University of Southern Queensland

Faculty of Engineering & Surveying

Electronic Systems for the USQ Formula SAE Racer

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Abstract

This document presents an overview of the fuel injection, traction control and automate gearshift systems intended for implementation on the 2005 USQ SAE car.

Design guidelines and 'in principle' specifications are presented for various components of the systems, background research and development is presented.

The procurement of various components of the systems has been accomplished, or is discussed, to leave the project on a sound footing for further work.

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R. Molloy

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Chapter 1

Fuel Injection

1.1 Introduction

Fuel injection is used in production cars almost exclusively, having displaced the carburettor as a fuel metering device in the late 1980s. The main advantage of fuel injection is that the amount of fuel delivered can be matched to the engines demand more precisely than a carburettor can manage over a broad range of operating conditions.

A major driver of the widespread adoption of fuel injection has been the introduction of environmental pollution legislation throughout the world. Such legislation has seen the adoption of the catalytic converter as a means of compliance by the vehicle manufacturing community, this device only operates effectively in a narrow band about the stoichiometric ratio of 14.7:1 air:fuel. The only way to effectively ensure this operating point is to control the mixture at all times...therefore the use of fuel injection.

In motorsport fuel injection has been widely adopted as a means of tuning engines for maximum power.

Three major steps in the evolution of fuel injection can be identified;

- Mechanical systems eg, Bosch D-Jetronic, Hillborn, Rochester (1967)
- Analogue electronic systems eg, Bosch L-Jetronic (1974)
- Digital electronic systems eg, Bosch Motronic (1982)

A further sub-division can be made into;

- Throttle body (single point) injection; fuel is injected at the throttle body, forming essentially an electronic carburettor. A disadvantage of SP systems is that no compensation is available for the difference in gas flow to the individual cylinders. Some argument is made for a greater mixing of air and fuel due to the passage along the intake runners.
- Multi-point injection (MPI), where the fuel is injected individually at each intake port. This allows control of the mixture for each cylinder, theoretically on every intake cycle.

The majority of fuel injection systems on the market today are electronically controlled multi-point systems. Although components are made by many different manufacturers, most of the underlying technology was developed by Robert Bosch GMBH due to the early acquisition of applicable patents.

1.1.1 System Overview

A generalised multi-point electronic fuel injection system as shown in Figure 1.1 consists of;

- The Engine control unit (ECU)
- Various sensors attached to the ECU
- A pressure pump to supply fuel from the tank

- The injectors, small high speed valves which meter the fuel

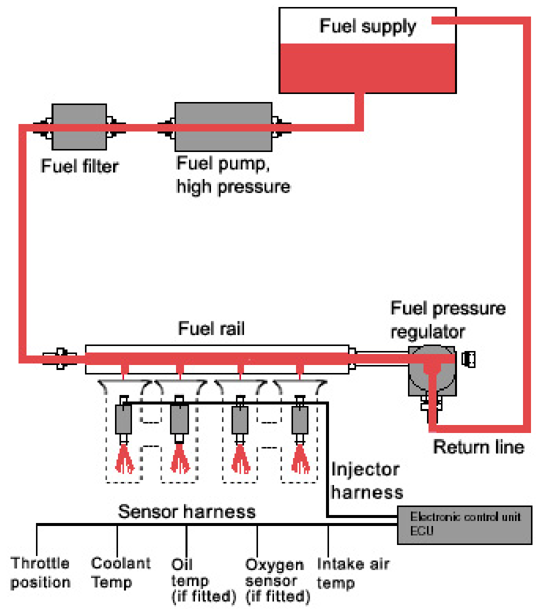


Figure 1.1: Fuel injection system

1.1.2 Sensors

Sensors are used in the engine control system to measure variables that affect the engines fuel and ignition requirements. Typically these include;

- Manifold pressure (MAP); a strain gauge based sensor that has replaced the earlier 'hot wire' or 'flap and potentiometer mass air flow sensors.
- Crank angle; a reluctor or Hall effect device used to determine the position of the motor with respect to top dead centre of the pistons in order to set ignition and fuel injector pulse timing.
- Throttle position (TPS); reports demanded engine power output to the ECU.
- Engine coolant temperature; the ECU applies a correction factor or mode change depending on the engines operating temperature.
- Exhaust gas oxygen (EGO); used for closed loop operation, provides feedback to the ECU to enable limit cycle control of A/F ratio around the stoichiometric

point. A typical EGO sensor operates at 300^{o}C and may contain a heater element to reduce non operational time.

- Cam angle sensor; required for fully sequential injection to synchronise the injector pulse to the intake valve opening.

To complete the listing of sensors, mention is made of the wide band EGO sensor, Bosch LSU-4 or NTK UEGO. Instead of providing a $+1, -1$ voltage about the stoichiometric point, this device reports the absolute EGO content, allowing the ECU to accurately determine the A/F ratio for each cycle of operation. Bosch sensors can be sourced second hand from Honda vehicles or new from CAPA performance for $332.51. It would be advantageous to the operation of the SAE fuel injection as it would provide finer tuning, but is not necessary.

1.1.3 Modes of operation

A guide to the various modes of operation of a fuel injection system is useful in understanding the sequence of events that occur when the vehicle is running. For a typical engine there are seven modes employed, the ECU selects an operating mode based on the instantaneous conditions determined from the sensors.

- Engine cranking; a low A/F ratio (rich mixture) is needed for the engine to start. A preset value for engine revolutions is stored in the controller as a switch point for this mode.
- Warm up; once started, the A/F ratio is kept rich to prevent engine stall and becomes a function of the coolant temperature.
- Open loop control; once above a preset temperature, mixture control is governed by the main open loop settings. Open loop mode is used where the EGO sensor is not hot enough to provide a useful signal for closed loop operation.
- Closed loop control; the most desirable condition, the instantaneous A/F ratio is corrected by feedback from the EGO. Emissions and fuel consumption are at a minimum due to tight control around the stoichiometric point.

- Full power; when the TPS reports a large throttle opening, a rich A/F ratio is provided for the duration of the heavy load. This results in maximum torque with poor economy and emissions control compared to closed loop operation. When the need for enrichment is passed, control reverts to either open or closed loop depending on the temperature of the EGO sensor.
- Deceleration; during deceleration a reduced A/F ratio scheme is implemented to reduce emissions due to unburned fuel.
- Idle; engine speed is controlled to reduce roughness and stalling due to varying loads, such as air conditioning or automatic transmission.

Ribbens, W B. 2003, *Understanding Automotive Electronics*, Elsevier Science, USA

Other modes of operation concern the sequence of injector firing, the case of a four cylinder engine is considered;

- Bank fire; all the injectors are operated at once, once every revolution of the engine. This method is the simplest electronically as it can be implemented without a crank angle sensor and requires only one drive transistor in the ECU. The disadvantages are; typically a larger injector is needed which may lead to poor idle quality, individual cylinder control of the A/F ratio is not possible, spark timing must be accomplished separately.
- Semi-sequential; two injectors are fired together. No cam sensor is required, this regime typically produces more mid range torque and a reduction in fuel consumption compared to batch fire. The ECU is synchronised to the engines cycle by a crank angle sensor and can control ignition timing in 'wasted spark' mode.
- Sequential; requires both cam and crank angle sensors to synchronise the injector pulse. Each cylinder is controlled individually allowing for the injection of fuel during the intake cycle when the airflow velocity is greatest. This ensures the best possible atomisation and greatest efficiency. A/F ratio and spark timing are controlled for each cylinder.

www.motec.com/products/ecu/tutorial.htm

1.2 Fuel Injection for SAE car

In motorsport use generally there is less emphasis placed on emissions and fuel consumption than producing maximum power. In this regard it is common to run in open loop mode, where an EGO sensor may be installed on the vehicle for data logging purposes rather than as part of the active control system. A recent development is the use of multiple oxygen sensors, such that the A/F ratio of each cylinder of the engine is measured individually. *Personal communication* Rodney Pammenter, Australian Champion Sprint Sedan

Given the inclusion of an economy trial in the SAE competition, the use of closed loop operation seems warranted. This will allow greater flexibility in tuning the car for circuit, acceleration and economy events; enhancing the possibility of scoring higher points in the competition.

1.2.1 ECU

Initial research indicates that the development of an ECU is beyond the ability of the author in the time available, due to the considerable hardware and software development needed to produce a reliable unit.

Consideration was also given to 'hacking' an AC-Delco computer, this ECU is fitted to many GM vehicles and is the most commonly modified OEM ECU. It is available from car wreckers for approximately $100. Usually the extent of reprogramming is limited to changing the fuel and ignition maps, in conjunction with other engine modifications aimed at increasing vehicle performance. They have been known to be fitted to vehicles other than original, but this option was discounted due to the lack of documentation on, and compilers for complete reprogramming. As an example of the program size, the listing for a Holden Commodore is 200 pages of machine code.

Instead, a choice is to be made from the range of commercially available units. Of the ECU's available in Australia (most of which are made here) the choice of the professional racer is almost invariably Motec or Autronic. Both have a comprehensive feature list, and are priced between $2000 - 3000, and up to $5000 for a 'top of the line' unit with all accessories. In view of the budget for the SAE car, both in actual and reported cost, it is desirable to find a cheaper alternative.

An alternative was found when the manufacturer of 'Adaptronic' engine computers offered an Adaptronic 420 unit to the team as sponsorship; the retail cost of the unit is $1000. It was found that this ECU offers a list of features comparable with the entry level Motec and Autronic units, and far in excess of the features found on other ECU's in the $1000 price range.

As supplied the ECU has the 'basics', programmable fuel injection and ignition; as well as 8 programmable I/O lines which may be used for driver instrumentation and gearshift functions. Provision is also made for traction control, the software of which will form part of this project. There are many other features such as; load shedding, idle speed and electronic wastegate control, that may not be used in this application.

1.2.2 Fuel injectors

As shown in Figure 1.2, the fuel injector is not an overly complex device, but they are made to close tolerances and have a precise function. Important considerations are spray pattern and the amount of fuel the injector will flow. This is helpfully given in units of either lb/hr, gm/sec, or cc/min depending on manufacturer or data source.

Much emphasis is placed on using the correct size injector for the application. Too small an injector can cause engine damage due to lean out at high RPM as the injector cannot flow enough fuel, too large an injector results in poor control of fuel mixture at low RPM as the injector cannot cycle quickly enough.

