Gasoline to E100 Engine Conversion for Eco Marathon Competition

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Abstract

Shell Eco Marathon 2016 will be held at London, the UK and KTH would be represented by team ELBA under the ethanol urban vehicle concept category. This is the first attempt with ethanol (E100) as the base fuel. The previous years' team competed with gasoline in the urban vehicle category.

This report discusses the work done by the ICE group under team ELBA and elucidates the planning, work process, accomplishments and challenges faced through the project. At this juncture it must be noted that work is ongoing to meet the larger competition goals.

The Eco Marathon project is carried out under the course "MF2090 Internal Combustion Engines, Project Work" throughout VT16.

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We would also like to thank our sponsors SKF, SHC and ECO2 for their support and ITRL for providing us the workspace and seclusion to develop an indigenous test rig and have a fully functional team room.

Contents

Introduction

The first task of the project was to understand the competition, its rules and regulations along with the deliverables of the ICE group. The rules and guidelines are revised each year for the competition and are available on the Shell Ecomarathon (2016) webpage (1).

The project commenced with inputs from the previous ICE group as we were inheriting their vehicle and work. Suggestions were made to utilize the existing engine (Honda GXV 57) with drivetrain and focus on mechanical and control improvements.

Key points from 2015 engine group:

- Engine might be underpowered
- 1 point optimization carried out at 3000rpm full throttle
- Robustness of connectors and harness must be improved
- Attempts of coatings unsuccessful
- Optimization of engine damper and flywheel is required
- Raising the compression ratio requires reasonable time and effort

These points provided a basic idea of the project and the possible difficulties that we would face.

Test Rig

To be able to perform tests with different load cases and different engine speeds, a test bench had to be developed. To load the engine, the test cell from previous year relied on a 3-phase asynchronous motor connected to a resistor pack of 144 Ohms. The asynchronous motor was managed through a frequency controller (VFD), which made it possible to adjust the rotational speed of the electric motor. Further, this motor was connected to the combustion engine with a driving chain, as can be seen in figure (1).

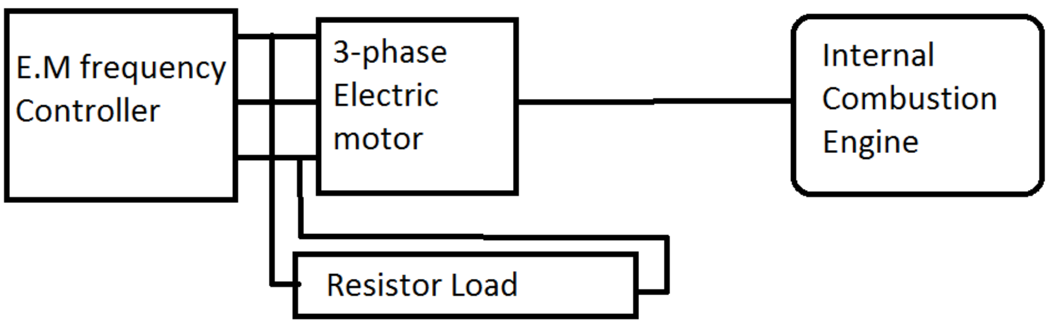

Figure 1 Schematics of the test rig

By demand from the school, the previous year´s test rig was not sufficient, mainly because of the safety issues with the test rig and the engine test engineer in the same room. With the motivation to eliminate issues like carbon monoxide poisoning and danger of moving parts coming loose, a new test rig had to be developed. The foremost tasks were

- control speed and load of the combustion engine externally
- Use the test rig for the coming year´s Eco car project
- Acquire data from Engine-runs in terms of different ambient and tuning parameters
- Handle the test procedures of the Engine for this year, as well as being modular enough for other engine types
- Mount auxiliary systems securely, i.e. Engine Control unit, Fuel supply, data acquisition system and ignition control

The different tasks were taken into account when designing the new test cell together with the rig.

Safety and Robustness

As mentioned, safety was a big issue from the previous year. It was decided to mount the test rig in another room, next to the old test room. The old test room was rebuilt entirely as a control office with computers. To monitor the actual test rig, a web camera was mounted in the new test room.

Further, to reduce the vibration caused by the ICE, it was decided to use rubber mountings in the new rig. This reduced both noise and vibration excitation in the electrical systems, as well as movement of the rig during tests.

Flexibility

The Engine test rig had to be easy to use with different engines and types to be useful in the future. This resulted in an engine test rig that is able to run engines with the output axle in both horizontal and vertical direction, and at the same time enable mounting engines with different mounting configurations.

Construction

The final test rig was constructed using CAD modelling for fast realization and visualization during the design phase. This means that the demands could be evaluated directly in the CAD-model. The resulting CAD-model of the base of the test rig can be seen in figure (2)

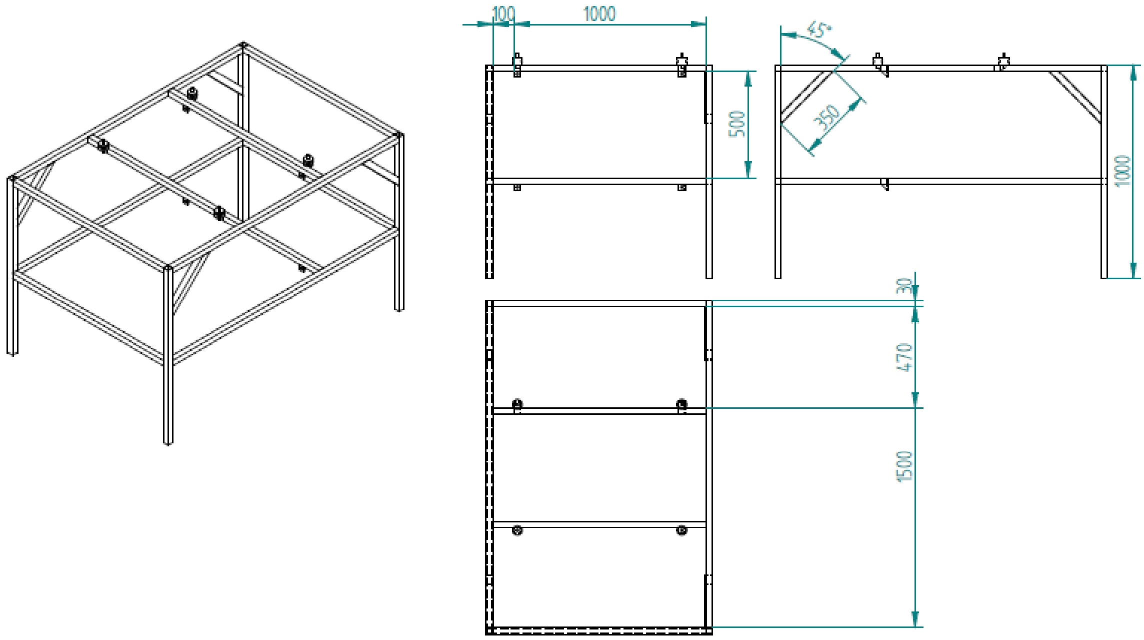

Figure 2 Blueprint of the base of the test rig

The choice of construction material was chosen to be steel in 30x30x1.5 square profiles. The choice was steel SS-EN- 50 100 mainly because of the low sensitivity to fatigue and reasonable tensile strength. To minimize the reduction of strength during welding, the test rig was mainly TIG-welded to have good control over the weld.

Although no calculations were made, based on experience from the previous year's rig, the dimensions were believed to be enough for small engines typically used for these projects.

