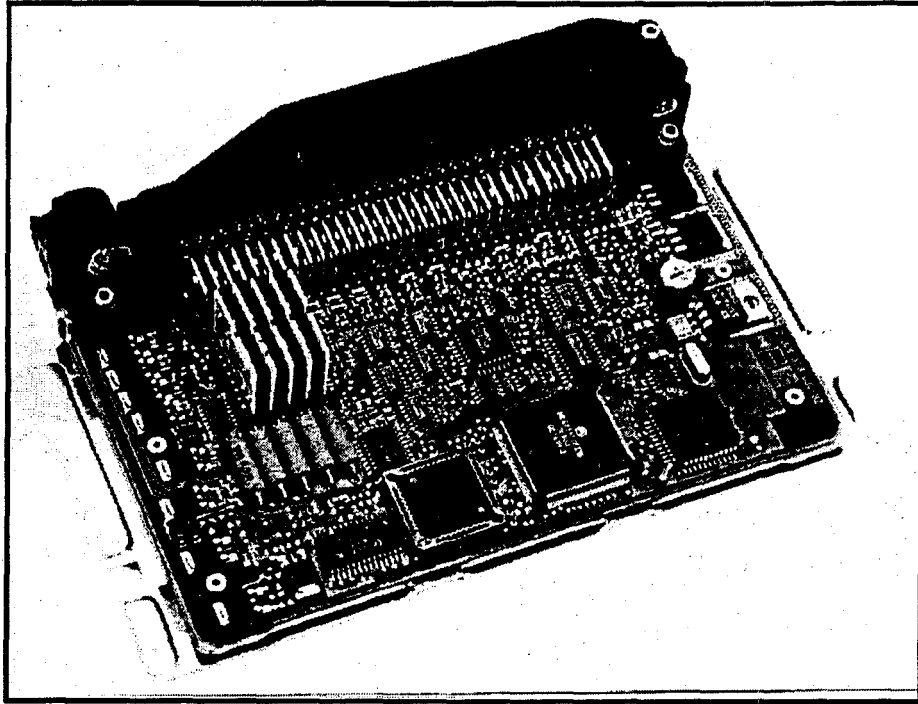


Figure 6. shows a picture of the new TCM with the case removed.

The largest integrated circuit at the bottom of the board is the Motorola microprocessor (a large black square). To the right of this is the CAN controller. To the left of the microprocessor is the PROM, which contains the program and calibration data. The TCM also contains a 256byte EEPROM so that data can be stored after power-down. This is used to store fault information and variant configuration.

At the top left of the main board can be seen five vertical hybrid boards. These are the pressure regulator drivers. The case itself acts as a heatsink. There are special tracks and holes cut into the board, which are in contact with the case, to conduct heat away. The circuit board itself is double sided, with additional components on the underside.