A generic formula for the sizing of fuel injectors is found in many articles on the subject. This is;

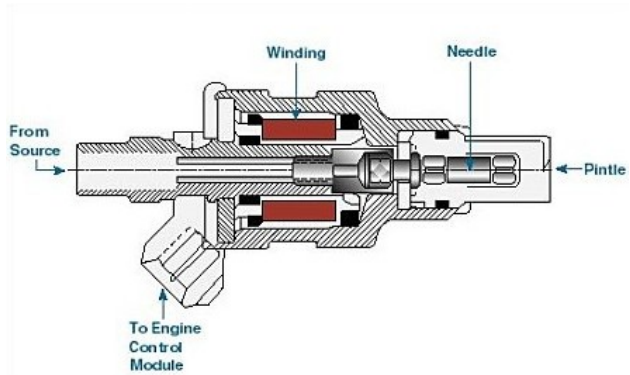


Figure 1.2: Section view of fuel injector

$$Flowrate(lbs/hr) = \frac{Max\,Hp \times Brake\,specific\,fuel\,consumption(BSFC)}{number\,of\,injectors \times duty\,cycle}$$

The conversion from pounds per hour to cc/min is given by; cc/min = lbs/hr × 10.515

`http://www.capa.com.au/library_injectors.htm`

Where BSFC is the ratio of fuel flow rate to brake power output of the engine at a fixed operating point, the units are $lb/hr/hp$. A generic figure for a naturally aspirated production engine is 0.5 and a suitable injector duty cycle is 80 percent for reliable operation of injectors. In the case of the USQ SAE car, the maximum power output possible is in the region of 80 hp and number of injectors = 4, giving;

$$Injector\,size = \frac{80 \cdot 0.5}{4 \cdot 0.8} \cdot 10.515 = 131.44cc/min$$

Also applicable and probably more specific is the following derivation;

$$\begin{aligned} Air &= \frac{\text{RPM}}{2} \times \text{displacement} \times \text{efficiency} \\ \text{Fuel} &= \frac{\text{Air}}{15.7} \quad (1.1) \\ & \quad (1.2) \end{aligned}$$

The units will be litres/minute.

Leading to;

$$stuff$$

It is difficult to find information on injector sizes at the lower end of the scale, as most attention is focussed on increasing the power output of larger engines. As calculated above, for the SAE car a 130 cc/min injector is indicated, which is quite small. As an example the BMW K100, which is a 1000cc motorcycle developing 90hp, uses 150 cc/min injectors, while commonly available car injectors range from 200 - 500 cc/min.

A comprehensive search of available data sources was conducted without producing a result until a mention was found on an internet news group that indicated the standard Hyundai Excel X2 injector was very small. A set of these injectors was sourced from City Auto Wreckers Toowoomba and tested in the workshop of Peter MacCallum Fuel Injection. It was found that the injectors flowed 120 cc/min at 2 bar, making them a suitable choice for the application.

While much emphasis is placed on correct injector size, an area that does not rate as highly in the available literature concerns injector spray patterns and placement.

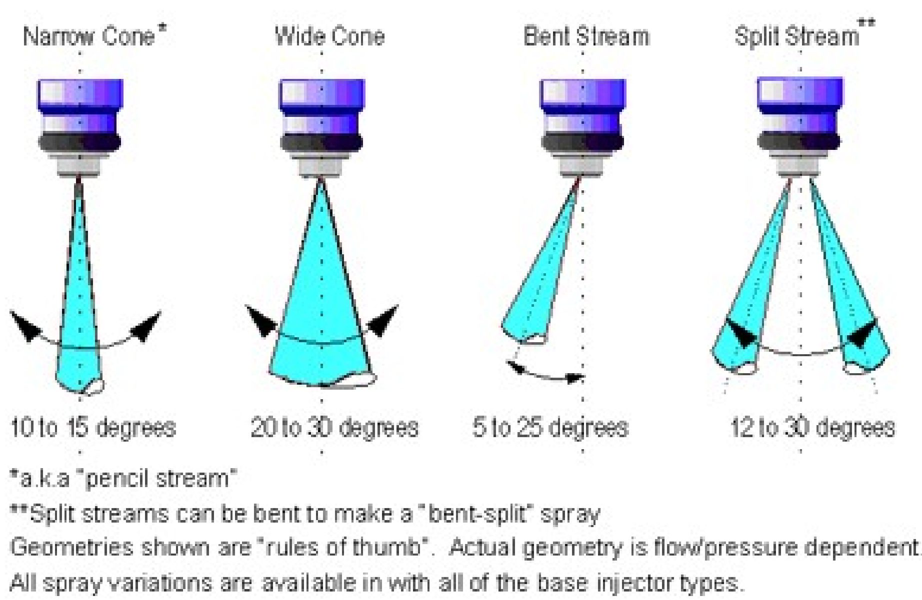


Figure 1.3: Fuel injector spray patterns

As depicted in Figure 1.3, a variety of injector spray patterns are available, the main purpose of which is to direct the fuel stream at the intake valve and prevent the spray condensing on the walls of the intake manifold. This increases fuel atomisation as the fuel stream is both physically broken up by the valve cycling at 60Hz and vaporised by combustion heat conducted through valve. Some cooling of the intake valve is experienced, which can be desirable. In the case of the SAE car, a split stream pattern would be ultimately desirable as the engine has a 4 valve head so each stream can be directed at one of the two intake valves; however, the injectors sourced have a tight cone pattern which is seen as a reasonable compromise.

Personal communication Peter McCallum, Peter McCallum Fuel Injection

1.2.3 Fuel delivery system

The purpose of the fuel delivery system is to supply pressurised fuel to the injectors, as illustrated by the components shown in red in Figure 1.1.

- Pressure pump
- Fuel lines
- Fuel rail
- Pressure regulator
- Surge tank, if needed

Fuel pressure required is generally in the range of 2-3 bar depending on the injectors design operating pressure; the desired flow rate is at least equal to the engines BSFC.

It is interesting to note that the sequence in which the injectors are fired also has a effect on the fuel rail dynamics. Bank fire(all injectors at once) is the hardest to keep the fuel rail pressure constant with and the rail charged. When all injectors open simultaneously, there is maximum depletion of fuel from the rail, this causes the pressure regulator to close off the return quickly to maintain pressure. This surging of pressure in the rail may cause fuel rail knock, produced as the rail is shocked by the rapid discharging of the fuel supply and the rush of replacement fuel accompanied by cycling of the pressure regulator.

Sequential injector firings are the most fuel rail friendly due to the minimal discharging of the fuel rail by the firing of only one injector at a time, however fully sequential injection requires more complex crank and cam angle sensors than bank fired systems.

A reasonable compromise is the use of a semi-sequential pattern where two injectors are fired at once, this minimises both sensor complexity and pressure fluctuations and is the system thought to be an appropriate choice for the SAE car.

1.2.4 SAE Rules relating to Fuel Injection Systems

The rules applicable to the fuel injection system fitted to the vehicle are reproduced below, and provide little restriction on configuration and component choice.

3.5.3.7 Fuel Lines, Line Attachment and Protection Plastic fuel lines between the fuel tank and the engine (supply and return) are prohibited. If rubber fuel line or hose is used, the components over which the hose is clamped must have annular bulb or barbed fittings to retain the hose. Also, clamps specifically designed for fuel lines must be used. These clamps have three (3) important features, (i) a full 360 deg. wrap, (ii) a nut and bolt system for tightening, and (iii) rolled edges to prevent the clamp cutting into the hose. Worm- gear type hose clamps are not approved for use on any fuel line. Fuel lines must be securely attached to the vehicle and/or engine. All fuel lines must be protected from possible rotating equipment failure or collision damage.

3.5.3.8 High Pressure System Requirements (A) Fuel Lines On fuel injected systems, any flexible fuel lines must be either (i) metal braided hose with either crimped-on or reusable, threaded fittings, or (ii) reinforced rubber hose with some form of abrasion resistant protection with fuel line clamps per 3.5.3.7. Note: Hose clamps over metal braided hose will not be accepted. (B) Fuel Rail The fuel rail on a fuel injection system must be securely attached to the engine cylinder block, cylinder head, or intake manifold with 2005 Formula SAE Rules 44 mechanical fasteners. This precludes the use of hose clamps, plastic ties, or safety wire.

Chapter 2

Traction Control Systems

2.0.1 Background to Traction Control

Traction control is part of a series of three technological developments that began appearing in vehicles in the mid 1980's. All three technologies originated from the Robert Bosch Company in Germany, and all address the issue of reducing slippage between the vehicles tyres and the road in various situations.

In chronological order, traction control developments are:

- Anti-lock brakes (ABS)(1978)

  Anti-lock systems sense a wheel lock under braking and cycle the brake rapidly via a high pressure pump to keep the wheel rolling. With the wheel rolling, more braking force is transmitted to the road and steering control is retained.

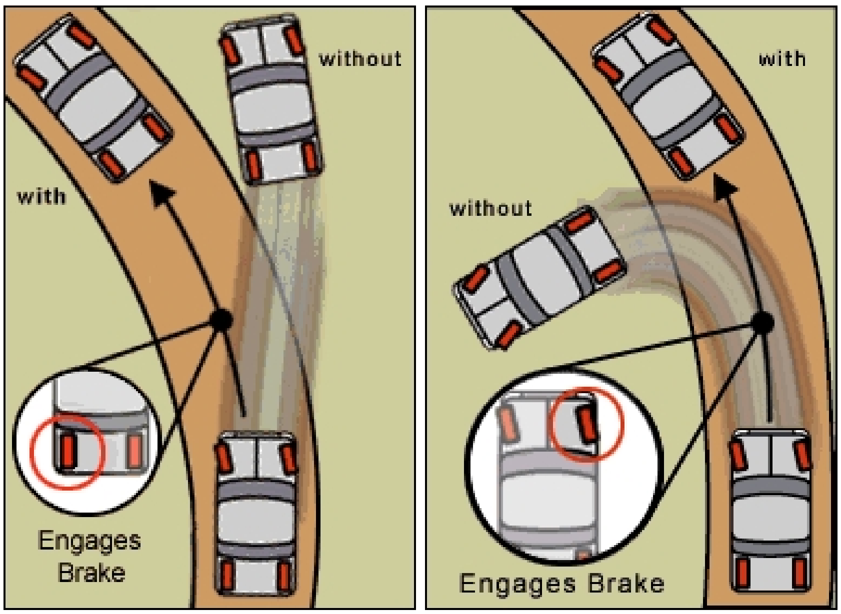
- Traction control (TC)(1985)

  This system acts in conjunction with the ABS to apply the brake on a spinning wheel; or in the case of traction loss due to excess power applied, the engine control unit (ECU) to modulate the engine torque.

- Stability control (ESC)(1995)

  Stability control adds lateral acceleration, yaw rate and steering angle sensing to the traction control system. The intention is to allow a computer system to control the brakes and engine in order to maintain the vehicles attitude within set parameters. The braking action of the stability control system is illustrated in Figure 2.0.1.