As can be noted from figure (1), the lower base consists of a table with welded mounts for rubber couching, which can be mounted in a vertical or a horizontal matter. The upper part of the test rig can be observed in figure (3). To reduce the risk of the chain jumping off the sprockets on the electric motor and the engine, the upper module was constructed in one piece, with the electric motor and the engine firmly mounted on the module. This allows for lower moment of the engine in relation to the electric motor and therefore low variation in chain tension during running. The upper module is connected to the base with rubber bushings to reduce vibration transfer into the base. This reduced the risk of the rig moving during operation and further reduced the vibration onto the electrical equipment.

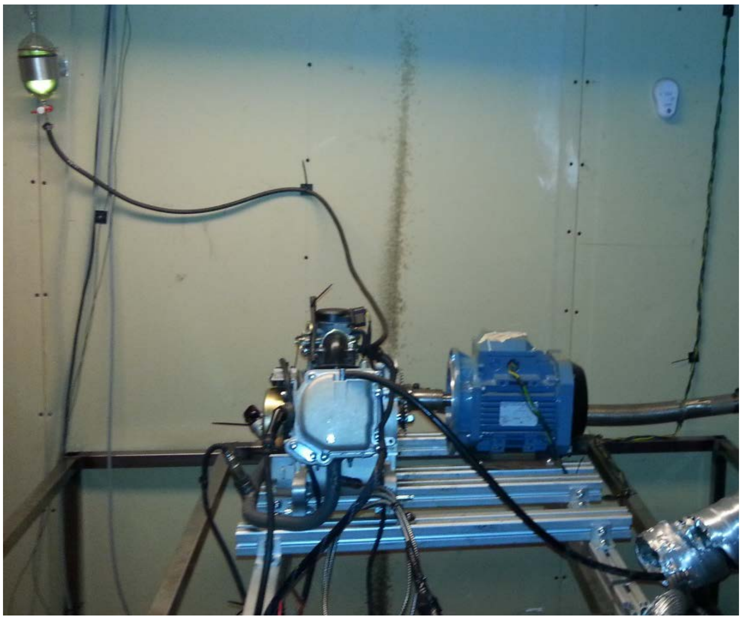

Figure 3 Electric motor and ICE mounted on the upper module of the test rig. Fuel supply system is in the upper left corner and CO sensor in the upper right corner

To mount equipment on the test rig, a mounting plate was introduced. This gave a surface for mounting the log-equipment, fuel supply system, engine control unit, lambda sensor unit and main relay. The main relay was used to enable the rig to be remotely shut on/off as a safety measure. The mounting plate also gives the equipment a protection in the event of parts braking loose from the engine.

Figure 4 Mounted logging equipment, ignition system, relay and battery.

Engine Logging

The ability to save data during test rig operation is an important feature that would provide visualization of transient behavior and log data for different engine speed and load settings. This enables the operator to make adjustments based on calculations with less runs and more precision thus giving the user a cheaper, faster operation with less chance of failure. This reasoned the need for a data acquisition susyem.

Choice of System

The choice was a data log system called Innovate SSI-4. The SSI-4 has the ability to log four different sensors, including RPM. It also has the provision to log lambda as an external serial input therby creating a log system of 4 analog inputs and 1 serial. The serial schematic setup is depicted in figure (5)

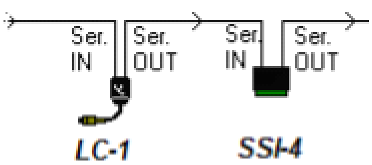

Figure 5. Schematic of logging equipment setup and connections

The analog setup is depicted in figure (6)

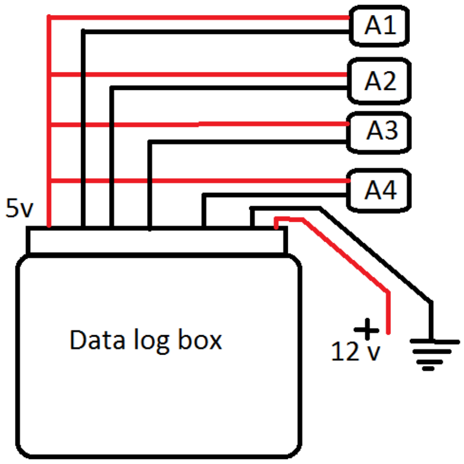

Figure 6 Analog setup of SSI4 logging boxdriven by 12V and measurement signal from 0-5V

Sensors

The sensor setup for the log-system was chosen to log the ambient conditions and the engine conditions in parts. The ambient conditions are interesting as a change in ambient temperature and pressure will act as an external disturbance to the system. In this case the ambient temperature is the most interesting as the ambient temperature has the biggest range of change and will have an important effect on the engine operation. The barometric condition was evaluated as low range because of the local height over the sea at Stockholm and London (race location) differs very little. Further, in the test cell, the ambient temperature may vary a lot during operation because of the heat from the engine itself. This means that during operation the temperature may affect the intake air density between runs, and thus affect the air fuel ratio.

The internal log options were chosen as follows:

- Lambda (serial)
- Engine oil temp (analog)
- Exhaust temp (analog)
- Engine speed (analog frequency)

The lambda is the most important factor for this as it tells the air fuel ratio and thus gives the most information of the actual condition of the engine. Further theengine oil temp has an important effect on cold running conditions. The exhaust temperature is mainly interesting as a measure to reduce fail risk and is reflective of combustion efficiency. The engine speed is chosen mainly because it will inform the test rig engineer where the operation point of the engine was during each point in time.

This will be described in greater detail under the Engine Control Unit section of this paper.

Hardware

System Requirements for E100

One of the primary tasks was to understand the needs of an E100 engine and to evaluate the possibility to use the existing engine setup for the task. The previous team had procured 3 engines wherein one was a spare, one was modified and the third mounted on the vehicle in 'ready-to-drive' condition. The modified engine was disassembled for studying the engine construction and feasibility for design modification.

Typically the requirements for a gasoline engine when converted to run on pure ethanol (E100) are:

- High compression ratio (~13:1)
- Turbocharging/boosting
- Direct injection system
- Ignition timing control

The following references are recommended for pure ethanol engine design (2) and gasoline engine modification for E100 (3).

While 'turbocharging' and direct injection are prohibited by the rules in the current edition of the competition, increasing the compression ratio and enabling ignition timing control were considered possible to execute and were included in the ICE group deliverables.

Engine Choice

Inspection of engine used 2015

The engine that was chosen and used by the internal combustion team Elba 2015 was the Honda GXV57. It was inspected and its features were documented in an early stage to decide whether to use the same type of engine again or whether to seek for another type. The Honda GXV57 is a 57 cc single cylinder engine with over-head valves. One significant disadvantage with this engine was its vertical shaft as this resulted in the use of a bevel gear. The bevel gear did not only reduce the overall efficiency, it also broke repeatedly. It was thought to be the torque peaks and vibrations from the engine that the bevel gear could not handle.

Since the bevel gear had caused many problems for the previous year's team, the idea of mounting the engine so that its output shaft would be horizontal was evaluated. The problem with such an action would be the risk of too little lubrication to the different components in contact, especially the piston rings sliding against the cylinder wall. It was found that the engine has a plastic gear that splashes oil inside it. This can be seen in figure 7. It would not function properly if the engine was to be tilted and an external oil pump would then probably be the best option for guaranteeing proper lubrication.

