An Improved ECU for Extending the Lifespan of Fuel Injectors

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Abstract

The research paper presents the outcomes of an improved Electronic Control Unit (ECU) designed for automobiles equipped with Electronic Fuel Injection (EFI). The primary objective was to find a sustainable solution for various issues caused by decayed Petrol fuel injectors recommended to be replaced, but not done due to reasonable justifications. The issues include emissions produced by improper fuel combustion, wastage of fuel and possible damage to engine since incomplete combustion leave residual matter inside the engine's combustion chamber. The ideology is to control the excess fuel released by decayed fuel injectors by modifying the control instructions produced by the ECU. Experimental results have proven that employment of the improved ECU could reduce the emissions up to 84.9 % with an average of 75.8% and most excitingly, the improved ECU is capable to renounce the fuel wastage caused by decayed injectors by a percentage over 70 %.

Keywords: EFI, ECU, Fuel Injector, Injector Pulse Width1 Introduction

Introduction

Having faith in a computer to accomplish vital functions performed at any complicated machine has become an emerging trend during the recent decades. The phenomenon is hardly exceptional for the context of automobiles, even in late 1960s. The literature witnesses that Volvo and Volkswagen have started their mass production of Electronic Fuel Injection (EFI) equipped automobiles based on Bosch D Jetronic analog systems in the late 1960s and early 1970s. By the beginning of decade 1980s, BMW and the leading Japanese manufacturers Nissan and Toyota have also developed the interest towards the computer-master control systems. Today, almost all the vehicle manufacturers prefer computerized systems to manipulate most of the functions carried out in an engine including the fuel control and valve timing.

According to the records of history, the emission regulations introduced in mid '70s and the energy crisis experienced in the same time span has contributed a significant influence for switching to EFI replacing the conventional carburetor based systems. This indirectly implies that computer assisted systems are better systems in perspective of efficiency in fuel consumption and environment friendliness with minimized emissions.

The EFI technology has undergone several stages of its evolution. As a result, fuel control technologies such as SEFI (Sequential Electronic Fuel Injection), MPFI (Multi Point Fuel Injection) and GDI (Gasoline Direct Injection) have been introduced time to time. None of these technologies have outdated, having their unique advantages and disadvantages. For example, according to the user's experience, SEFI (Sequential Electronic Fuel Injection which fires each injector separately gives slightly better fuel mileage and less emission at lower RPMs compared to MPFI, but automobile engineers prefer MPFI as a better technology due to various reasons.

Once any computer controlled fuel injection technology is accompanied with other engine technologies such as Variable Valve Timing (VVT) or continuous variable cam phasing, tuned/Multi-path or Variable Length Intake Manifolding (VLIM or VIM), Exhaust Gas Recirculation (EGR), better results are obtained. For examples, engines empowered with Toyota's VVTi technology (Variable Valve Timing with intelligence) or DVVT (Dynamic Variable Valve Timing) by Daihatsu / Perodua are well known for lesser fuel consumption.

The research is focused on an issue allied with Gasoline (petrol) fuel injectors. The problem encountered with these injectors is, once they are decayed, they release excess amount of fuel than the required to have a complete internal combustion. As a result, fuel consumption will go unreasonably high and emissions such as partially burnt HC (hydrocarbons), toxic gases such as CO (Carbon Monoxide), NOx (mono-nitrogen oxides) will be released to the atmosphere in inexcusable amounts. Although the EFI system manipulated by ECU is incorporated with a feedback mechanism in a closed loop in order to regulate these excess fuel release and emissions, it was noticed that when decayed injectors are employed, the system is losing its tolerance. This can be further explained as follows: a sensor named as oxygen sensor (Lambda sensor in industrial terminology) is placed in exhaust manifold to measure the proportion of oxygen (O2) in the exhaust gas (after combustion), enabling the ECU computer to determine whether the air plus fuel ratio (vary between 14.7 to 1) is too rich or too lean for optimum combustion, if not plan the next successive injections to reduce the effect accordingly. These oxygen sensors are expecting the injectors to release a proportionate amount of fuel according to the Injector Pulse (a Pulse Width Modulation) determined by the ECU considering multiple input parameters (from different sensors - explained later) including the feedback. But once injectors are decayed, they tend to release more fuel than estimated to be released at a particular energizing (An injector is an electro mechanical device comprised of solenoid coil, when energized, the solenoid core is pulled back allowing the compressed fuel around 40 psi to spray out). With the feedback control, the system attempts to regulate the situation, but not always effective, because the Lambda sensor may operate beyond its limitations. This where an improved ECU is necessary with better feedback based control system.