Figure 2.1: Braking action of ESC in Understeer and Oversteer



http://www.mucda.mb.ca/Stability.htm

As fitment to vehicles of 'traction control' systems becomes more common the lines between the various systems are increasingly blurred. A stability control system implies that ABS and TC are fitted, however, both TC and ABS may function as stand alone systems.

2.0.2 Applications to Road Vehicles

The general premise of traction control in road vehicles is to prevent loss of control of the vehicle due to driver error. This can occur as a result of control inputs such as swerving to avoid an animal, panic braking, going too fast around a corner, or excessive acceleration.

In these situations the computer systems can react much faster than a human to correct an error, and the driver may be unaware that any intervention has occurred.

In the case of loss of traction due to excess engine torque being applied to the wheel, the traction control system acts to modulate the power produced by introducing a sequential ignition and fuel cut via interaction with the ECU.

As described in Kachroo, P. 1993, a further application of ESC systems is in the development of automated highways, where the stability control of autonomous vehicles is of interest.

2.0.3 Applications to Racing Vehicles

The use of traction control is causing great debate in motor racing. In most classes of racing driver assist technology is currently banned; although the difficulty of enforcing such a rule is leading to traction control systems being allowed.

In racing vehicles TC systems are usually employed to maintain wheel slip within set limits under acceleration. It is left to the drivers skill to control the brakes and set the vehicles attitude on the road. In its simplest form, a limit is applied to the engines rate of acceleration to prevent the wheels being accelerated beyond the limit of assumed tractive force.

Most classes of racing have alternately allowed and banned TC systems, with the 2005 CART and Formula 1 rules allowing traction control to be used. NASCAR remains the exception; due to the general ban on digital electronics in the formula the governing body is convinced that effective policing of the rule is possible.

A recent article in "Circle Track and Racing Technology" magazine states;

> The overseeing powers of CART and Formula 1 have conceded that the digital electronic evolution of engine management has progressed to the point where they can't effectively police electronic traction control (ETC). NASCAR and other U.S. racing sanctioning groups with less technically elaborate race cars and in-house expertise and resources are bound and determined to stay this digital tidal wave.

http://circletrack.com/techarticles/general/139_0211_traction_control/

Motorcycle racing has also seen the use of traction control systems in the World Superbike series as it is permitted under current rules. British teams have admitted that a traction control system is used by Ducati and also Yamaha, who have a bolt-on kit available for any of its racing customers. http://www.crash.net/uk/en/news_view.asp?cid=5&nid=105891

2.1 Traction control in SAE racing

The main purpose in applying traction control to the SAE car, as with any racing vehicle, is to enhance driver control and reduce human error. As the drivers of this car are not necessarily skilled at the performance driving, the provision of a system which will assist in preventing loss of traction during acceleration is desirable to improve driver confidence, performance and safety.

2.1.1 Sensor selection

It is common in most road vehicles to machine a toothed ring on the wheel hub and generate a pulse train from the teeth of this ring passing a sensor. The resulting signal from each wheel is used as an input for the speedometer, as well as TC and ABS systems. For race applications where radiated heat from braking surfaces may be a problem, a toothed ring can be mounted on the inside of the suspension upright as shown in Figure 2.1.1.

In the case of the SAE car requirements for an effective sensor are;

- Small size
- Fast operation
- Rugged construction
- Reliable operation

Figure 2.2: Wheel sensor on a CART vehicle

http://www.machinedesign.com/ASP/strArticleID/55440/strSite/MDSite/viewSelectedArticle.asp

- Light weight

Several options are available;

- Team developed sensor
- Inductive proximity sensor
- Hall Effect sensor

Initially it is proposed to use an inductive proximity sensor to generate a pulse train from holes in the brake disc which would act to reduce manufacturing complexity introduced by machining a suitable ring on the wheel hub, and negate weight gain produced by adding a chopper wheel to the hub assembly.

Many models of sensor exist from a variety of manufacturers that would perform the task well eg. Balluff or Pepperl and Fuchs, although from the point of view of the SAE project expense must be minimised, which largely excludes the major brands.

A suitable low cost solution is available from AutomationDirect in the form of;# AE1-AN-2A, 8 mm diameter, 10-30 VDC, 3-wire, NPN, unshielded, 2.5 mm nominal sensing distance, normally open output, 2.5KHz switching frequency, 2 meter cable $39.

Figure 2.3: AE1-AN-2A Inductive proximity sensor

www.automationdirect.com.au

To use this sensor it is proposed to mount it so that there is 2mm clearance between the end of the sensor and the disc, the sensor will be triggered by the holes in the disc.

Another alternative is the ZD-1900 hall effect sensor from Jaycar. This device is small, light, rugged, and cheap, and has been used extensively in automotive electronic ignition systems for many years.

Figure 2.4: Jaycar ZD-1900 Hall Effect Sensor

http://www1.jaycar.com.au/

Use of this sensor would require chopper wheels to be fitted to the vehicle which would marginally increase weight and require good alignment.

2.1.2 Configuration of the sensors

Based on the I/O capabilities of the Adaptronic ECU, 2 sensors will be used. It is proposed that one will be installed on a front undriven wheel and the other on the gearbox or rear axle.

This configuration should prove adequate as;

- The difference in acceleration of the front wheels will be negligible as neither is driven, therefore it will not matter which wheel is used as a reference.
- Differences in rotational velocity are of no interest to the traction control system, although more accurate control could conceivably be achieved during cornering by comparing the left and right side conditions separately.
- Only the driven wheel is of interest at the rear of the car; a sensor reading rear axle acceleration from the gearbox output or differential case will be effectively reading the acceleration of the driven wheel.
- A scaling factor can be applied during processing to account for final drive ratio and difference in the number of pulses per revolution front to rear.

2.2 Mathematical modelling

2.2.1 Vehicle Dynamics

The limit of force that can be exerted on a vehicle to accelerate, decelerate, and maintain or change direction, is ultimately dictated by the tractive effort the tyres are able to exert on the road, which can be empirically described in terms of a slip condition at the interface.

Various complex dynamics exist between the road-tyre interface, vehicle suspension and operator inputs, acting to make the force that can be generated before slip dependant on;

- The vehicles attitude on the road, which depends largely on the operator inputs.
- The ability of the suspension to maintain contact between the tyre and road, which depends on the dynamic tuning of the suspension system to accommodate a particular disturbance.
- The instantaneous co-efficient of friction between tyre and road, which depends on the interaction between the particular tyre compound, road surface material and surface conditions (dry,wet,snow).
- The stiffness of the vehicle chassis, which depends on the material, design and loading.

However, if wheel slip is the desired control variable much of the intervening dynamics can be disregarded because there is a direct relation between longitudinal wheel slip and input torque.

This project will concentrate on longitudinal slip control, due to its focus on implementing a slip controller for the SAE car under acceleration. It is considered that by this control, an improvement in lateral slip will also result.

2.2.2 Equations of Motion

Forces at the wheel under acceleration are identified as;

- Engine torque
- Vehicle mass
- Tractive force

The major forces acting on the car as a whole are;

- Driving force from the wheels
- Aerodynamic drag

- Rolling resistance
- Mechanical drag
- Road incline

For the purpose of the project a simplified model will be used as illustrated by the following figure.

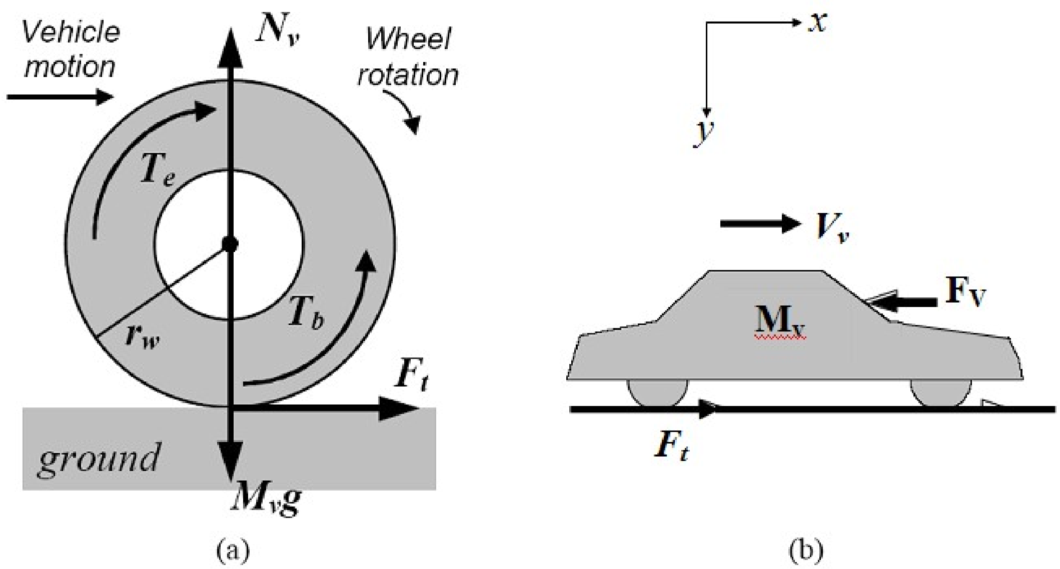


Figure 2.5: (a)Wheel and (b)Vehicle dynamics

Applying Newton's 1^{st} and 2^{nd} laws to the model, and with reference to Morton, MA. 2004 and Olson et al 2003, equations for linear and angular velocity may be developed.

Figure 2.5 (a) depicts a single wheel constrained to move longitudinally in the x direction, summing forces and moments gives;

$$\begin{aligned} N_v &= -Mg \\ \dot{\omega}_r &= \frac{T_e - rF_t}{I} \\ &\text{and;} \\ F_t &= \mu N_v \end{aligned} \tag{2.1}$$

Where μ is the co-efficient of friction, M is the mass of the vehicle, g is the acceleration due to gravity and J is the polar moment of inertia of the wheel.

Considering figure 2.5 (b); the front wheel is assumed not to slip as it is not driven, and the rear wheel is assumed to be the same radius as the front. So that the dynamic equation for the vehicle motion is;

$$\dot{V} = \frac{nF_t - F_v}{M_v} \tag{2.2}$$

Where n is the number of wheels on the vehicle.