Figure 7. Plastic gear for oil splash lubrication inside the engine

The over-head valves are positioned vertically into the combustion chamber which can be seen in figure 8. This was regarded as a limitation as trying different injection angles for possible gain in efficiency would be difficult. Further, the cylinder head and the engine block was cast as one piece. This reduces the possibilities for increasing the compression ratio through shaving off the cylinder head and generally limits modifications of the cylinder head.

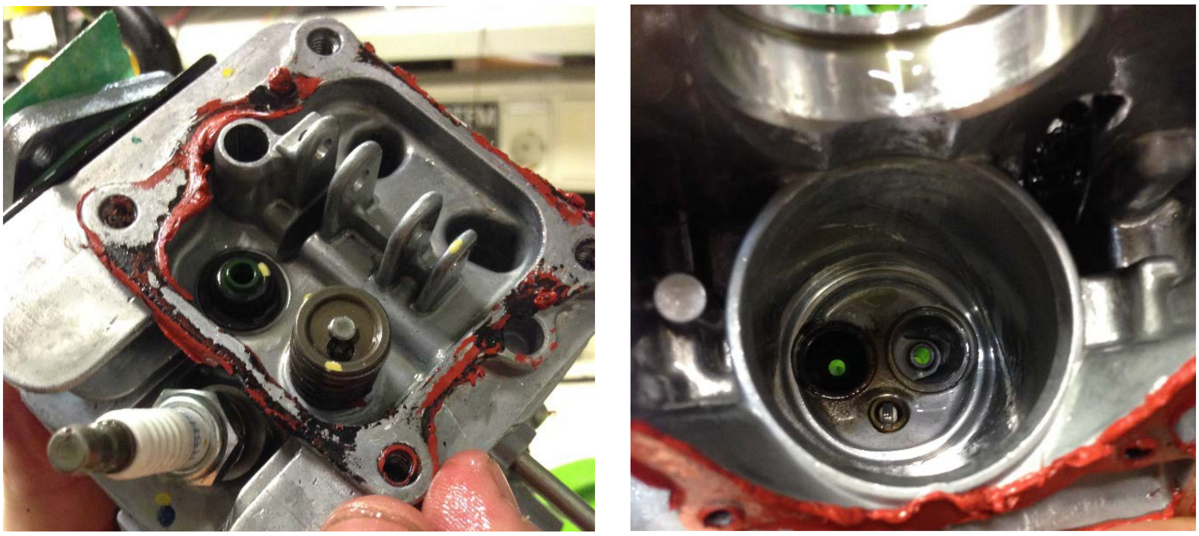

Figure 8. Valve position in the cylinder head of the Honda GXV 57

To increase the compression ratio, last year's team tried increasing the height of the piston through welding which turned out to be difficult without getting porosities in the welded material. They also tried manufacturing longer connecting rods but did not have sufficient time for verifying if the outcome was an improvement. However, it was found during the disassembling that one of the bolts connecting the connecting rod to the crank shaft was in contact with the crank shafts sliding surface which is not favourable for durability. It was therefore clear that increasing the compression ratio can be complicated and aiming for simplifying the possibilities was a priority.

The engine uses push rods with rocker arms for opening the valves wherein the push rods are pushed by one plastic cam lobe. This is also a limitation for changing the timing of the engine.

The drawbacks with the old engine are listed below as a result of what was found during the inspection:

- Low compression ratio
    - The GXV 57 has a compression ratio of 8:1 (4)
    - Previous team had tried to make mechanical modifications to increase the compression ratio (such as increasing the piston crown height by welding) and increasing connecting rod length but these techniques did not bear fruit
    - The engine had a single plastic cam lobe and the valves were pushrod actuated making valve timing modification a challenge
- Fixed ignition timing
    - The engine had a TCI ignition system with fixed timing
    - The previous team did not develop a timing control unit which is essential for E100
- Engine mounting and drive
    - The engine had a vertical driveshaft which necessitated a bevel gear leading to additional losses and increased weight
    - The engine mounting bracket was complicated and large thereby adding to the overall vehicle weight
    - Engine damping was considered ineffective
- Unibody construction
    - The GXV 57 had an inseparable cylinder head and block rendering compression ratio modifications difficult

After completing the evaluation of the GXV 57 and the needs of E100, it was decided that a new engine would be chosen. The major criteria for new engine selection were:

- Naturally high geometric compression ratio
- Horizontal driveshaft
- Modifiable and availability of spare parts
- Modern engine construction
    - Fuel injected
    - Overhead camshaft
    - Force feed lubrication for mounting flexibility
    - Match torque output of optimized GXV 57
    - Ignition control capability

Based on the selection criteria, the following engines were shortlisted:

Engine	Fuel System	Compression Ratio	Peak Torque, Nm	Horizontal Driveshaft
Yamaha Neo's 4	Fuel Injected	12:1	3.15 @7000rpm	Yes
Honda NSC 50	Fuel Injected	10:1	3.53 @7000rpm	Yes
Honda GXH 50	Carbureted	8:1	2.7 @4500rpm	Yes
Honda GX 25	Carbureted	8:1	1 @5000rpm	Yes
Viarelli GY6	Carbureted	10.3:1	2.8 @7500rpm	Yes

The technical specifications of the listed engines may be referred from (5), (6), (7), (8) and (9).

While the Yamaha Neo's 4 and Honda NSC 50 engines were the most advanced and favored, due to sourcing issues we decided on the Viarelli GY6 which is a Honda based 50cc motor design from the 1980s.

Although this motor is dated, it provided a good match to our new engine criteria and since price, sourcing and spare parts were not an issue we decided on the GY6. 3 motors were ordered along with a set of spare parts which included the cylinder head with valve train, performance camshaft, crankshaft with connecting rod, head and exhaust gaskets and piston with pin and rings.

To summarize the strong points of the GY6:

- High natural compression ratio
- Separate head and block construction which enables further compression ratio increase
- Overhead camshaft provides opportunity for valve timing and lift modifications
- Forced feed lubrication (gerotor pump) provides engine mounting inclination flexibility
- Easy to source engines and spares from within Sweden

GY6 Engine Construction

Upon receiving the new engines, one engine was disassembled for a construction study and considerations required for mounting the engine on the test rig, on the vehicle and the drive sprocket mount on the crankshaft were evaluated.

The GY6 is a moped engine and hence the engine body is cast along with the swingarm which houses the CVT. The first step was to separate the transmission portion which was not of interest for the project. The engine was available with a starter motor and after discussing with the mechatronics group, it was decided not to use the starter motor as it would be redundant. Engine cranking would be performed by the big BLDC motor as was in the previous year.

The engine had a simple construction with 2 over head valves which were rocker driven by an overhead camshaft.