Then it is obvious to raise the question 'why not replace the injectors?'. In this context, automobile mechanics have various justifications for not doing so. The first acceptable reason is difficulty of finding an appropriate injector for replacement from the local spare parts market even for some widely used Japanese vehicle models. For example, the Nissan FB 14. And for some rare vehicle models, compatible brand-new fuel injectors are totally unavailable. It is realized that the entire vehicle cannot be removed due to unavailability of a part of it. The next reason pointed out by the mechanics is the cost. It was studied that the average cost for a Fuel Injector Replacement with quality injectors may vary between $231 and $342 (26,000 LKR to 48,000 LKR). Most of the time vehicle owners are reluctant to replace brand-new injectors due to high cost and both mechanics and vehicle owners are therefore used to satisfy only with injector cleaning (in deed it is a recommended remedy) and a process called 'EFI Tuning' rather than replacement because even a decayed injector may still functioning properly (the electro mechanical function) after cleaning other than releasing fuel in little amount of more than required. In other words, if excess fuel consumption and emission issues are discarded, still it is usable device.

It is worth to mention that most vehicle owners and even mechanics believe that the ECU can be re-programmed during the EFI-Tune Up sessions suiting for the decayed injectors, but it was studied that it is not allowed by the manufacturers. That means the ECU only concerns and trusts the Lambda sensor (the emission control is already automated within itself, therefore no re-calibration of sensors is required in most of the occurrences), other external instructions attempting changing the program code will be either neglected or may damage the system. What actually happening at the EFI Tune Up sessions is scanning the engine in order to identify the faulty sensor modules those need to be calibrated or totally replaced. For example, if the injectors are in good condition (in deed they can be cleaned for better performance) and noticed that there is an abnormal fuel consumption or emissions found in exhaust gas in excess quantities, probably the scanner will figure out that the Lambda sensor is malfunctioning and recommended to be replaced.

If the mechanics really wants to exceed the limitations, that is actually violating the vehicle manufacturer's recommendations and proceed to modify the Injector Pulse Width, need to modify the EFI circuit by adding components such as resistors in between the sensors and the ECU or even internal modifications need to done. A variable resistor is used to determine the appropriate value of the resister to be added to the circuit by following the trial and error method.

This implies the EFI Tune Up process happening in local context seems to be not a computerized procedure in all the times, sometimes a hardware modification. That means it is a much difficult and even a risky task for the mechanics. In addition to risk of damaging the sensitive electronic components or computer elements while modifying the circuit, some sensor readings may be ambiguous for the computers in some extreme conditions since the operating ranges are shifted or off-set values are being forcefully added. Things will work fine for most cases, but some complicated calculations will be undergone in some extra ordinary situations may be confusing due to invalid input values or ranges specified by the sensors. For example, in some occurrences, the average fuel consumption calculated by Toyota Aqua is 99.9 Km per Liter, which not a realistic feature. those are stochastic (un predictable) in behavior and the probability of occurring such unacceptable results may be elevated by such unrecompensed modifications without proper long-term studies of after-effects and entirely carried out on trial and error methods.

The improved ECU developed by us is facilitated with easy re-programmability with any ordinary computer or Windows tablet PC via the USB interface. Even it is not necessary always, since control buttons are embedded on-board to the device and adjustments can be done with comparatively lesser effort according to the readings of exhaust gas analyzer. Then the vehicle can be prepared for the emission test with confidence.