If the states of the system are velocity of the vehicle and angular velocity of the wheels, letting x_1 = front wheel and, x_2 = rear wheel, the following equations are derived;

$$\begin{aligned} x_1 &= \omega_f = \frac{V_v}{r_w} && (2.3)\\ \dot{x_1} &= \frac{\dot{V_v}}{r_w} = \frac{n\mu N_v - F_v}{M_v r} && (2.4)\\ x_2 &= \omega_r && (2.5)\\ \dot{x_2} &= \dot{\omega_r} = \frac{T_e - r\mu N_v}{I} && (2.6) \end{aligned}$$

Percentage slip can be expressed as;

$$s = \frac{\omega_r - \omega_f}{\omega_r} = \frac{x_2 - x_1}{x_2} \tag{2.7}$$

$$\text{Where } \omega_r \geq \omega_f s = 1 - \frac{x_1}{x_2} \Rightarrow 1 - s = \frac{x_2}{x_1}$$

To put equation 2.7 into the general form $\dot{x} = Ax + bu$, the derivative is taken so that;

$$\begin{aligned} \dot{s} &= \frac{d}{dt}\left(\frac{x_2 - x_1}{x_2}\right) \\ &= \frac{\dot{x_2}x_1 - x_2\dot{x_1}}{x_2^2} && (2.8) \end{aligned}$$

Substituting equations 2.3 to 2.6 into 2.8 and rearranging gives;

$$\dot{s} = \left[\frac{F_v - nN_v\mu}{M_v r\omega_r} - (1-s)r_\omega \frac{N_v\mu}{I\omega_r}\right] + \frac{1-s}{I\omega_r}T_e \tag{2.9}$$

(2.10)

2.2.3 Desired wheel slip

It is shown in Olsen et al (P.4) and Morton, M A. (P.5) that maximum tractive force generated by a rubber tyre on dry asphalt occurs in the range of 10 - 20 percent slip.

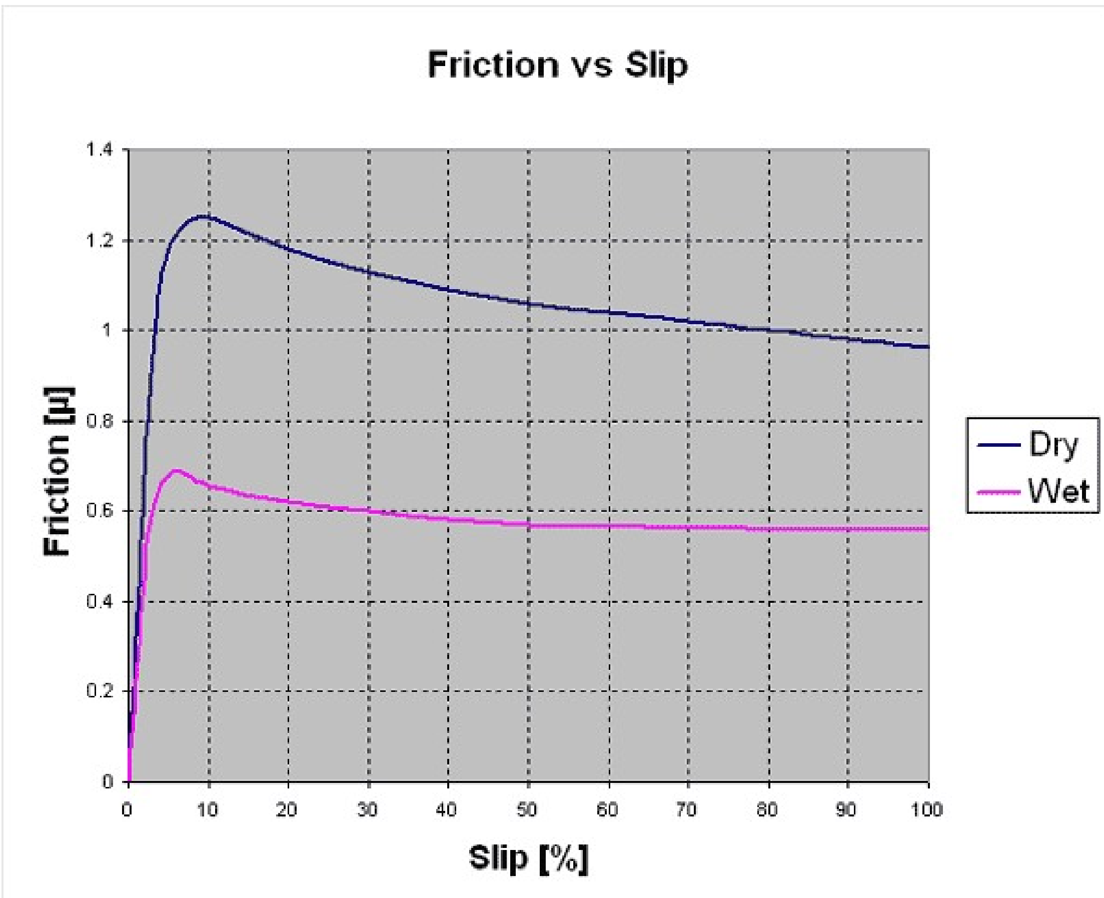


Figure 2.6: Wheel Slip vs Friction Co-efficient

2.3 Algorithm development

The basic premise of the traction control algorithm to be developed is to compare front and rear wheel velocity and adjust engine power output to maintain a desired difference between the two.

Provision has been made within the Adaptronic ECU for this purpose, it is possible to retard the ignition in 0.2 degree increments by storing a negative value in 'globalIgnTrim', and introduce ignition and fuel injection pulse cutting through the use of bit masking.

Within the ECU the raw pulse count from front and rear wheel speed sensor inputs are converted to a frequency form and are available as the variables 'masterSpeed' and 'slaveSpeed', slavespeed is chosen to represent the rear wheel to indicate that this is the controlled variable.

In a departure from the methods presented in Morton, M A. and Kachroo, P.; and from concepts contained in Billingsley, J. *Controlling With Computers*and the course ENG4406 *Robotics and Machine Vision* the following control method is developed.

A measure of slip is obtained as per Section 2.2.2 using the variables 'masterSpeed' and 'slaveSpeed'; $\dot{s}$ is derived from the rate of change of the variables using a free running timer, which also provides an estimate of the vehicle velocity.

Control action is defined as;

$$u = a \times V_v + b \times s + c \times \dot{s} \tag{2.11}$$

Where a, b and c are empirically evaluated co-efficients; although it is thought that more work on the mathematics would produce a robust definition.

Control action is proportional to the;

- Difference in velocity of the wheels (slip)
- Rate of change of slip of the wheels

2.4 Conclusion

The algorithm suggested above was not implemented due to the late development of the concept; a proportional algorithm was implemented in a test rig consisting of the ECU and pulse generators and shown to work.

Given the success of the proposed control method in other applications (balancing pendulum et al) it is considered that the method will be successful.

2.4.1 Launch control

Launch Control is a useful by-product of a combination of electronic systems in the race car. Essentially it is function within the Traction Control system designed to automate standing starts to maximise the initial acceleration. It is activated by pressing a button on the dashboard when the car is stationary. This brings in a secondary rev-limit (for example 6000 rpm) The throttle can then be fully depressed without over-revving the engine, then the clutch is engaged, after which the traction control system controls the wheelspin for consistent starts. When a preprogrammed engine speed is reached a gear shift sequence is activated, ensuring that shifts are performed consistently.

It is conceivable that refinements may include a vehicle velocity vs slip relationship and some hand over criteria, specific shift point for each gear may be implemented.

Chapter 3

Gearshift actuator

3.1 Rationale

Several purposes drive the consideration of a gearshift actuator on the SAE car. These include;

- Enhancing driver safety by providing the driver with a means to change gear without removing hands from steering wheel.
- Assisting the driver by automating upshifts during the acceleration test.
- Difficulty experienced shifting gears on the 2004 car

3.2 Design

Design options exist in the areas of;

- Power type to be used for actuation;
  - Compressed air (Electropneumatic)
  - Vacuum

  - Electricity

- Connection of actuator to gearbox;

  - Rod

  - Cable

The force needed to cause the gearbox to shift is measured at 100N on a 65mm lever arm, for reliable operation 150N is suggested; stroke length required with this lever arm is 20mm.

$$\frac{150}{0.065} = 2.3\text{kNm}$$

3.2.1 Compressed Air

Electropneumatic systems are commonly used in drag racing applications; usually a single acting cylinder to upshift a sequential gearbox or automatic transmission. Activation is by driver controlled switches or an output from the ECU.

The system consists of;

- Air storage tank
- Pressure regulator
- Valves
- Switches and plumbing

For the SAE car consideration is needed to determine a suitable operating pressure, ram size, and storage tank size. The assumed working pressure of the storage tank is 7 bar, 100psi, so that the tank may be recharged during breaks in competition from air supplies on site or from a small compressor.

For a working pressure of 0.7MPa the actuator diameter required is;

$$\begin{aligned} A &= \frac{F}{P} = \frac{150}{0.7} \\ &= 214\text{mm}^2 \\ D &= \sqrt{\frac{A \times 4}{\pi}} \\ &= 16.5\text{mm} \end{aligned}$$

A 20mm diameter ram with 50mm stroke is commonly available, specifically AutomationDirect # DIC20M50 $39 is applicable.

Air consumption will be $314mm^2 \times 25mm = 0.008L$ per gearshift. From the SAE 2005 rules, estimated top speeds are 60kph for the autocross event (2 ×800m laps)and 105kph for the endurance event (22km). From gearing tables in the dissertation of Jeremy Little (2004), 110kmh = 4^{th} gear; thus requiring 8 gearshifts to go from 30 - 110 - 30 kph. The endurance event may then require up to 100 gearshifts to complete (8 × 10 laps + some safety factor) and is the greatest concern. This indicates that a minimum of 0.8L of air is required (100 × 0.08), in order to ensure operation for the duration of the race 2L will be specified.

Using the principle that minimising the area of material used in construction will minimise the weight of the vessel;

$$\begin{aligned} A &= 2\pi r^2 + 2\pi r h \\ V &= \pi r^2 h = 2 \times 10^6 \\ A &= 2\pi r^2 + \frac{4 \times 10^6}{r} \\ \frac{dA}{dr} &= 4\pi r - \frac{4 \times 10^6}{r^2} \\ r_{min} &= 68.3\text{mm} \\ h &= 136.6\text{mm} \end{aligned}$$

So that a reservoir of 137 mm diameter and 137 mm height is required. There does not appear to be a specific ADR or AS applicable to the construction of air pressure vessels for use in vehicles; so AS1210-1997, ‘Pressure vessels’, is considered applicable.

Without considering the detailed design of a storage tank, a guideline to material thickness may be obtained from the standard. The minimum wall thickness from table 3.4.3, p.87, is 2mm; for unstayed flat ends,section 3.15.3 (p.131) is applicable;

$$\begin{aligned} t &= d\sqrt{\frac{p}{Kfn}} \\ &= 137\sqrt{\frac{0.7}{3 \times 43 \times 1}} \\ &= 10.09\text{mm} \end{aligned}$$

Where d = diameter, p = pressure, K = efficiency of joint, f = tensile strength of material, n = factor for longitudinal welds in the end plate.