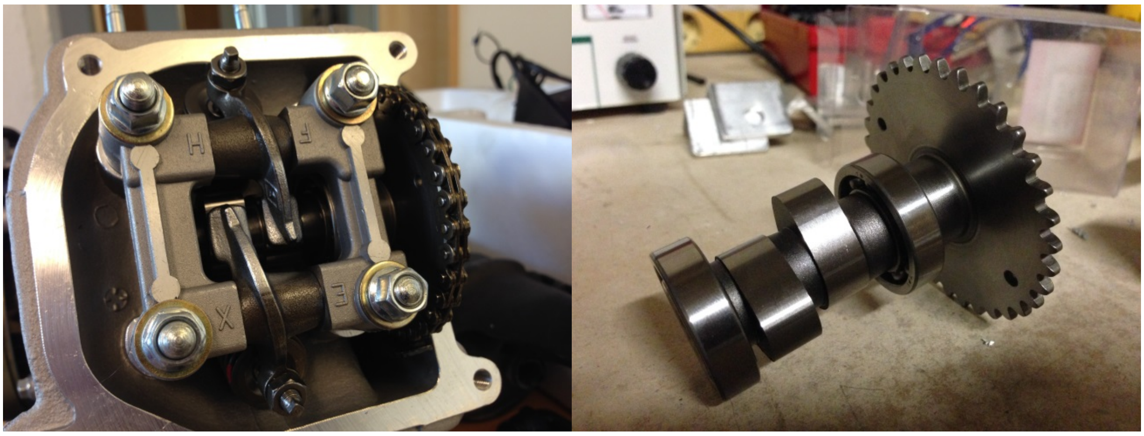

Figure 9. Valve rockers and performance camshaft of the GY6

The valve timing and maximum lift were studied. The maximum lift of both the valves was 4.5mm. The valve timing is given as follows:

Intake		Exhaust		Overlap
IVO	16.97° BTDC	**EVO**	16.28° BBDC	66.26°
IVC	50.65° ABDC	**EVC**	49.29° ATDC	
Duration	247.6°	**Duration**	245.6°	

BTDC-before top dead center

ATDC-after top dead center

BBDC-before bottom dead center

ABDC-after bottom dead center

It is observable from the camshaft that the lobes are identical and hence the valve timings too must be identical. The deviation in timings can be attributed to error in measurement.

The engine has a HEMI combustion chamber with a curved piston crown. The rings are standard 3 piece set with two compression rings and one 3 piece oil control ring. The connecting rod is unibody with a semi-floating piston pin.

The cylinder head and block portions were separable and measurements were made for determining maximum thickness that could be removed in order to increase the compression ratio from 10.3:1 towards 13:1 while considering the dynamic valve-piston clearances. Paper impressions were used to approximate the clearance volume.

Intake and Fuel system

The intention was to use the same fuel injector that was used the previous year; the injector of the Honda Zoomer. The previous team did not have any problems with the injector and since our application is similar, the fuel injector was thought to be suitable despite the change of fuel. The advantages of using an injector is that the volume of injected fuel per cycle can be controlled by changing the injection time duration. Also, the injection timing, at a certain crankshaft position, can be controlled. These two parameters are useful for improving efficiency as fuel and air mixing can be improved and the lambda value can be kept at a set value in real time. The injector together with the previous year's injector mount can be seen in figure 10.

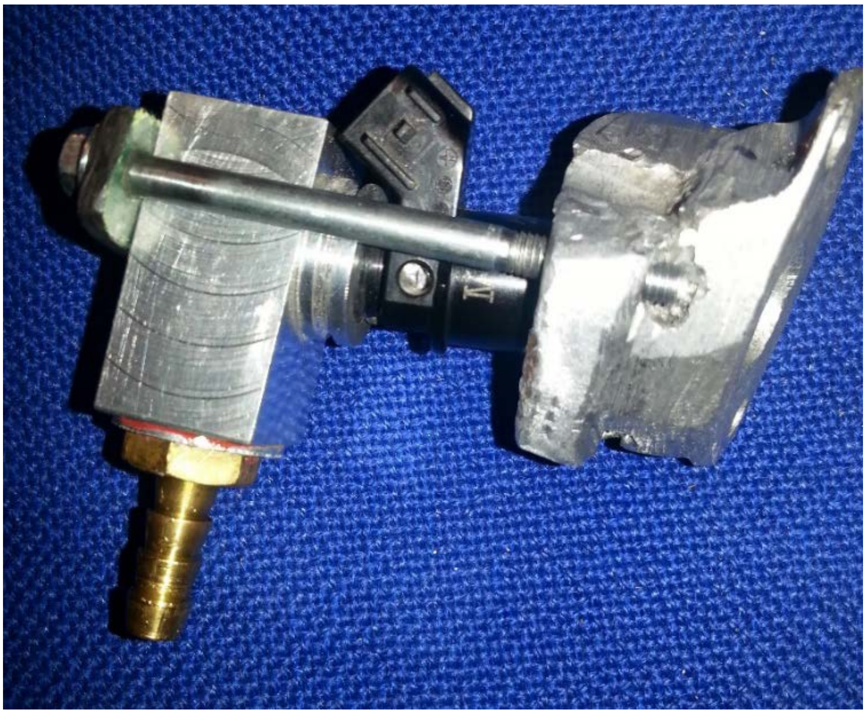

Figure 10. Honda Zoomer injector used by the previous team coupled to a handmade intake manifold.

However, as a first step the original carburettor was used for running-in and mapping of the engine in the test rig. The carburettor gave a few problems in the beginning. At first, the fuel tank was situated at a lower level to the ground compared to the carburettor and was therefore pressurised for the fuel to flow into it. Even though low pressures were used, the carburettor flooded. The fuel tank was therefore moved to a higher level to avoid this problem after a number of different attempts with lower pressures. Further, the air/fuel-ratio can be adjusted on the carburettor and it was found that the ordered ones were not pre-set by the manufacturer. Therefore adjusting the carburettor is recommended to make sure it was working properly.

At first a simple mechanism was built to enable throttle opening at five different positions for an initial mapping and testing of the engine in the test cell. The toolbox in Matlab that was used for setting up the engine tests for mapping of the engine required more precision of the throttle positions and therefore a more precise mechanism was built for that purpose.

An interface was welded together to enable mounting the injector and throttle body to the intake of the cylinder head. This can be seen in figure 10. Further, the flow rate of the injector was also measured using gasoline to verify that the flow rate would be enough. The fuel line was pressurized up to 3 bar (max. allowed pressure) and the injector opened. The time it took to inject 100 ml of fuel was measured and that yielded a flow rate of 36 cc/min which would be sufficient for 3.66 hp at the crankshaft output according to (10).

ongoing work involves mounting the injector onto the engine to test it together with the new ECU. The next step is to fabricate a throttle body and then mount it together with the injector. According to the competition rules, the engine has to have an idle mode which necessitates THE presence of a throttle body. The intention is that the throttle shall have two states, fully open and idle.

Exhaust System

An exhaust system was built from existing piping at ITRL. A complete engine of the same kind (GY-6) was found in the storage room and the exhaust pipe was taken from there. The muffler was removed and the pipe was cut down to a desired length after which mounts for the lambda sensor and the temperature sensor were welded on.