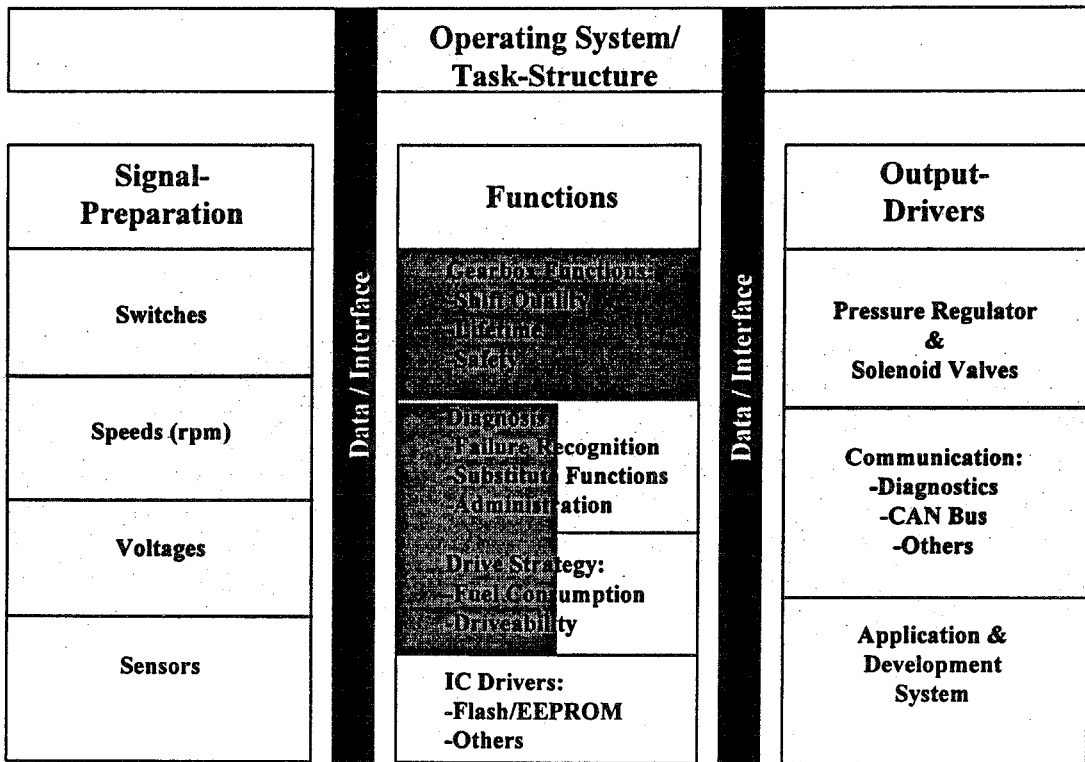
Software

A new approach has also been used to write the software for the transmission system. For the first time software sharing has been introduced between ZF and Bosch, each responsible for certain software modules. The reasons for choosing to develop the system in this way are as follows:

1. ZF have transmission control expertise.
2. Bosch have hardware and control unit expertise.
3. Each can then write the software module in which they have the greater knowledge.

Thus, major synergies can be developed. An overview of software responsibilities is shown in Figure 7.

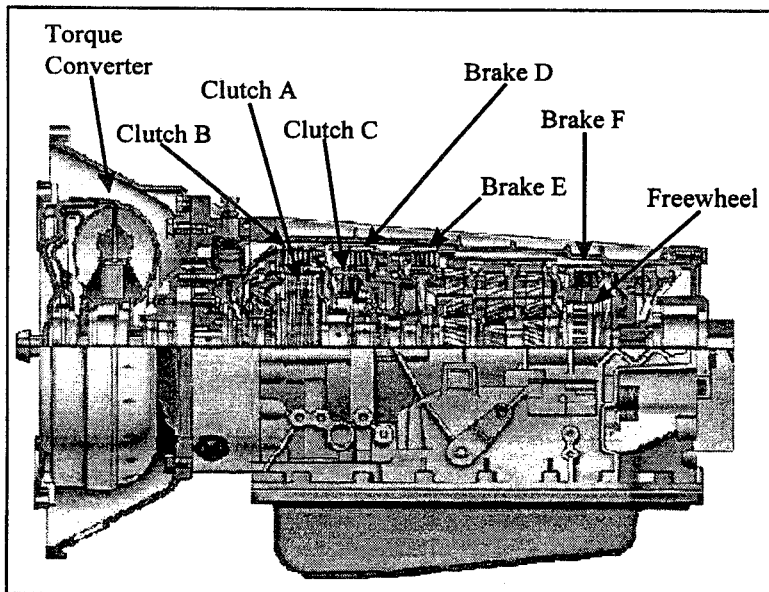
Figure 7



Key: ZF Responsibility, Bosch Responsibility

A Brief Review of the Mechanical Transmission System

Figure 8 5HP24 Transmission Diagram



The development of the new Jaguar V8 engine led to a demand for a new five speed automatic transmission, the 5HP24, which was specially adapted for this engine. The transmission concept was centred around the tried and tested ZF 5HP30 production transmission based on Wilson planetary gearing. This set-up means

that all gearshifts (including double downshifts) are possible with just three clutches and three brakes. Table 4 shows which shift elements are closed in each gear.

Table 4 Shift Elements Closed in Each Gear

| Gear | Clutch | | | Brake | | | Freewheel |
|------|--------|---|---|-------|---|---|-----------|
| | A | B | C | D | E | F | |
| 1 | ■ | | | | | ■ | ■ |
| 2 | ■ | | | | ■ | | |
| 3 | ■ | | | ■ | | | |
| 4 | ■ | ■ | | | | | |
| 5 | | ■ | | ■ | | | |
| R | | | ■ | | | ■ | |

Key - Shaded area indicates shift element closed in given gear.

Considerable importance was placed on the reduction of transmission power losses and noise levels.

The transmission has been designed to cope with both low input speeds (to allow low engine idle and to meet emissions regulations) of 500rpm and high input speeds, at which gearshifts can still occur, in excess of 7000rpm.

The wide gear ratio spread, overdrive top gear and low inertia torque converter fully satisfied the exacting performance requirements for off-the-line acceleration, high maximum speed and fuel economy

Table 5 5HP24 Specification

| | |
|----------------------------|--|
| Transmission | 5HP24 5 speed automatic |
| Torque Converter | With slip controlled lock-up clutch; Torque from 120Nm to 300Nm at 2000 RPM |
| 1 st Gear Ratio | 3.57 : 1 |
| 2 nd Gear Ratio | 2.20 : 1 |
| 3 rd Gear Ratio | 1.51 : 1 |
| 4 th Gear Ratio | 1.00 : 1 |
| 5 th Gear Ratio | 0.80 : 1 |
| Reverse Gear Ratio | 4.10 : 1 |
| Lubrication System | Maintenance Free |
| Weight (with oil) | 95Kg |

Torque Converter Clutch

The torque converter clutch developed for the 5HP24 has a high power to weight ratio as well as a high level of hydraulic efficiency. The converter clutch piston is spring loaded to ensure good converter engagement

quality. The TCM is able to operate the clutch in closed loop “slip controlled” mode as well as fully open or closed. In slip controlled mode a small level of slip is allowed by the TCM, thus improving driver comfort, by increasing the transmissions ability to absorb driveline shunts, without sacrificing fuel economy.