The total volume of material used in its construction is 414473 mm^3, using 2800 kg/m^3 for aluminium, the weight is 1.2 kg. Use of composite material may reduce the weight, however filament wound construction is necessary.

Suitable ready made bottles can be found in the form of;

- Welding gas suppliers; 1.6 kg CO2 steel bottle, (111 × 235 = 2.2 L).
- Fire extinguisher; 2.5L, operating pressure, 1000kPa, steel body $80
- Aluminium cylinders are available from performance parts suppliers, but tend to be expensive and larger than required.

Detailed specification of the valves and plumbing used in the system is also necessary to ensure that the time constant is not too large, it is considered that 0.5 second would ensure effective operation.

3.2.2 Vacuum

To use intake manifold vacuum as a power source, a storage tank with volume exceeding the capacity of the actuator × the number of shifts at low vacuum is needed. When the throttle is closed, vacuum is built up, which can then be used to shift gears when the throttle is open. While the vehicle is driven on a circuit where there is a deceleration between gearshifts there should be no problem, however if multiple shifts are made at high throttle openings the reservoir will be depleted.

The working pressure of a vacuum actuator is 1 bar at good vacuum, such as delivered by a dedicated pump, and 0.5 bar when using intake manifold vacuum on an engine in good condition.

The actuator diameter required is;

$$\begin{aligned} A &= \frac{F}{P} = \frac{150}{0.05} \\ &= 3000\text{mm}^2 \\ D &= \sqrt{\frac{A \times 4}{\pi}} \\ &= 62\text{mm} \end{aligned}$$

In an attempt to quantify the time constant of a vacuum actuator Poiseuille's law is applied with Δ P = 0.5 bar = 50 kPa and assuming a tube diameter of 10 mm, length 300 mm and viscosity of air at 1.789 E-5.

$$\begin{aligned} \Delta P &= V\frac{8\eta l}{\pi r^4} \\ 50000 &= V\frac{8 \times 1.73 \times 10^{-5} \times 0.3}{\pi 0.01^4} \\ V &= 37.8m/s \end{aligned}$$

Reynolds number;

$$\begin{aligned} R &= \frac{\rho V d}{\mu} \\ &= \frac{1.229 \times 37.8 \times 0.01}{1.73 \times 10^{-5}} \\ &= 26853 \end{aligned}$$

If this calculation is correct the airflow in the tube may be turbulent, in which case the velocity will be lower. This result indicates that the vacuum actuator, if connected to the reservoir via a 10 mm tube and appropriate sized valve is capable of full stroke in 0.1s, which is a lot quicker than thought, and in the region of an air cylinder.

Doing the calculation over with a tube diameter of 5 mm gives a velocity of 2.4 m/s, and a time to full stroke of 1.6 s. This is in line with previous experience and seems realistic.

The size of reservoir required is then, say 10 gearshifts 0.075 L per shift = 0.75 L. A part that may suit the application is found in a Holden Commodore HVAC system; it is a spherical ABS unit 130 mm diameter, 1.2 L. Various sized actuators are also found as throttle actuators in cruise control systems or as part of the HVAC system.

3.2.3 Electricity

The use of electrical power is seen as a viable option as the generating system on the vehicle of makes enough power (300W) to allow repeated operation of the shifter without depleting the battery. An electric system offers a clear advantage over a vacuum system in that there is a constant power source, and some advantage over the electro-pneumatic system due to reduced complexity.

An investigation of commercial electric actuators was undertaken with little useful result as the stroke length and force requirements could not be met. Few examples were found of an electric actuator in this application, one is shown in figure 3.1 which appears to use 2 solenoids in a push/pull arrangement.

It was decided to develop an actuator based on an automotive starter motor solenoid. The force produced by a standard solenoid was measured at 120N, which was judged to be sufficient to operate the gearshift. Two solenoids were obtained and the coils removed to be mounted end to end in a new case; the configuration is shown in appendix B.

The solenoid thus produced did not perform the required function. At this stage the proposed construction had been presented to a number of undergraduate and professional electrical engineers, who advised that 'it should work'. No investigation by the author of the principles of solenoid operation had been undertaken.

Upon investigation it was found that the failure of the end product may be attributed to the use of aluminium in the design due to its lack of permeability. This was done to reduce the weight of the solenoid, but produced the following areas of concern;

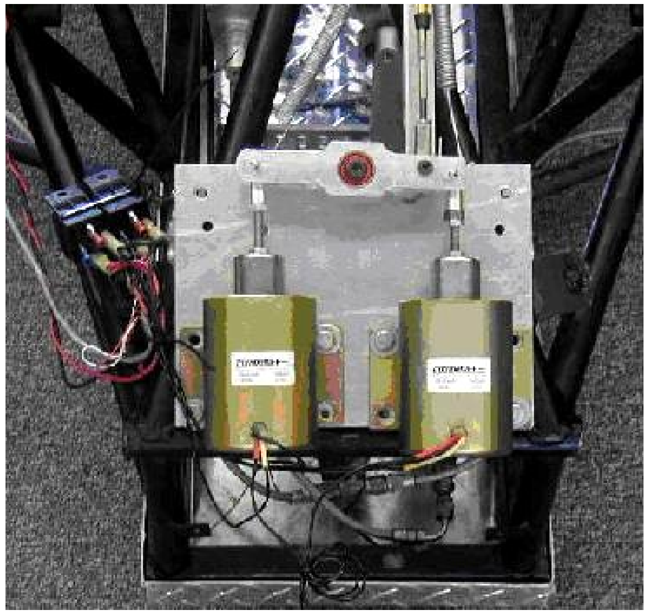


Figure 3.1: Electric solenoid gearshift actuator

- Outer case; the steel case used in the original solenoid completes the magnetic circuit around the outside of the coil, without which the force produced is dramatically reduced.
- End caps; magnetic attraction of the end cap to the slug is used to increase the force produced at the end of the stroke. As the slug is naturally pulled into the centre of the coil the end cap circuit is relied on to bias the flux in the direction of travel.
- Rod; should have been steel to increase the volume of permeable material in the core.

Reconstruction of the solenoid following these guidelines may result in a device that produces the required force; although some calculations were done the result was inconclusive and finite element analysis may be the only way of showing this potential. The weight of the device at present is 1.25 kg and reconstruction using steel will increase this to 1.7 kg.

A further attempt was made to produce an electric shift device; based on a motorcycle starter motor, shown in appendix C. The motor is driving an 80mm lever arm through a 5:1 reduction gear and torque limiting clutch; the device weighs 1.5 kg. No testing was done on this device except to check the current draw (20A). A problem that has not been addressed is that of returning the lever arm to centre after a gearshift, which is necessary for correct operation of the gearbox. It is proposed to use reed switches to sense the position of the arm and control it via the ECU.

In principle a sequence is enabled that cuts the ignition, drives the actuator to the limit of travel causing a gearshift, then returns the arm to the centre ready for the next shift. This introduces some complexity to the implementation; which may be avoided by the use of springs to centre the arm if enough torque is available from the motor to drive both gearshift and return spring.

Electric actuation methods were pursued as it was thought the resulting system would be less complex than the use of compressed air, would not require recharging, be cheaper to build, and lighter.

3.2.4 Connecting link

As the connection link is to transfer operating force from the actuator to the gearshift mechanism of a motorcycle engine, a link is to be provided that is capable of both push and pull. It appears that two methods exist, cable or rod. Of these choices, the rod appears to be the easiest to implement provided the actuator can be mounted in an appropriate position.

In the case of a cable system, either one cable capable of transmitting a compressive load, or two cables used in tension are needed. It is likely that two smaller cables in a pull/pull arrangement would be lighter than a cable large enough to be used in compression.

To determine the connecting rod size and material, consideration is given to buckling load and tensile stress. From *Fundamentals of Machine Component Design* p.209 buckling load is considered using Euler's equation. In the suggested application the rod is a pin ended column therefore $L_e = L$, and as it is thought that aluminium would offer the lightest weight of readily available materials, E=70 GPa. From the desired load rating plus a safety factor of 2, P_{cr}=300N giving;

$$P_{cr} = \frac{\pi^2 EI}{L_e^2}$$

$$\begin{aligned}
300 &= \frac{\pi^2 \times 70 \times 10^3 \times I}{400^2} \\
I &= 69.48mm^4 \\
69.48 &= \frac{\pi d^4}{64} \\
d &= 6.13mm
\end{aligned}$$

Check tensile stress;

$$\begin{aligned}
A &= \frac{\pi 6.13^2}{4} \\
\sigma &= \frac{300}{29.51} \\
&= 10.16\text{MPa}
\end{aligned}$$

So that the shifter device may be connected to the gearshift mechanism by means of an aluminium rod 400mm or less in length with a diameter greater than 6.13mm if a 65 mm lever arm is applied to the gearshift shaft.

3.2.5 Result

Various systems for implementing gearshift actuation by remote switch have been explored, no detailed design or testing has been done.

It is considered that;

- Further work on the ‘motor in a box’ actuator will produce a good result; although the current draw is not exceptionally high, it may be a problem during extended operation and wiring and control circuitry must be sized accordingly. Cost of a motorcycle starter motor is $300, a general purpose 300 W DC motor is equivalent, these are priced at $40 but are larger and heavier. `www.oatleyelectronics.com/motors.html`

- Further development of the solenoid actuator presents many unknowns; at present there is no weight or power saving over the motor device although it is smaller.

- The use of compressed air as a power source is seen to be problematic due to the requirement that the system be recharged at intervals. It may possible to fit a small compressor such as used for tyre inflation although this will increase the weight of the system. Cost of this system is estimated at $400, weight 2.5-3 kg.

- If the calculations are correct, the use of vacuum as a power source may be feasible as suitable lightweight ABS plastic actuators and reservoirs are found in automotive applications. Two actuators would have to be used, one for each direction and large bore valve block manufactured. A further advantage is the safety of the system, there are no high currents or high pressures present removing fire and explosion hazards.

Chapter 4

Conclusions and Further Work

There is much further work to be done on the various projects presented in this report. Although the components for a fuel injection system were assembled and tested no implementation was attempted. Without the ECU installed the testing of a traction control algorithm was limited to simulation. Further implementation of a gearshift device could have been attempted through the construction of a separate controller, for which the design was done.

Significant ground work has been done in regard to the systems presented and it is hoped that this contributes to a better outcome for the 2006 SAE team.