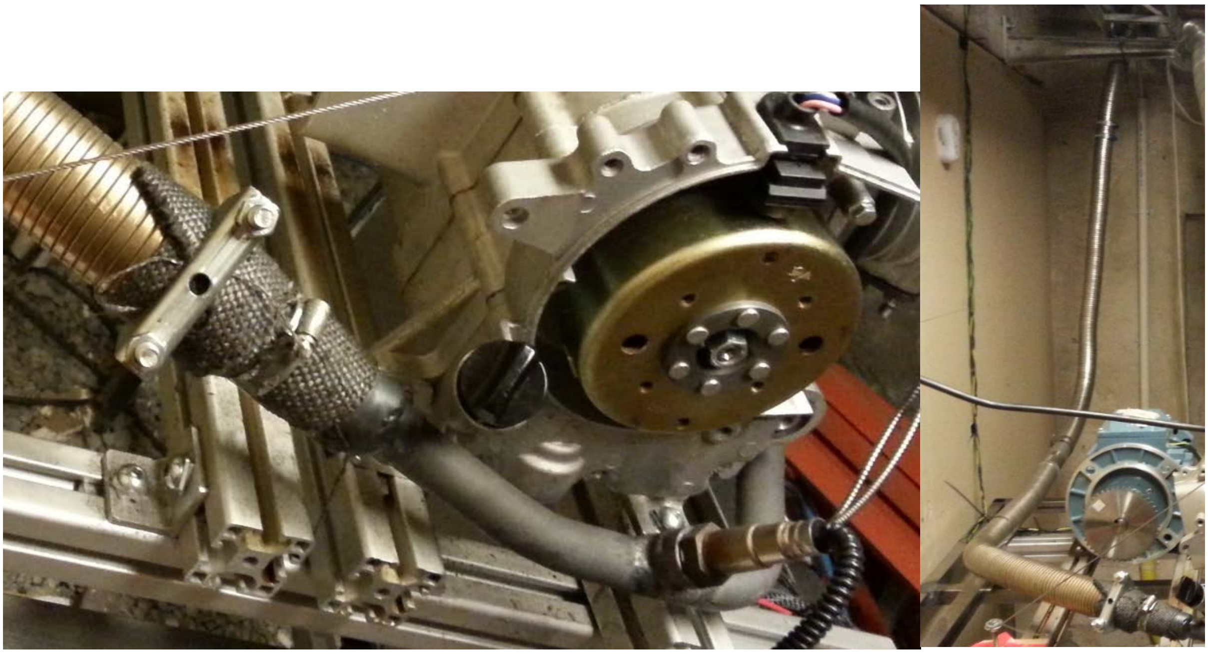

Figure 11. Exhaust system setup on test rig. An interface was welded on the exhaust to fit into the flex pipe. The interface was insulated with fire resistant blanket and hose clamps. The flex pipe leads to the outside of the building through a hole

To evacuate the exhaust gases from the test cell, the piping and exhaust fan from last year were used. The fan did not work efficiently enough and the CO sensor in the test cell went off repeatedly. This lead to a big headache (literally). A solution needed to be found quickly to this problem and it was decided to insulate the exhaust better and lead it all the way to the exhaust vent of the building using flex pipes. This worked better and the final setup of the exhaust system can be seen in figure 11.

Encoder

An encoder was mounted on the engine via a belt and pulley assembly to enable crankshaft position monitoring. The encoder of the previous team, Yumo E6B2-CW3En was used with new pulleys that were ordered from Aratron in Solna. This was due to the avialable pulleys being too small to fit on the crankshaft and keep the same reduction, 2:1.

The two pulleys from last year had 20 teeth on the engine crankshaft and 40 teeth on the encoder respectively, but the new ones have 30 on the crankshaft and 60 on the encoder. The engine rotates twice for every rotation of the encoder. The encoder produces 1024 pulses/rotation plus an index pulse for every rotation which can be used for the TDC reference. It also produces a 90° out of phase pulse to determine the direction of rotation.

To mount the encoder onto the new engine a bracket was built from aluminum. The smaller pulley was bored out so that it could fit onto the 14 mm diameter crankshaft portion and a threaded hole was made through the pulley so that it could be fastened to the shaft. An adapter was made for the bigger sprocket since its 8 mm hole was too big for the 6 mm diameter axle on the adapter. The adapter was press fitted to the shaft so a screw was not necessary. To tension the belt, a hole was drilled on the bracket and then the bracket was mounted. The belt was tensioned to desired tension and a new hole was made on the bracket. The setup of the encoder can be seen in figure 12.

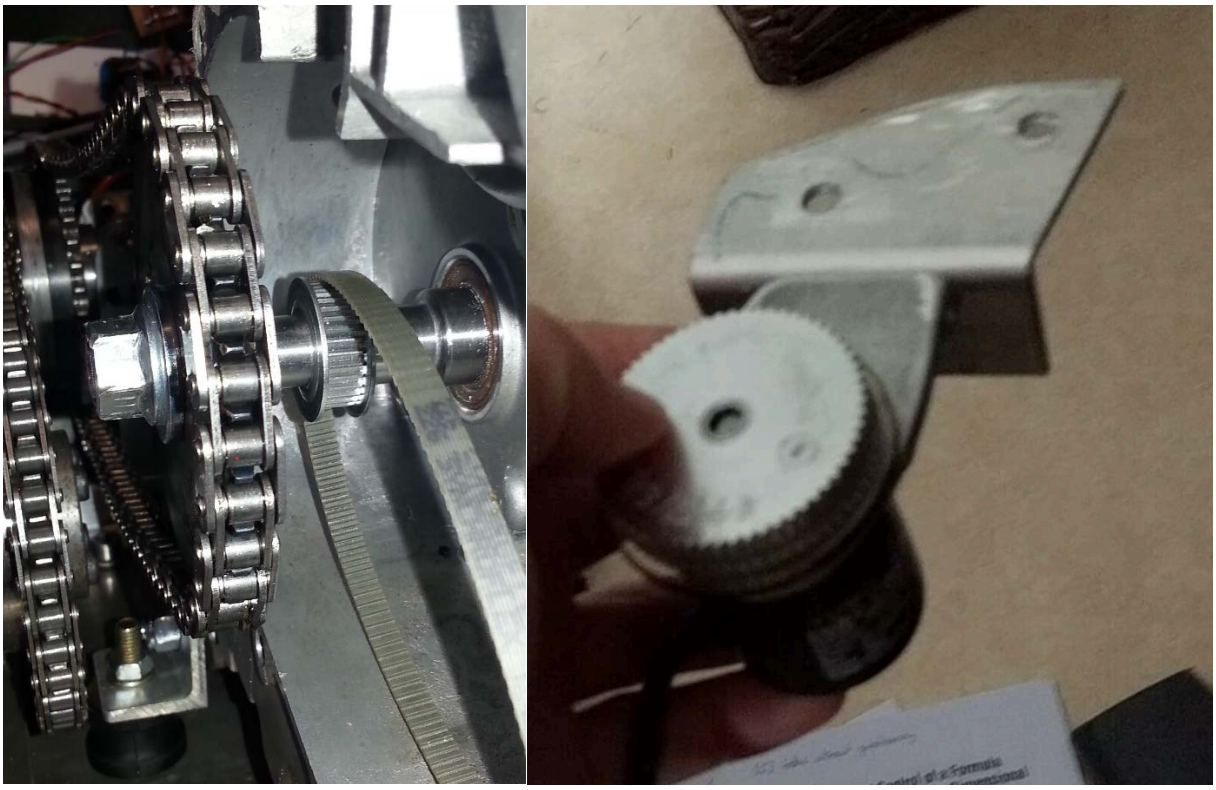

Figure 12. Encoder setup. To the left, pulley and belt mounted on crankshaft on the output side of engine. To the right, encoder mounted on bracket which was bolted on engine

Engine Drive Sprockets

To enable power transfer from the engine to the drivetrain in the car, a chain would be used to be able to use last year's drivetrain. For this to be possible a new sprocket needed to be fabricated since the interface between the previous engine and the new one with the drive sprocket was different. For simplicity and to keep the same gear ratio, an adapter was welded to the old sprocket as well as removing some extra material to save weight. This adapter was taken from the new engine since it had the same splines as on the crankshaft.

The same applies to the test rig, a new sprocket would have to be made in order to use last year's electric motor. An adapter was also made for that sprocket to maintain the same gear ratio. Both sprockets can be seen in figure 13.