Related Work

Similar research ongoing or already done regarding decayed injector were extremely rare to found and almost none. A possible reason for the situation may be re-using decayed injectors is not a recommended procedure by the manufacturers. And the problem of difficulty or unavailability of appropriate injectors for some vehicle models may be specific to the local context. Nevertheless, the concerns need to be taken to account when designing a new ECU were studied.

Such a research conducted by a group of Japanese researchers and electronic engineers representing FUJITSU TEN TECH., who are developing power train (Power-train control module caries the similar meaning of the ECU for automobiles, the term is adopted by the manufacturers Ford and GM. Other synonyms used for ECU by different vendors are, Injection control unit by Peugeot, Citroen, Fiat, Alfa and Lancia, DME or DDE: Digital Motor Electronics or Digital Diesel Electronics by BMW and Mini Minor, ECM: Engine control module.) ECUs for leading automobile manufacturers including Toyota Motor Corporation and SRM 2000, led by Norimitsu Yukumatsu (Yukumatsu, 2001) reveals the fact that, though ECUs were Initially developed for emission control, but many advanced functions are expected from recently developed ECUs, such as fuel injection, ignition timing, transmission, and electronic throttle control. They further mention that heat dissipation is a major problem encountered with a typical ECU in long-run, need to be taken very serious in attention, otherwise the operating voltages may deviate from there precise values due to semiconductor effects. And they do recommend using special software for inspections such as an actual-vehicle simulator – CRAMAS (ComputeR-Aided Multi-Analysis System). In addition, utilizing efficient Real Time Operating Systems (RTOS) that complies with ITRON (ITRON is a Japanese open standard for a real-time operating system) specifications to be specifically designed for ECUs rather than generic purpose RTOS.
A group of researchers employed for a corporate research facilitated by University of Zilina, Silesian University of Technology and Lublin University of Technology, Poland, led by Milan Sebok (Sebok, 2015) have done an interesting study on measurement of the gasoline engines injection system. They have done a deep study on the construction and operation of a typical fuel injection system and analyzed its building blocks (electronic part). They also proposed method for the detection of the injector malfunction, relying on the analysis of differential current characteristic those they have studied. They have noticed that the rising current curve for injectors must be partially different from the curve of an ideal inductor current due to forces act upon an active injector core, caused by friction, spring tension and fuel pressure. Furthermore, the injector opening time is related with the current characteristics while the closing time relates with the voltage characteristics. They finding were extended to the followings: The time required to open the 12 – 16 Ω injector is approximately 1.5 ms. This time is a function of the fuel pressure, injector spring force, inertial core properties, electromagnetic coil, core and injector material. The time required to close the injector is only half of the opening time. Closing of an injector is done by the spring attached and the fuel pressure, no electricity involved. According to our perspective, outcomes of their study are a perfect guide to synthesis of an effective Injector pulse.

F. Ommi and his research colleagues representing the Tarbiat Modares University, Tehran, Iran and the Iranian Space Agency (Ommi, 2008), discovers the fact that, the liquid fuel reach the end of the port after the intake valve is opened and it takes approximately 4.5 ms to reach the cylinder after intake valve opening at 2600 rpm. They emphasize that the structures of the injector has a significant influence on fuel plus air mixture preparation procedure and eminently affects the subsequent internal combustion characteristics varying on a wide range of operating conditions in port-injection gasoline engines. The other important variables those impact on an efficient fuel injection are the fuel temperature, fuel injection pressure and the model of fuel spray model. The fuel spray model is a mathematical model involving many parameters and may be simulated with software artifacts in a laboratory. A basic fuel spray model will predicts fuel evaporation in engine cylinders while a comprehensive fuel spray model incorporates with predicting liquid fuel spray motion and evaporation in a detailed manner.