Chapter 5

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Appendix A

Project Specification

University of Southern Queensland
Faculty of Engineering and Surveying

ENG4111/2 Research Project
PROJECT SPECIFICATION

FOR: Reuben Molloy

TOPIC: Electronic Systems for USQ FSAE Car

SUPERVISORS: Chris Snook

PROJECT AIM: Implementation of programmable fuel injection, ignition and traction control on the USQ SAE race car

SPONSORSHIP: USQ Faculty of Engineering
Andy Wyatt (Adaptronic)

PROGRAMME: Issue A, 14/3/05

1) Fuel Injection;
   - Research and compare available ECU's
   - Research and specify appropriate fuel injectors and high pressure pump
   - Design high pressure fuel system to comply with FSAE rules
   - Implement system on vehicle

2) Traction Control
   - Research and specify wheel velocity sensors
   - Research, design and implement traction control algorithms in ECU
   - Implement system on vehicle

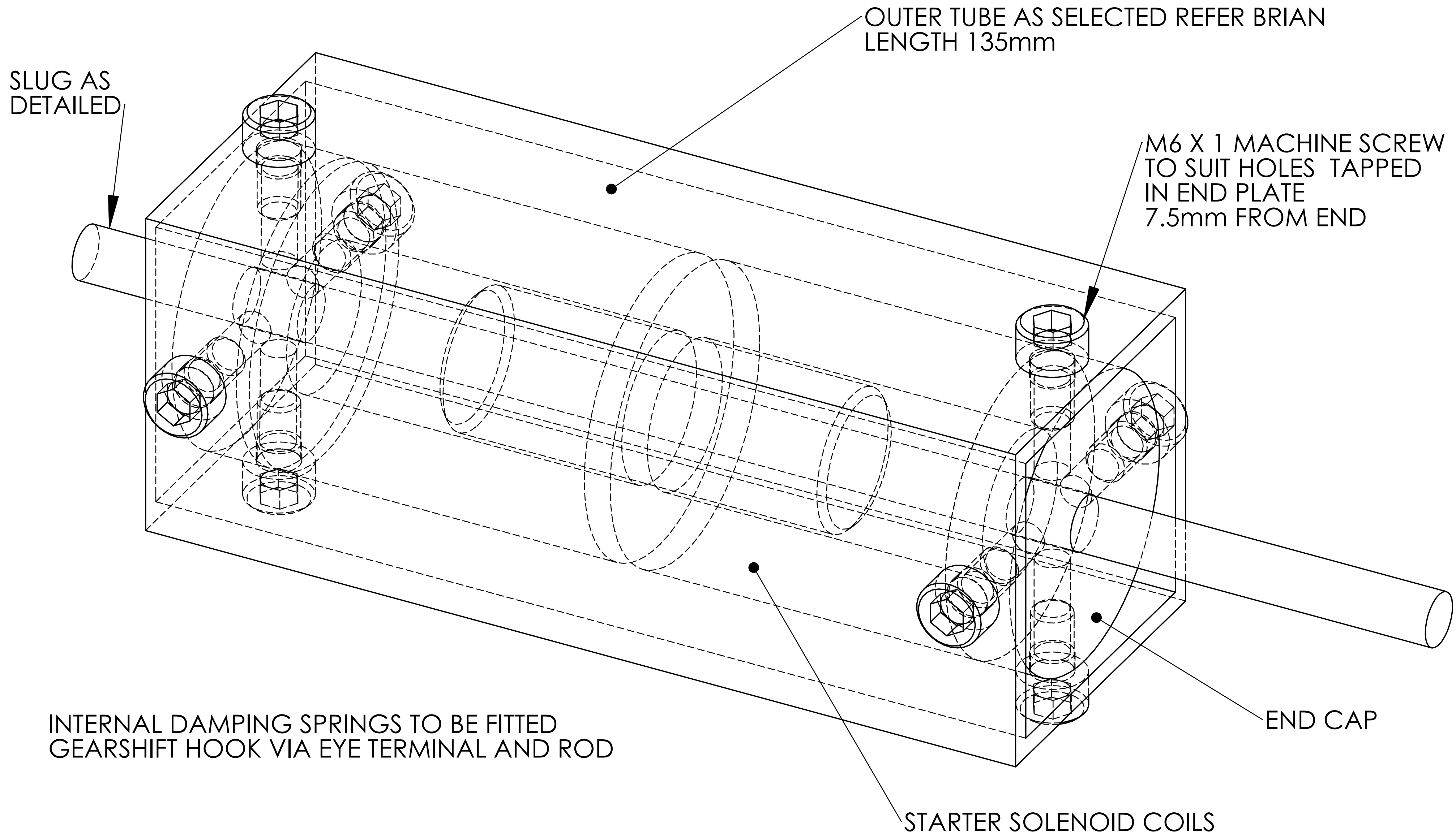
3) If time permits;
   - Design electric actuated gear shift mechanism
   - Integrate system with ECU for automatic shift at programmed engine speed
   - Provide for driver actuation of system
   - Implement system on vehicle

AGREED__________________ (Student) _______________________ (Supervisors)

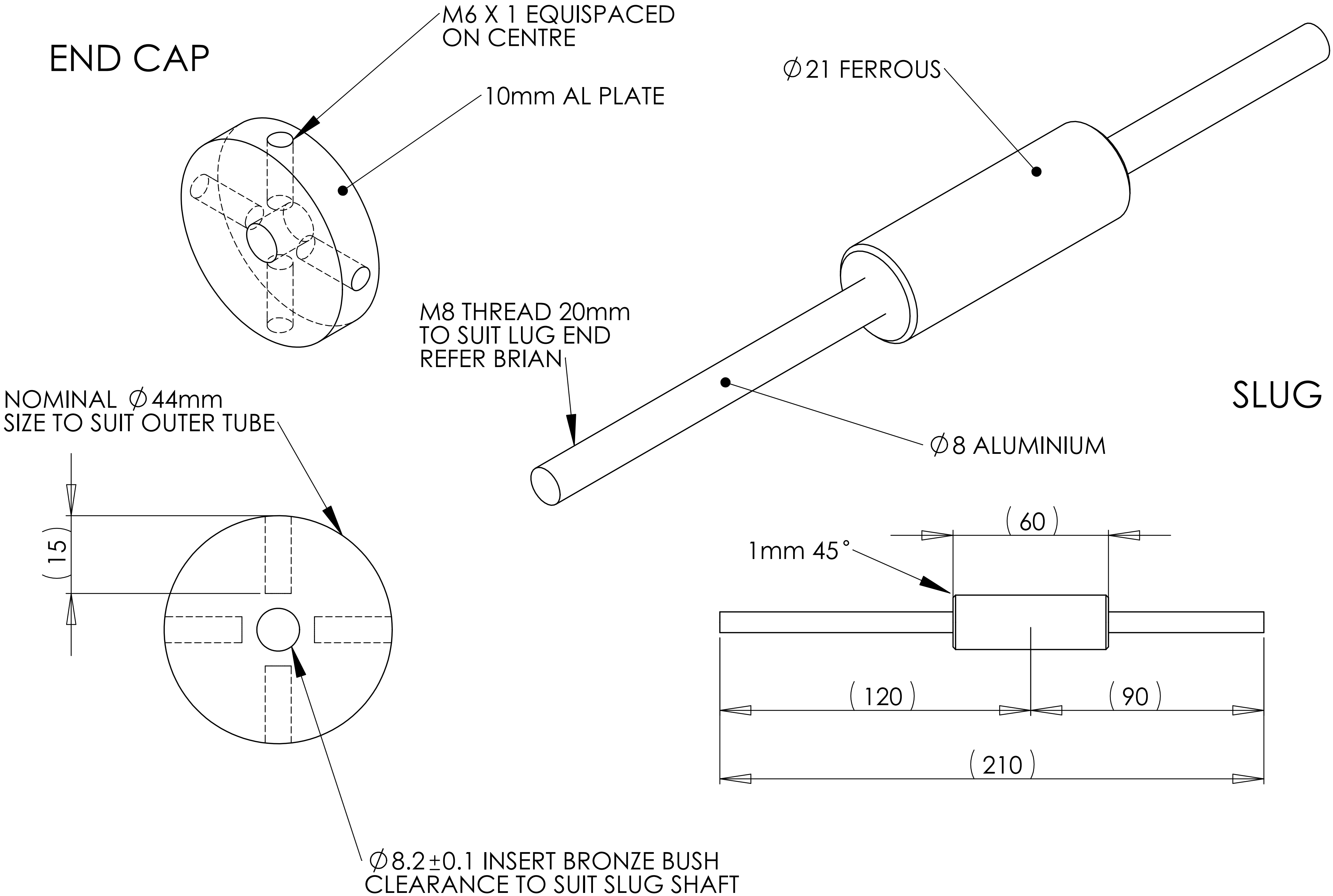
(Dated)___ / ___ / ___

Appendix B

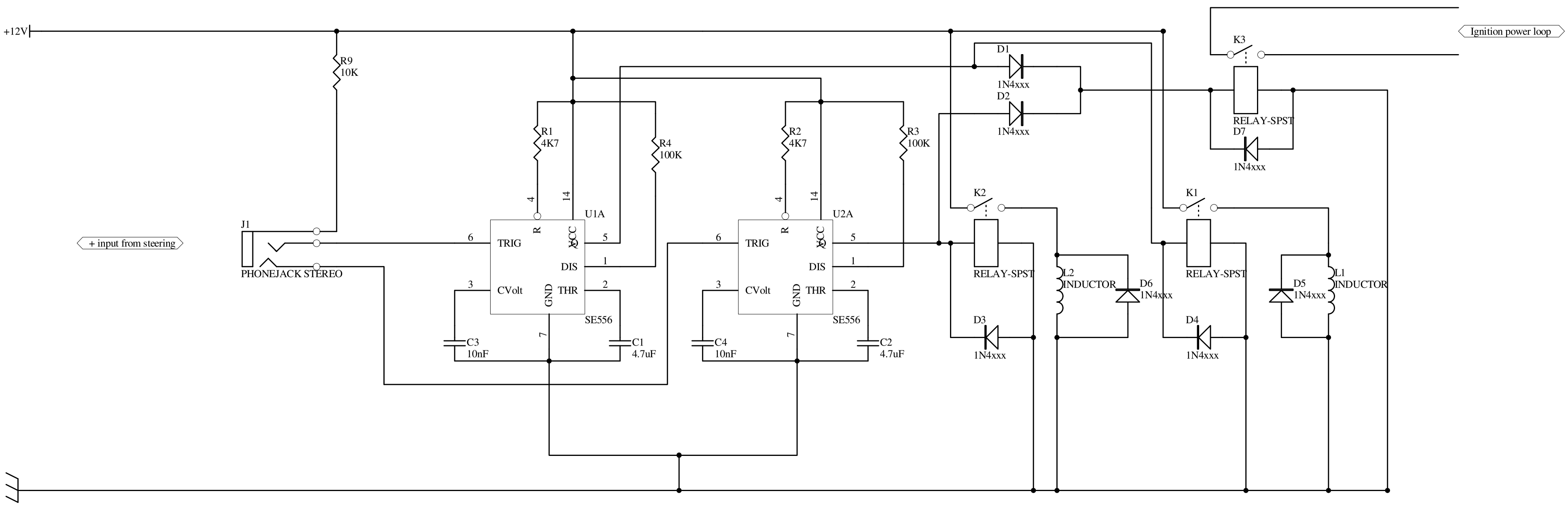
Electric Solenoid Gearshift



ELECTRIC GEARSHIFT ASSEMBLY				
ZONE E	REV.C	FASTENERS: 8Xm6X1 MACHINE SCREW	15/06/05	APPROVED



USQ SAE CAR ELECTRIC GEARSHIFT - SLUG AND END CAP				
ZON E	REV.	MATERIAL DETAIL: MS CENTRE AL OR BRONZE ROD	09/06/05	APPROVED