To avoid noise, a tangential spring component configuration was selected for coupling the torque converter clutch piston. This prevents circumferential play and therefore noise.

An increasing friction coefficient is required against the speed differential to ensure the slip controlled converter clutch can be controlled without friction vibrations (shudder). The friction coefficient characteristic is determined by the properties of the steel friction surface (the lining) and the oil. During development of the coating, the objective was to achieve a friction coefficient which is as constant as possible throughout the coating lifetime. To prevent an unfavourable friction coefficient on a new coating which had not worn in, and therefore avoid “green shudder”, the wearing in process is performed during manufacture of the coated discs using high temperature treatment.

Hydraulic System

The functions of the hydraulic system are as follows:

1. System pressure setting with respect to turbine (input) torque.
2. Individual clutch control corresponding to data from transmission electronics.
3. Lock-up clutch control.
4. Providing the transmission with cooling and lubricating oil.
5. Emergency gear control (limp-home mode) in case of power failure or malfunction.

The hydraulic system is based on the known design of the 5HP30 transmission, although improvements have been made to hydraulic control valves and actuators. The hydraulic control valves are made of aluminium covered with a hard coat layer.

All actuators are fitted with a filter in the access duct so that, in the event of dirt finding its way into the transmission oil, the system is protected.

The capacity to cope with low input speeds determined the size of the internal oil pump (crescent pump). To cope with the high speeds required, the excess oil flow from the pump flows back to the intake side of the pump via a flow control valve. This prevents power losses and ensures cavitation free operation up to maximum speed.

The compact arrangement of the engaging clutches ensures that pressurised oil can be supplied via just six dynamically sealed rectangular rings. This also gives a further reduction in drag torques.

Electrical System

The transmission contains five pressure regulators and three solenoid valves.

The load dependant system pressure, the clutch control valves and the lock-up clutch are energised by the five pressure regulators. These are 2/2 proportional valves. These have been optimised with regard to cold weather behaviour and precision of control.

The solenoids are used to actuate the auxiliary valves and are 3/2 electrical valves. The valve response time and flow rate were optimised in order to obtain improved response behaviour.

Table 6 shows which of the solenoids valves and pressure regulators are used in each gear. Pressure regulator four controls the lock-up clutch.

Table 6 Which Solenoid Valves and Pressure Regulators Are Used in Each Gear

| Gear | Solenoids | | | Pressure Regulators | | | | |
|------|-----------|---|---|---------------------|---|---|---|---|
| | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 |
| 1 | ■ | | | ■ | | | | ■ |
| 1P | ■ | | | ■ | | | | ■ |
| 2 | ■ | ■ | | ■ | | | ■ | ■ |
| 3 | | ■ | | ■ | | | ■ | ■ |
| 4 | | ■ | | ■ | ■ | | ■ | ■ |
| 5 | | | ■ | | ■ | | ■ | ■ |
| N/P | ■ | | | | | | | ■ |
| R-S | ■ | | ■ | | | | | ■ |
| R | | ■ | | | | ■ | | ■ |
| | | ■ | | | | ■ | | ■ |

Summary

Our aim was to deliver to the customer a “best in class” transmission system” befitting the new Jaguar XK8. This has been achieved through:

1. A brand new transmission, the 5HP24
2. A new “state of the art” 32-bit Transmission control module.
3. A new shift control strategy, overlap shifting.
4. C.A.N. Serial communications, allowing real time information interchange between modules.
5. Joint software development between ZF and Bosch, sharing expertise.
6. The introduction of new features, such as driving situation recognition.

It is hoped that this package will deliver the quantum leap required to make an impact on customer perception and that Jaguar will become the marque which other manufactures benchmark against.

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| AJ-V8 Brochure | Jaguar |

Acknowledgements

The Author would like to thank both ZF and Bosch for their hard work in the development of the 5HP24 transmission system. In particular, the contribution of the following people to this report was greatly appreciated.

- P Wendel Dipl. Ing, Transmission Development and Testing (ZF)
- G Bauknecht Ing. Grad, Transmission Development and Design (ZF)
- G Gierer, Development - Electronic Control Unit, Hydraulics (ZF)
- K Thiele Dipl. Ing, Electronic Transmission Control (Robert Bosch GmbH)
- C Schmidbaur Dipl. Ing, Development Software/Hardware (ZF)