 

Figure 13. Two sprockets made for the new engine. Left: Sprocket connecting ICE to electric motor on the test rig. Right: Sprocket connecting ICE to drivetrain in vehicle with chain

Compression Ratio

To increase the thermal efficiency of the combustion engine, the compression ratio was increased. The original compression ratio was 10.3:1. The goal of the modification was to have a compression ratio around 13:1 to utilize the knock resistance capability of ethanol and have good efficiency. To adjust the compression ratio, first the combustion chamber volume had to be calculated. With 50cc stroke volume, the calculation gives:

$$\frac{(50+x)}{x} = 10.3$$
$$50/9.3 = x = 5.37$$

Where *x* is the combustion chamber volume. To have a compression ratio above 13:1, the volume had to be reduced to

$$50 = x(13-1)$$
$$x = 4.16$$

To know how much the compression ratio could be increased, the combustion chamber was measured using wetted paper. It was possible to measure the piston-to-valve clearance. The measurement was done in cold conditions, and was about 2.5 mm. Based on this knowledge, the decision to reduce the deck height by 1 millimeter. With a bore of 39 mm, the compression ratio increased to

$$5.37 - \frac{3.9^2}{4}\pi \cdot 0.1 = 4.175$$
$$\frac{50}{4.175} + 1 = \varepsilon = 12.976 \simeq 13$$

where ε is the compression ratio. This means an increase in theoretical thermal efficiency of

$$1-\frac{1}{\varepsilon^{\gamma-1}}=\eta$$

$$\frac{\eta_2}{\eta_1}=\frac{1-\frac{1}{\varepsilon_2^{\gamma-1}}}{1-\frac{1}{\varepsilon_1^{\gamma-1}}}=1.057 => 5.7\%$$

From the standard compression ratiocompared to the old enginewith 9:1 compression ratio, the increase in thermal efficiency is 10.3 %, not regarding eventual difference in the combustion chamber form. Further, the reduced deck height decreases the squish height, pushing flow towards the center of the combustion chamber thereby creating turbulence and reducing end gases volume on the opposite side of the spark plug. This should further increase efficiency and is to be seen as an additional advantage.

Camshaft Modifications

The fact that the engine has an over-head cam shaft offers the possibility of changing the valve timing for improvements in efficiency and was therefore regarded as a significant advantage with the GY6. The option of modifying the profiles of the lobes of the cam shaft was therefore evaluated. For a company to professionally grind the cam shaft, much time is required and many parameters are needed including exact profile of the original shape of the shaft and the desired shape. The option of milling the lobes was not a possibility as the shaft has been hardened and might destroy the blades of the milling tool. Therefore, the workers at the production department did not want to offer their NC-mills for that purpose. A proposal for the next year's team is to evaluate the possibility of grinding the cam shaft at an early stage and contact a company with the right capability of grinding it. If enough time is available, changing the profiles is definitely possible and can give much gain in fuel efficiency.

Drivetrain, Engine Mounting and Operation Cycle

The existing drivetrain architecture which provided a parallel hybrid capability was retained. The engine mounting location was to be conserved and new engine mounts were developed which largely simplified the mounting approach. L-bracket mounts (figure 14) which were used from last year's test rig were carried over to the new rig and it was decided to use them for the engine as well.

The brackets have dramatically reduced the engine mount weight from the previous year and with the elimination of the bevel gear it can be said that the engine and mounts together have provided weight saving, although this has not been quantified. The dampers for this year are larger at 30mm diameter and 25mm thickness from the previous year with M8 bolts for fastening. The mounting on the vehicle side was enabled using helicoils on the baseplate.

For the operation cycle, a popular amongst participants in the EcoMarathon is the pulse and glide (10) otherwise known as the coast and burn technique. The merits and demerits of this strategy were discussed and the major limitation of the application of the strategy this year would be the varying elevation of the track. As previous races were performed on flat tracks, the application of the technique was straightforward. This is a simple yet effective strategy for fuel efficiency boost and could be considered in full or part to be implemented in the overall drive cycle depending on the track conditions.

Figure 14 New engine mounts and damper

Engine Control Unit

An ECU from the previous year was inherited with this project. This ECU was a closed loop PI-controller of lambda. The PI-controller utilizes the broadband lambda sensor for feedback and adjusts the injector opening time accordingly. The reference value in the inherited controller is taken from the CAN-bus, and is normally set in the back ECU, the master for the driveline. The ECU is based on an Arduino Duo with 32-mbit ARMm processor.

To be able to start the engine at cold conditions, this was not sufficient for our case. As the whole project had focus on the future, and to be able to hand over a product with the ability to modify and further develop, a focus was set to build a complete engine ECU with open and closed loop control of fuel, ignition timing as well as being robust, as the previous controller had problems with the injector opening when the signal was not given. At the time of writing, the work with the ECU is in progress.

PI Closed Loop Control

The PI-controller from last year will be kept as it had been working with good results according to last year's team. This also means that the Encoder input from last year's ECU will be reused. The encoder has a 2:1 rotation ratio, that is, the combustion engine rotates two rotations during one rotation of the encoder. Using z-phase as TDC marker and A-B phases as counters for the rotation, it is possible to directly determine the position for one 4-stroke cycle and thus control injector opening angle. The controller layout can be seen in figure 15. Notable is the reference value directly taken from CAN-bus. Further, a safety feature for voltage above 5 volts is introduced to save the processor during operation. This essentially means that the combustion engine will be shut off if the lambda controller would give a too high voltage. To avoid this, open loop is introduced.

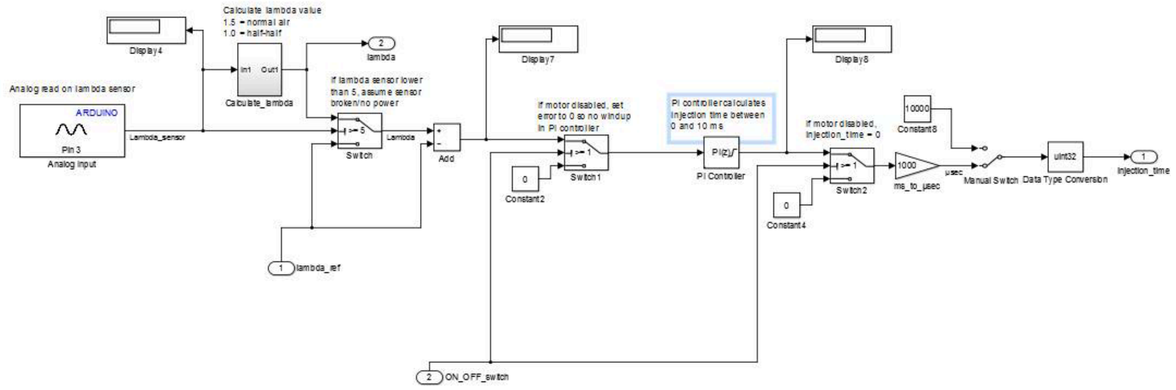

Figure 15 Model based programming is used for the ECU; this figure shows the basic setup for the PI-regulator controlling the fuel for the engine

Ignition Angle Control

One important factor for modification was controllable ignition angle. This feature makes it possible to increase the maximum efficiency of the engine further, as well as reduce ignition angle during operation if knock (detonation) occurs. To implement this feature, the code controlling the injector opening angle and opening time is utilized. The control of the ignition coil is very similar. Instead of opening time, the ignition coil is charged during “dwell time”. Dwell time is a function of the voltage over the coil. The coil functions as a transistor, i.e. the coil is fed with constant 12 volts and ground, and the base is grounded (Low) during the dwell time. When the coil is charged, the spark will jump over the electrodes at the spark plug.

As the control of the ignition coil is very similar to the injector with open loop ignition angle, but with open loop values of dwell time, the code could be reused with different outputs of the microcontroller.