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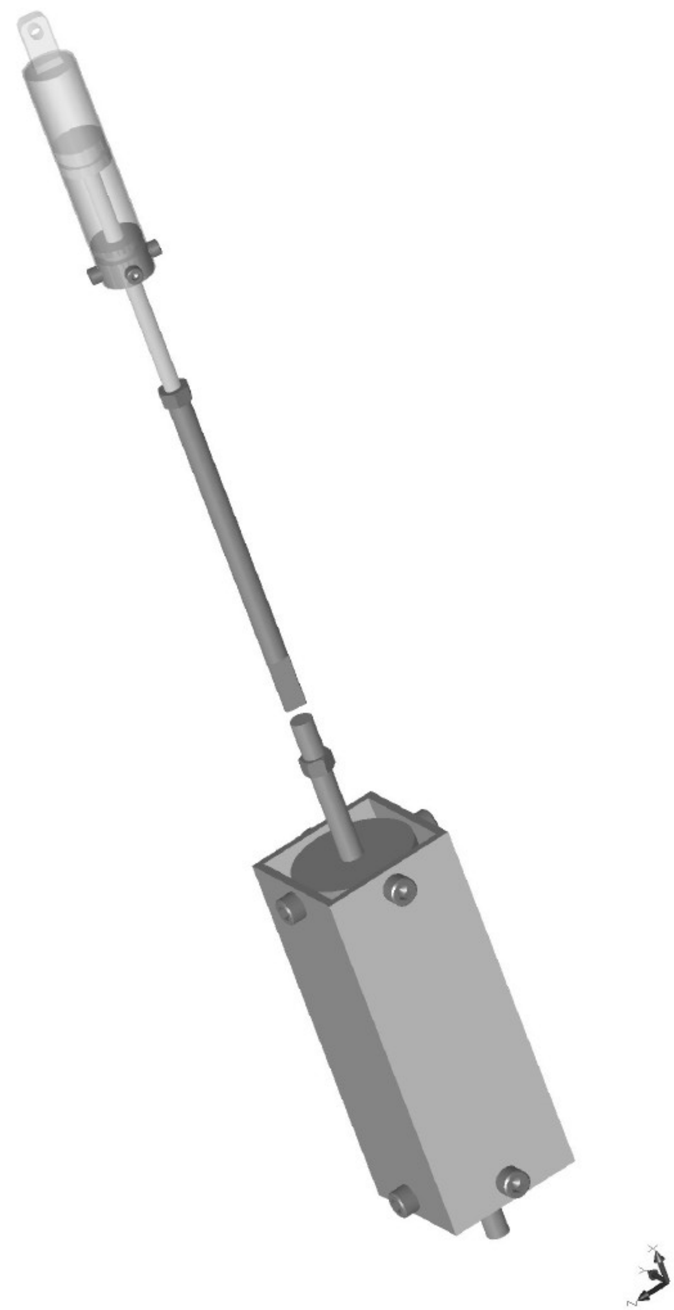