An Indian group of researchers including Avinash Kumar Agarwal from Engine Research Laboratory, Indian Institute of Technology have also done recent study on crucial factors of designing EFI engines for locomotive engines (Agarwal, 2011). They support to emphasize that electronic fuel injection systems offer colossal flexibility to the complicated process of fuel injection while concerning about the emission control. They have listed the advantages of involvement of ECUs for fuel injection as: digital setting of parameters, precise and dynamic control of injection timings and injection duration, elimination of mechanical hardware, online fault diagnostics, optimized fuel injection for each cylinder and every determine the operating point considering the load and speed conditions, possibility of cut-off of fuel to individual cylinders, and protection of engine against modular malfunctioning. What they have noted regarding the injector pulse that may be useful for our research is, retarding the fuel injection timing with EFI pump leads to lengthy injection pulse width hence increases the total hydrocarbons (THCs) in exhaust and also upsurges the exhaust temperatures due to after-burning of hydrocarbons. They do recommend to increase the mean effective injection pressure (MEIP) of the EFI pump if expected to reduce the emissions such THCs, further.

Jonathan A. DeCastro mentions in his master’s thesis (DeCastro, 2003) supervised by the Virginia University that, lean, premixed, pre-vaporized injections may be best for the reduction in emissions, but may cause stabilization problems such as flashback or auto-ignition due to use of disproportionately high pressures. They have studied that a phase-shifting controller is applicable to implement a better closed-loop control of the system. The idea of using a phase-shifting controller is really impressing since we were keener in alternative switching control techniques for custom developed ECUs. A group of researchers from MIT including J.P. Hathout (Hathout, 2000) who have developed a model-based control system for studying the combustion instabilities of fuel injection state that, such a study may comprised of the deeper levels of physics such as acoustics, the heat-release dynamics, their coupling, and the injection dynamics. They reveal that the control signals to be sent to fuel injectors relies on diverse parameters, especially the type of fuel injector. For example, a pulsating of a Proportional Injector cause oscillations in the mass-flow rate in response to a voltage input, then the mass-flow rate will be proportionate to the input voltage while a Two-Position (on-off) fuel injector will behave differently in following injection dynamics. These two different types of injectors maintain their uniqueness in attributes related to injection dynamics and appropriate for specific cases. For some instances, a low bandwidth proportional injector is capable of keeping the system with quite low pressure perturbations, where a two-position injector may not suit.

Another issue they have observed with two-position injector was the effect of bandwidth limit. For example, once it exceeds 50 Hz, the injector was incapable of tracking the command from the controller and tend to stay opened all the time. Since we are supposed to cope with Two-Position (on-off) fuel injectors, the study was relevant and worth to know the limitations of Two-Position injectors.

Another group of researchers representing the National Engineering Laboratory for Automotive Electronic Control Technology, China (Cunlei, 2014) has done a recent study on relevant domain, focusing on how to overcome the fuel wetting effect of PFI (Port Fuel Injection) engine. One of their key findings relevant to our study is that, most emissions are generated at cold start and transients. According to them, the short-term transient fuel (STF) caused by sudden throttle change, while the function of long-term transient fuel (LTF) is reimbursed by manifold air pressure fluctuation.

All the above studies figure out the prominence of accompanying a research to instrument an improved ECU to address various disputes amalgamated with fuel injectors. And it is obvious to realize the gravity of the study, it is a real challenging task since many concerns need to be taken in to account beforehand moving to the phase of implementation.

Methodology

Beforehand understanding the development strategy, the fundamental knowledge regarding the Electronic Fuel Injection systems may require. The following section is to satisfy that requirement.

The Basic EFI Theory

A typical EFI computer, known as ECU obtains six (06) inputs to determine its ultimate output, the injector pulse for injectors. Most ECUs synthesis an injection pulse based on every tach pulse especially when the rpm is increased, the frequency of injection pulses is also need to be increased.

The first input is the rpm (revolutions per minute) of the engine. This is obtained from the gearbox of the vehicle. A primary input to determine the injector pulse, has a strong dependency.

The second is the Airflow or the Manifold Pressure. There are two major types of sensors depending upon the methods used for measuring the Airflow known as Mass Airflow and Speed Density. Mass airflow type systems monitors the opening of throttle affected by the rpm to determine the airflow. Sensors using this method are installed on the engine's air intake system and abbreviated as MAF (Mass AirFlow sensor). In industrial terminology, the same sensor is known as the 'Hot-wire sensor' because a heated wire is employed to generate the electrical signal. The other type of sensors named as MAP (Manifold Absolute Pressure sensor) use the theory of speed density, rely on the manifold pressure change when the throttle is opened on demand of more fuel. A solid state pressure transducer is used to measure the pressure in the intake manifold combined with rpm and air temperature to determine the airflow indirectly. Therefore, either MAF or MAP sensor is employed as an input to the ECU as a primary input.