The ignition coil that will be used in the project is a BREMI 11 856. Made for passenger cars it allows for high spark energy during operation. This results in the ability to use higher electrode distance in the spark plug, which is beneficial for lean combustion. The dwell time at 12 volts for the specific coil is 2.5 ms.

Figure 16 Picture of the ignition coil type

To control the spark angle, the ignition angle uses a 1-D look up table, with engine speed as input. The operation principal of the combustion engine is full load during operation, which means that other points of load other than full will not be reached. An exception is idle, but the reasoning is that the combustion engine will not be used for propulsion during idle rpm and only on full load. Thus, the 1-D ignition table is sufficient.

Open Loop Control

To be able to control the combustion engine during cold starts and lambda-malfunctioning, an open loop control was introduced. The open loop is determined by two parameters: ambient air conditions, and engine oil temperature. The ambient air is used as an input to adjust for air density during different conditions. The difference in air density is laid in as a compensation 1-D map, and is purely based on ideal gas-theory, as can be seen in figure (17), where the compensation values for different air temperatures is introduced:

Air Temp C -40 to 125	Fuel Comp % -90 to 500
-10	9
-5	8
0	6
10	3
15	2
20	0
25	-2
30	-3
35	-4
40	-6
50	-9
60	-12
70	-15
80	-18
90	-21
100	-24
110	-27
115	-28
116	-29
120	-30

Figure 17 Ambient air temperature based compensation for open loop control

To enhance the open loop control, one more compensation table is introduced, which enables the operator to map the engine during different engine temperatures, one 1-D compensation map for engine oil temperature is introduced. This makes it possible to adjust for cold start and warm up conditions. Further, an open loop 1-D map for injector opening time is introduced in the Simulink model for mapping of the open loop, with engine speed as input. It should be clear for the reader that this is where the main open loop mapping is done, the two aforementioned tables is strictly for compensation, to adjust for different conditions.

Both oil temperature and air temperature are Bosch NTC-circuit sensors, which is widely used in passenger cars.

Exhaust Temperature Input

Exhaust temperature is used as a mapping input for the operator. This is strictly an operator input to see what the exhaust temperature is during adjustment of fuel and ignition. Through this, it is possible for the operator to adjust fuel and timing to reduce the risk of hardware failure during operation. The exhaust temperature sensor is a K-type thermocouple with a serial amplifier. The exhaust temperature sensor is mounted 20 mm away from the exhaust port and is of the 3 mm type.

This input is one possibility for future work, as it gives one more control parameter to be introduced.

Idle Control Output

One idle input will be introduced in the ECU. This will control a solenoid of some sort to enable idle conditions for the ICE. In its first iteration, it will be an open loop solenoid. This is one area for future improvements, as closed loop idle is a big advantage for stable idle conditions.

Starting and Loading the Engine

Instruments

A 2.2 kW ABB induction motor is used to start and load the engine. The electric motor is regulated by a variable frequency drive which has 144 ohms of additional braking resistance to dump the energy generated by the ICE. The resistor bank has a capacity to dissipate 2.4 kW of energy which is sufficient for the engine in consideration. A Fluke scopemeter was used to measure the potential across the braking resistors.

Figure 18 Resistor banks, VFD controller and Fluke scopemeter used for power measurements

Starting the engine

To start the engine, the electric motor is used to crank the ICE to a speed of 1500 rpm which corresponds to a motor speed of 750 rpm (there is a gear reduction of 2 between the electric motor and the engine crank due to the sizes of the two sprockets). Since the electric motor is controlled by a variable frequency drive (VFD), a correlation between the speed of the motor and the input frequency was established which formed the basis for regulating the speed of the engine (the chart has been appended to this report). Corresponding to the crank speed, the frequency is around 13 Hz, at which the VFD is set and the engine motored.

A point to note when starting the engine using the VFD is that the braking resistors need to be disconnected so that the engine doesn't get loaded while trying to start, see figure 19. This is applicable if the engine is required to run in idle mode wherein it would stall if loaded. However, the engine will continue to operate so long as the motor is running but again this is not a recommended operating point for the engine. When the motor reaches the crank speed, the ignition is turned on and the engine firing commences. At times the engine required the throttle to be pulled to assist in the cranking. The moment the engine speed exceeds that of the motor controlled by the VFD, an error message would be displayed (when braking resistors are not connected) and supply to the motor would be cut. Under this condition, the engine will run at the no load condition and the electric motor does not have any power input from the VFD.

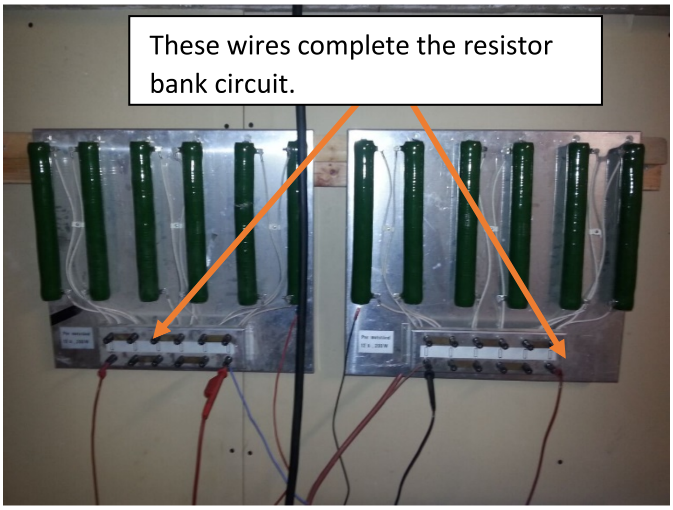

Figure 19 Resistor bank circuit

Loading the Engine

To load the engine, the braking resistor bank must be connected to the VFD to dissipate the generated energy. The principle behind loading the engine is that the VFD controls the electric motor speed and tends to reduce the engine speed from the no load condition (maximum speed at the given throttle position) to a lower value depending on the VFD setting (*Both the electric motor and the ICE run in the same direction, only the regulated speed of the motor would be lower than the engine*).

The electric motor is the dominant of the two and hence the engine speed is always dictated by the VFD of the motor. Hence while loading the ICE, the VFD is first set to run at a speed that is close to the no-load speed of the ICE. The speed of the ICE is then gradually decreased by lowering the frequency of the VFD using the potentiometer which consequently leads to loading the engine.

Taking the Measurements of The ICE Power

The potential is then measured across the ends of the resistor banks which is used to estimate the power generated by the ICE. The relation between the energy dissipated through the resistor banks and the power generated by the ICE is that the VFD routes any power generated by the ICE through the resistor banks and since the ICE is the only source of power, the potential across the resistor banks is a direct indication of the ICE power.

The power calculation is determined from the relation $P = V.I = \frac{V^2}{R}$, where V is the potential across the resistor bank and R is the total resistance of the resistor bank. Engine torque can be determined from the relation $T = \frac{60P}{2 * \pi * \mathrm{N}}$,where T is the engine torque, P is the engine power and N is the engine speed in rpm.

VFD Settings and Operation

The VFD has been pre-set in a ready to use condition. However, in the event a reset is required, the following settings need to be performed.

Brake resistor active setting: $06.00 \to 0$

Potentiometer frequency control: $02.00 \to 4$

Show total power: $00.04 \to 7$

To get familiar with VFD operations refer (12) and (13).

Scopemeter Settings

A Fluke scopemeter was used to measure the voltage across the resistor bank. To visualize the voltage reading, the following settings are required:

- Set Input to DC
- Set measurements to VAC+DC
- Perform correct scaling on voltage

Testing Procedure and Approach

Initial testing was performed to check that all installed test apparatus were functional, for instance the ignition kill switch, logging switch, logging channel connections, voltage readings across load bank and exhaust evacuation from test area.