Figure B.1: Solid model of electric solenoid gearshift actuator

Appendix C

Electric Motor Gearshift

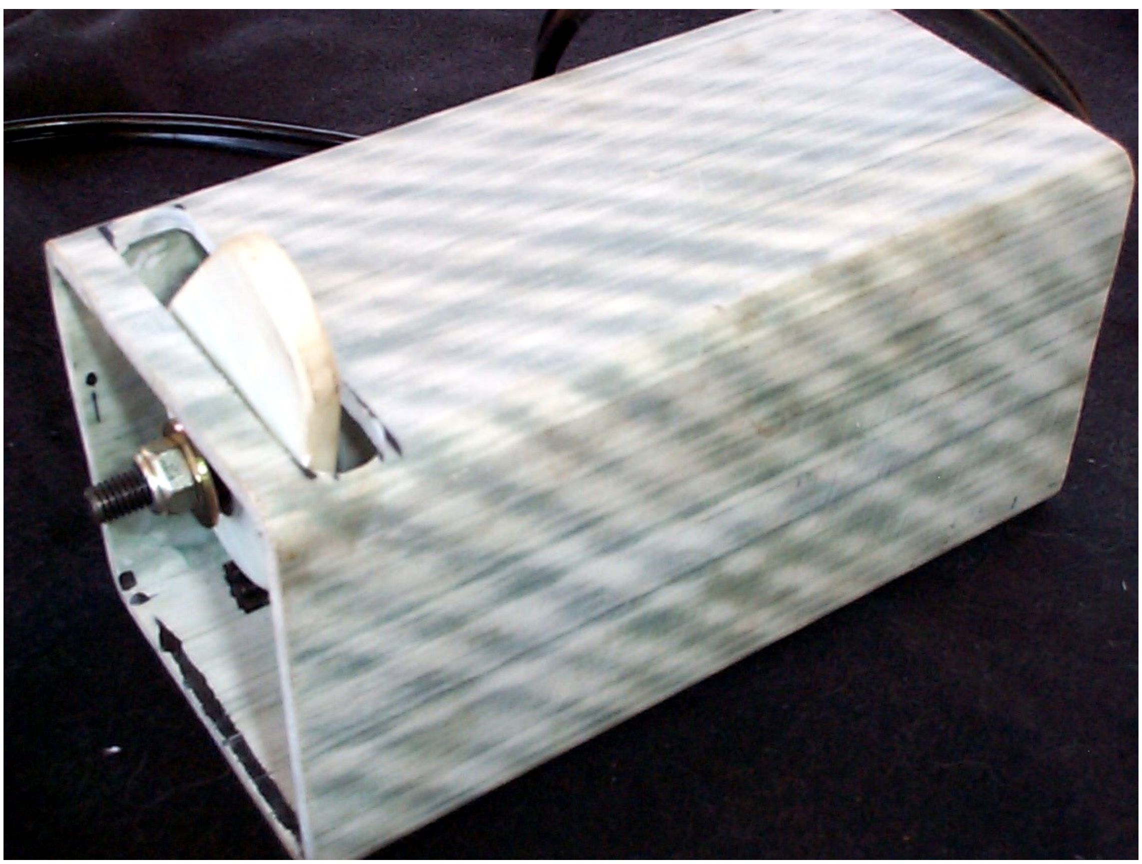

Figure C.1: Motor-in-a-box gearshift actuator

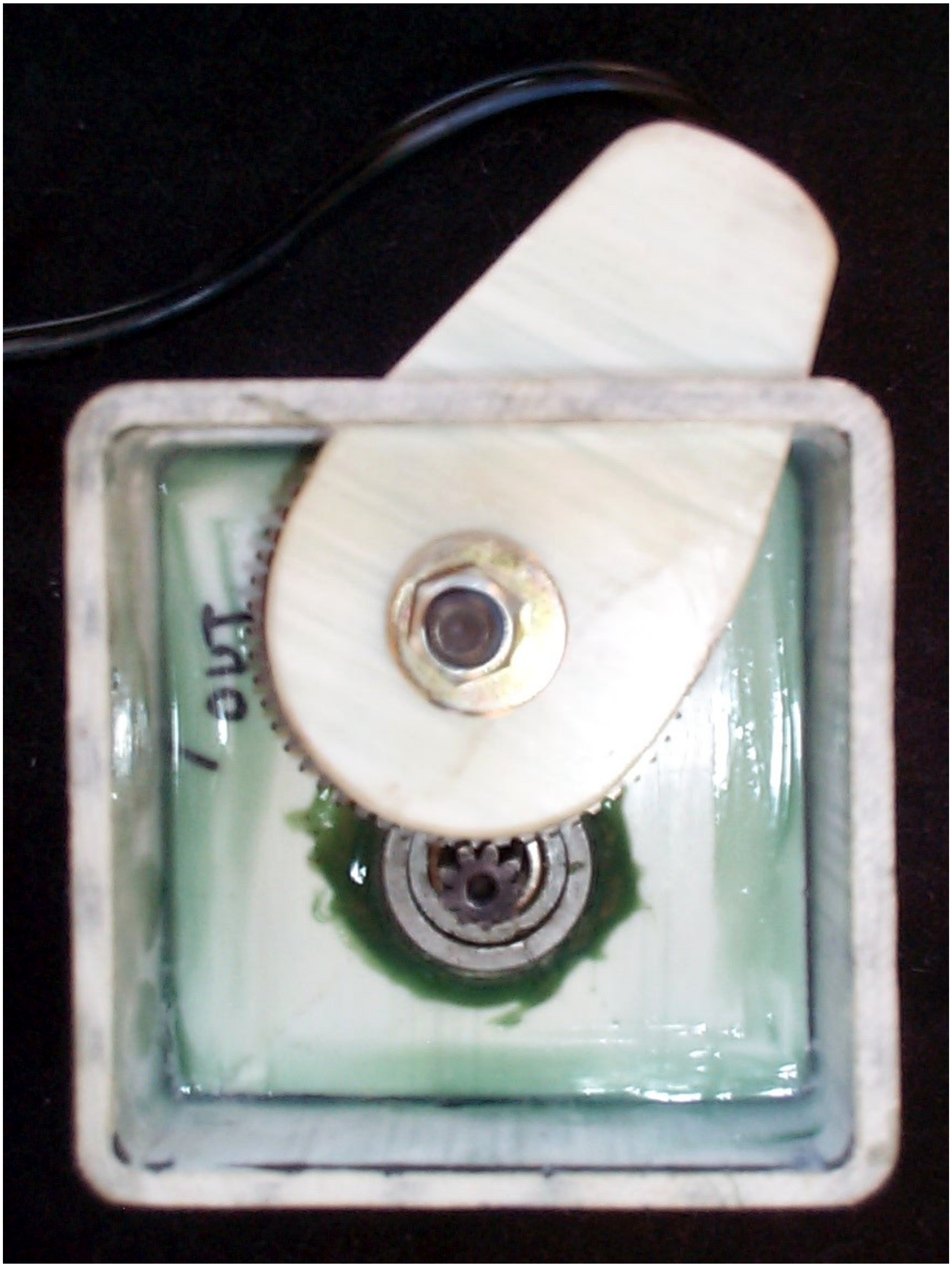

Figure C.2: Drive end view of motor-in-a-box gearshift actuator

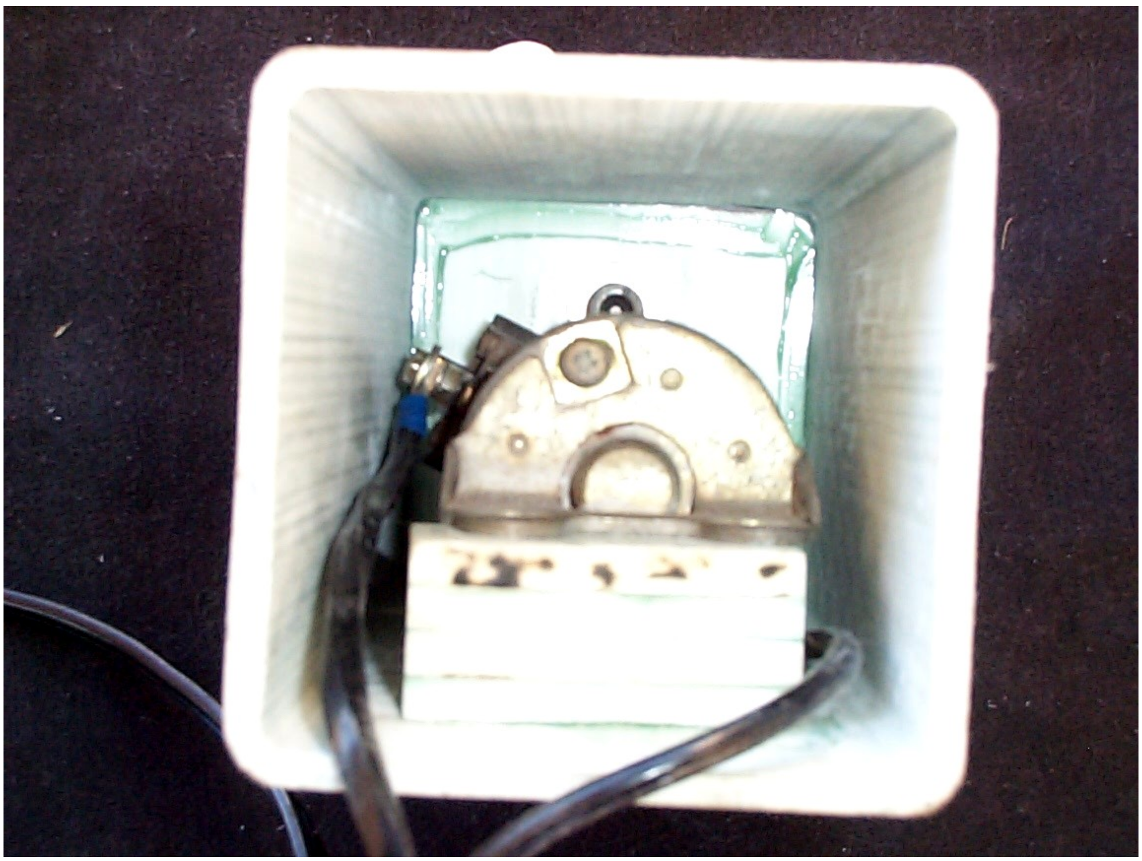

Figure C.3: End view of motor-in-a-box gearshift actuator

Appendix D

Fuel injection components

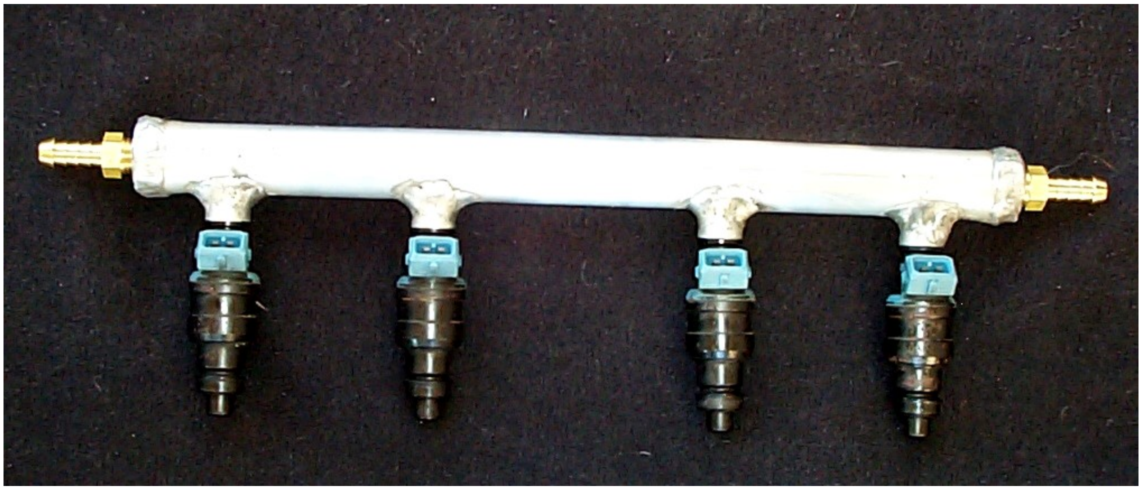

Figure D.1: Fuel rail and injectors

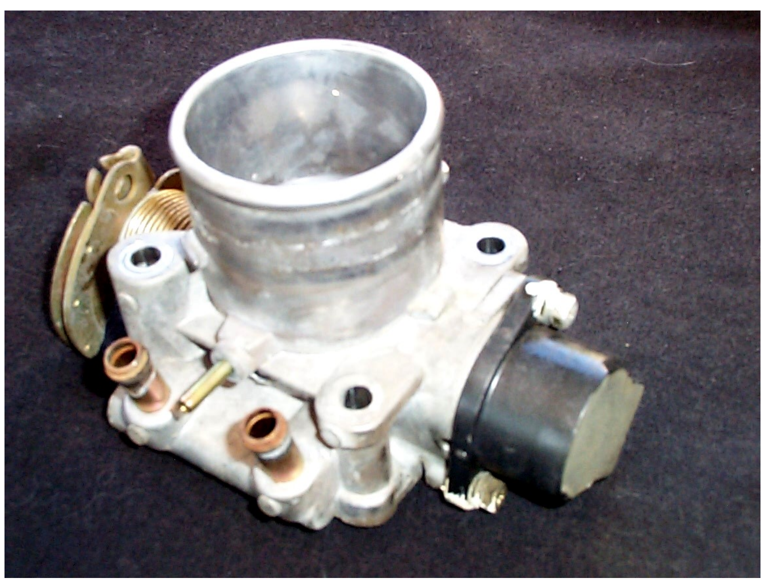

Figure D.2: Throttle body

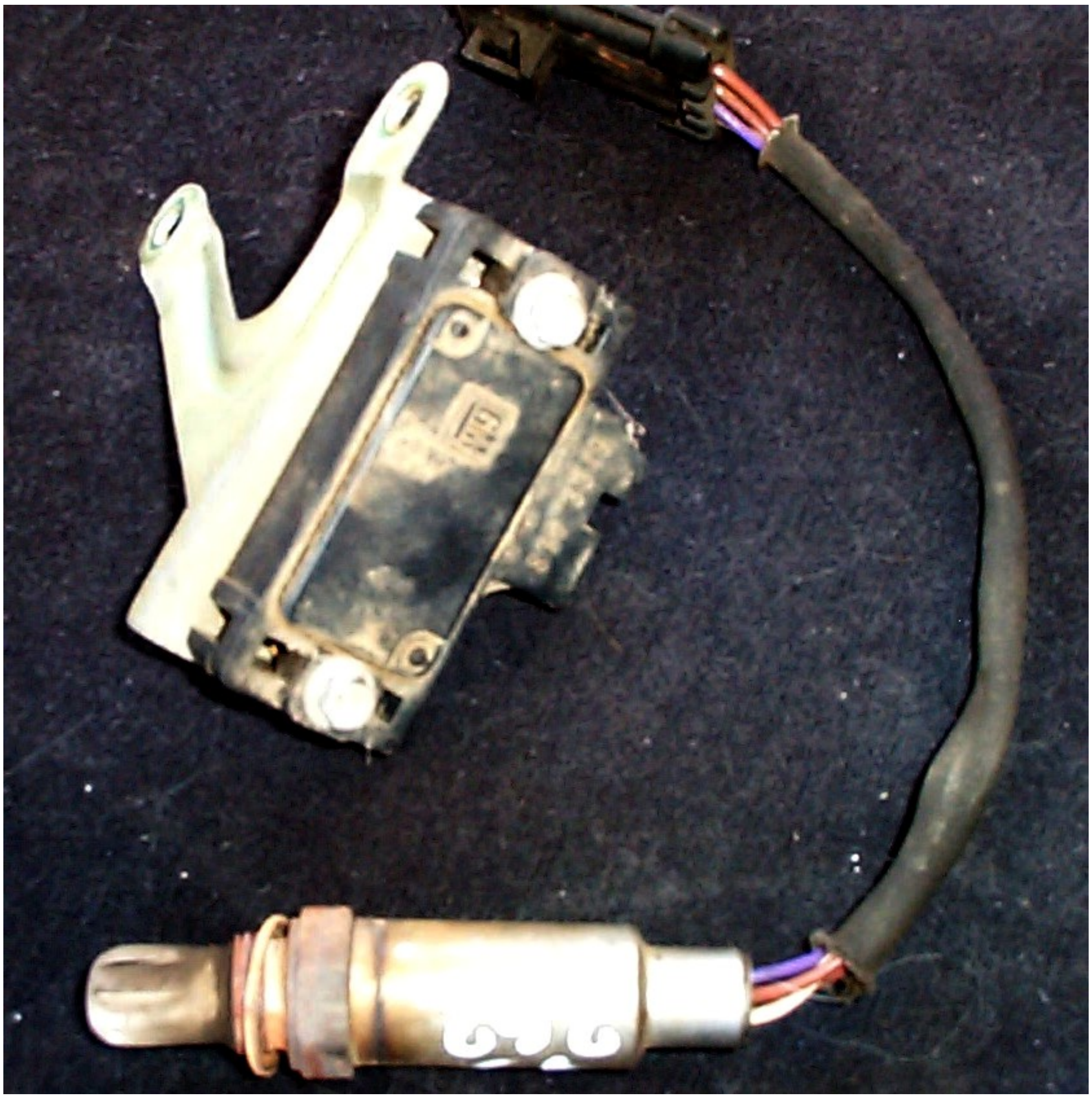

Figure D.3: MAP and HEGO sensors