The third sensor is the Throttle Position Sensor (TPS) which is secondary input to ECU. The key responsibility of this sensor is to inform whether a rapid opening of the throttle has occurred, so the ECU can compute for catering the increased fuel demand. Technically, this situation is called moving in to rich condition (excess presence of fuel, lack of air) from a lean condition (excess of air, lack of fuel). Basically relying on the rate of change of throttle blade angle, a potentiometer attached to the throttle shaft will produce an electrical signal accordingly. This simulates the functionality of an accelerator pump on a carburetor based system.

The fourth and the fifth sensors are the Water Temperature (WT) and the Air Temperature (AT) respectively. Both are secondary inputs to the ECU, WT is required only when the engine is cold (to prepare the fuel plus air mixture as rich, simulating the functionality of choke in traditional systems), once the engine exceeds the temperature limit 120 degrees, this input is no longer needed. The necessity of AT is optional for non speed density systems because mass airflow systems are already measuring the air mass entering the engine. But much important in the context of speed density systems, because there is an inverse proportionate relationship between the density of air and the temperature.

The sixth sensor, which plays a key role in this research is the Oxygen (O_2) sensor. This is the only after-combustion sensor to obtain the feedback to establish the closed loop control system. But under full throttle conditions, this sensor input is ignored by the ECU because then the engine need to produce the maximum power from a richer mixture. This is called an open loop mode and the ECU generate the injector pulse width mapping the appropriate values from a set of data tables embedded to the ECU and relying on the other sensor inputs. The Figure 01 illustrates the summary of the content.

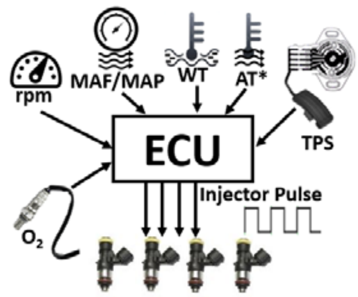

Figure 01: Input parameters of a typical EFI ECU

In summary, the crucial input parameters for a typical ECU are the rpm, MAF or (MAP plus Air Temperature) – commonly AirFlow (AF), Throttle Position (TP), Water Temperature (WT). The O_2 Sensor is not actually an input, but a feedback value. Therefore the actual input fed to the ECU will be the injector pulse width generated by itself in the previous iteration (i). In other words, the pulse width (PW) in successive iteration ($i + 1$) is determined by the last computed PW itself. The relationship among the injector pulse width (PW) width and the influential factors can be formula as below:

$$PW_{i+1} = f\,(\text{rpm, AF, TP, WT, } PW_i) \qquad (1)$$

For running engines (temperature above 120 degrees) the WT component can be ignored. Therefore a reduced formula can be derived as stated below:

$$PW_{i+1} = f\,(\text{rpm, AF, TP, } PW_i) \qquad (2)$$

According to formula (2), it is straight-forward to realize the actual driving forces of a typical ECU.

Figure 02 is to further explain the concept of closed loop control for excess fuel release and emission control employed in a typical EFI system. The controller stated here is a PID (proportional–integral–derivative controller) controller.

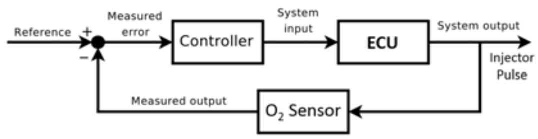

Figure 02: General overview of the closed loop

From the next sup-topic onwards, the paper describes the design, implementation, testing and the evaluation of the improved ECU.