To start with the testing a run-in cycle was prepared although testing difficulties made it hard to follow this cycle, 2 engines were run-in at part-load and low load conditions for an average of 4 hours. Initial testing was to obtain the engine power, torque and exhaust lambda value as responses. A provision was made for exhaust temperature measurement as well but it was not utilized due to the lack of an amplifier.

The testing process at the start was arduous due to exhaust gas leaks and insufficient suction from the exhaust vent fan which caused the entire test area to smoke up and trigger the CO alarm for most of the time. This was a critical health and safety issue for the ICE group members and personnel at ITRL and was hence attended to with priority. The solution was to provide a direct exhaust pipe connection rather than to relay the exhaust through the evacuation fan. Additionally, seals were mounted on the exhaust piping interfaces that were earlier susceptible to leaks. Following this the exhaust problem was largely solved.

The logging equipment had some connection issues which was resolved in a couple of days after understanding the circuit diagrams. Initial testing had some uncertainty on engine running condition due to non-sustaining run. This was later realized to be because of the constant loading of the engine even when it was set at idle condition which naturally caused it to stall. It is suggested that future teams read through the electrical loading section carefully as although it was not complicated, the intricacies were not explained at the start and hence the understanding was arrived at after reasonable time and effort.

Once the engine run-in was completed, the next task was extracting the base engine performance map. The idea was to use the model based calibration toolbox (MBC) of MATLAB to speed up the process through design of experiments (DoE) and data modeling.

The DoE used was a space-filling design which is a typical experimental design approach for cases where the response behavior is not clear. This was preferred as power-torque curves were not readily available for the GY6 and the manufacturer does not provide this information either.

A 50 point DoE was generated and after filtering physically non-feasible points, 47 test points were required to be tested.

There were numerous practical issues with the test setup which stalled test plans and delayed obtaining results. The carburetor proved to be very erratic in its runs with mixtures too rich or too lean. The carburetors from other engines were fitted to check on the possible defect of the original one but all the carburetors seemed to be performing the same way. Adjustment of the air-fuel ratio screw did not help either. Due to these limitations it was decided to attempt to retrieve the full throttle performance curve of the engine at the very least. While this run was being attempted, the drive chain broke loose and stalled the testing once again.

It was observed that the chain had heated up and the oil lubrication used was ineffective due to oil splash and the inability to retain the oil. It is recommended to have some spare chains and to use grease in place of oil. The chain was found to have mild abrasive wear around some rollers however, due to lack of time it was decided to fix the chain, oil soak it and use it again. There were also some misalignment issues between the engine and load motor which was rectified.

In total 34 test points partially from the DoE setup and from the full throttle attempt was logged. Limited data was now available until 60% throttle and remaining data points at 100% throttle opening.

While this is not conducive for accurate data modeling since it relies on interpolation techniques within the tested data points, to show the capability and have an idea of the application of the tool, a test data based representative map of the engine torque and lambda value was modeled.

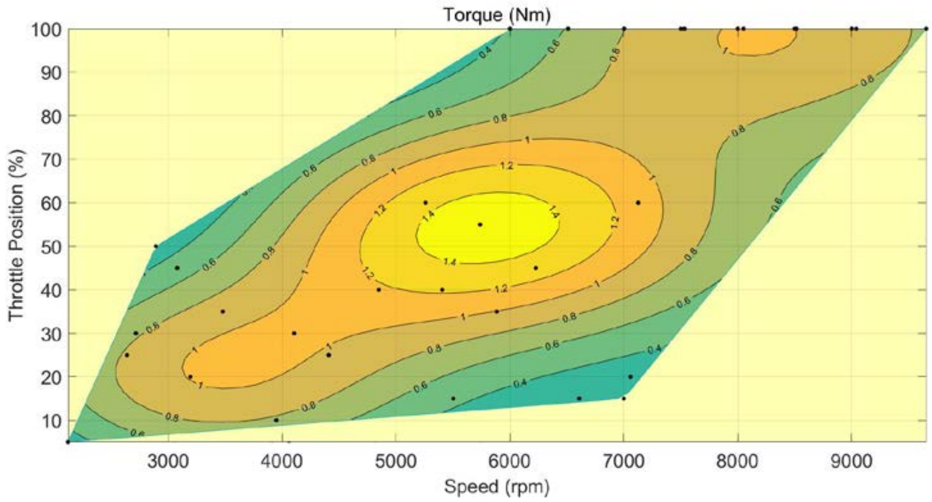

Figure 20 Torque as a function of throttle position and engine speed based on tests

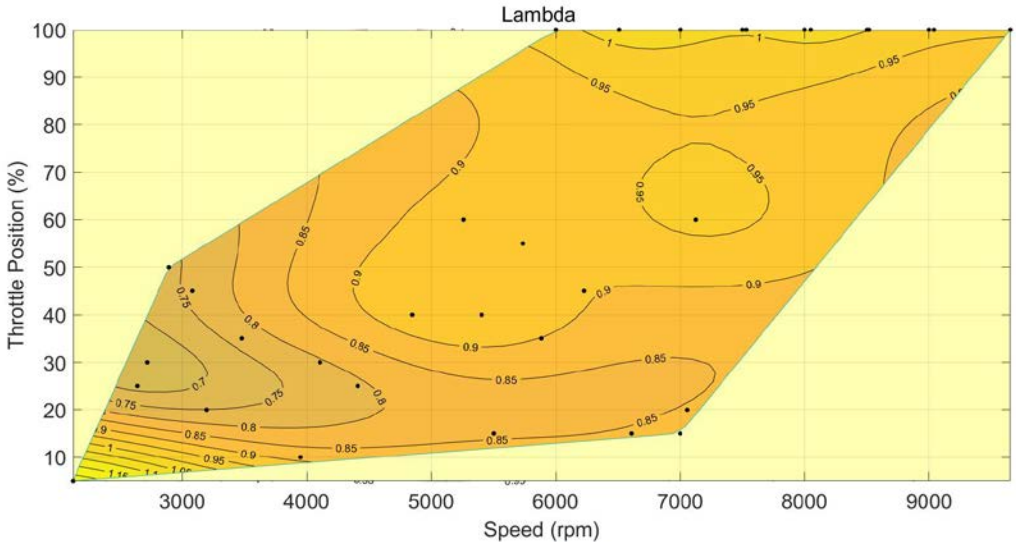

Figure 21 Lambda as a function speed and throttle position

It can be observed from the torque plot that the peak torque and power values are not achieved through the limited testing performed. This is attributed to the erratic carburetor behavior which varies from one carburetor to another and was inconsistent with air-fuel ratio screw adjustments and did not correct with the installation of an air filter. Since the engine ran extremely rich with the air filter, the tests were performed without an air filter.

Summary

The purpose of this project was to have a functional vehicle running on ethanol before the EcoMarathon competition and to optimize it for fuel efficiency. Since a decision was made to change fuel type for this year, last year's results needed to be reevaluated with that in mind. With last year's results and recommendations in mind, the ICE team decided to change the engine to delete the bevel gear and get an engine more suitable to run on Ethanol.

A decision was made to use a scooter engine, GY-6, after some extensive research due to its relatively high compression ratio, simple construction and availability of parts. As this report is written, the car is not fully functional. However, a functional engine test cell has been built which consumed much of the time of the project and tests on the new engine have been conducted. The next step before the competition is to implement a fuel supply system to run the engine on ethanol and make an engine map based on the new fuel and controls.

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