Analysis and Design

As stated in the Figure 03, the improve ECU, named as ECU 2 was designed to collaboratively work with the existing ECU (the Master CPU here onwards). Actually, the complicated computation task assigned to the Master CPU remains as it is while the ECU 2 keep modifying the injector pulse originated by the Master CPU according to the decayed condition of the fuel injector (which is exceeding the limitations of self-adjustments based on feedback from O2 sensor supposed to be executed by the Master CPU).

ECU 2 is a programmable computing device comprised of microcontrollers which perform its fundamental computations relying upon a variable called 'Modify Rate'. The modify Rate heavily relies on the decayed condition of the fuel injector, cannot be pre-determined, other than the readings of an exhaust gas analyzer. Starting from the default value 100%, the value is being gradually decremented until the emissions are satisfactory lowered, without interrupting the performance of the engine (the process is stopped before the ignition knock is reported). The theory is to expand the off-width of the injector pulse to cut-off excess fuel release. Then the calibration data is recorded and stored in the flash memory. The updating of ECU 2 can be done annually or bi-annually, but a compatible exhaust gas analyzer is required.

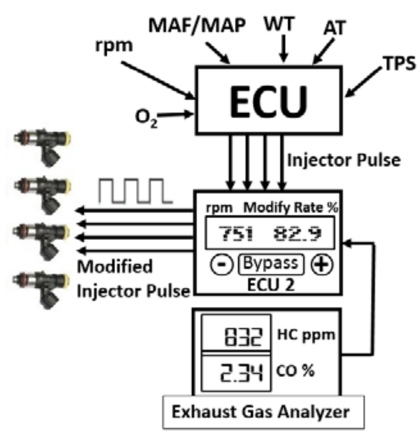

Figure 03: System Overview (Top level architecture)

Implementation

The ECU was constructed by a series of PIC Microcontrollers those are operated on a processing speed of 20 MHz (instructions are being executed at a speed of 5 MHz), which is an adequate configuration to perform computations. The microcontrollers are communicating between them real time, with I2C communication, a communication protocol specified for short-distance inter-IC communication. The injector pulse originated by the master ECU was captured (at the rising edge) without a noticeable delay (the pulse width is calculated using the time difference between the occurrences of the rising edges of two consecutive clock cycles. Usually, this is 2-5 microseconds, a negligible) and re-generated using a PWM (Pulse-Width Modulation) module embedded to the microcontroller. The determinant parameters of the duty cycle are the injector pulse captured above and the Modify Rate. As the switching device (to energize the fuel injectors), a 40 A solid state relay (SSR) is employed. There is a special reason for selecting a SSR because there's no moving contacts as in mechanical relays, enabling fast and reliable switching.

Results and Discussion

Evaluation of the system was done based on the emission measurements, before and after employing the calibrated ECU 2 using a standard exhaust gas analyzer. Samples were collected at the idling speed, usually around 750 rpm, at 1500 rpm and 2500 rpm. The statistics recorded for a Nissan FB14 (YoM 1997) are tabulated in Table 01 for the analysis.

Table 01: Comparison of emissions, before and after installing ECU2 (Nissan FB14 1997)

		rpm	**HC (ppm)**	**CO (%)**	**CO_2 (%)**	**O_2 (%)**
Before	Idle (750)	920	1233	5.07	11.2	11.25
	@1500 rpm	1723	868	2.84	14.3	11.76
	@2500 rpm	2620	517	2.12	13.9	12.98
After	Idle (750)	721	158	2.94	5.06	13.90
	@1500 rpm	1550	110	1.82	3.99	14.50
	@2500 rpm	2326	82	1.31	3.76	14.70
Reference (SL)			**< 1200**	**< 4.50**		

An interesting observation done, although more emissions were expected at higher rpms due to increased rate of fuel burning, the opposite was experience. That means, the emission of pollutants began diminishing slightly with the increasing rpm. The phenomenon can be further deliberated with experimental data denoted by Figure 04. The figure basically summarizes the variation of a selected pollutant CO (Carbon monoxide) with the increase of rpm from idling (approximately 750) to 2500 studied with six different vehicles with different injector decay conditions.

It is worth to discuss on the attributes of each pollutant mentioned in Table 01 to determine which parameter is more influential to consider for the calibration process of ECU 2. HC or Hydrocarbons, concentration in the exhaust is measured in parts per million (ppm). This is the unburned fuel after the internal combustion. If HC in ppm is high, that means some portion of fuel is partially burnt (incomplete combustion), simply due to excess fuel in the combustion mixture. Another interpretation is the fuel wastage. An approximate relationship between the percentage of wasted fuel and the ppm of HC is about 1/200 (1.0% partially burned fuel produces 200 ppm HC). Which means if the measurement of HC is 1200 ppm (maximum allowed under Sri Lankan emission regulations), 6% of fuel will be wasted. But we emphasize, even 6% is too much, the emission regulations must be restricted to at least 200 ppm as practiced in some states of US and some European countries.

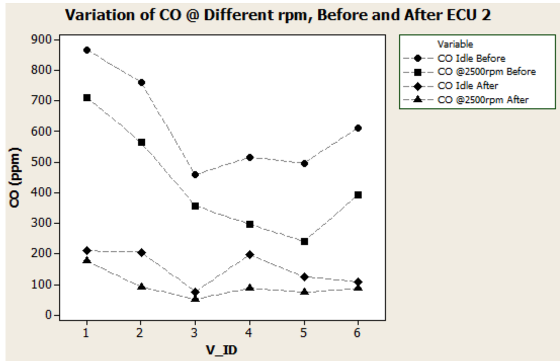

Figure 04: Variation of CO emission with rpm, with and without ECU 2

CO, Carbon monoxide is another measure for partially burned fuel. But cannot rely on this figure, because a device called catalytic converter installed at the exhaust system does convert CO in to CO2 chemically, since CO_2 is comparatively less poisonous for breathing. Therefore the amount of unburned fuel cannot be exactly determined by this parameter. That depends upon the condition of the catalytic converter, this device can be damaged in long term use of poor quality petrol.

Emission of CO_2, Carbon Dioxide is unavoidable because this a result of complete combustion of fuel. It is generally 1-2% and higher at 2500 RPM than at idle. Maximum percentage under usual conditions is around 16%.

O_2, Oxygen, the oxygen percentage is a clear indicator of the transition from lean to rich mixture. When the mixture is rich, most of the oxygen is burnt during the combustion. On the other hand, if more oxygen found in exhaust mixture means a lean condition has occurred, employing less oxygen for combustion. The figure can be also used for diagnosis, leaks in the manifold or exhaust systems or combustion failures can be detected.

An additional parameter measured by the equipment's found in majority of the Eco Test centers established in Sri Lanka is the Lambda (must not hesitate with sensor). This indicates the estimated Air/Fuel Ratio. Varies from 14.7:1 to 1:14.7. The ideal Lambda value is 1(one) below that the A/F mixture is rich and above – lean.

The study led to determine that, CO is the ideal parameter to use as an input to the ECU 2 as well as the most successful indicator to evaluate the outcome of calibrated ECU 2. Because it has a clear relationship between the unburnt or excess fuel, which is an obvious effect of a decayed injector. The achievements of recognizing the correct determinant is shown in Figure 05, the reduction of CO emission after introducing ECU 2.

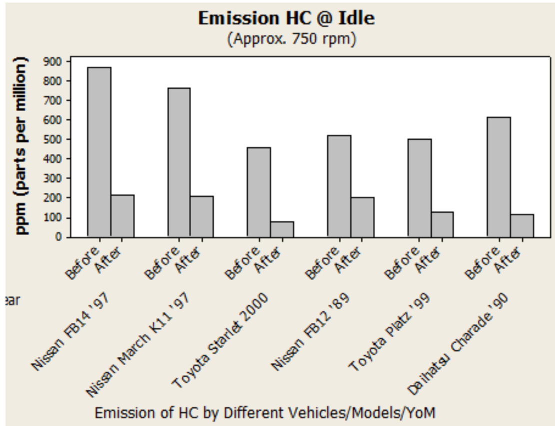

Figure 05: Reduction of CO emission after employing ECU2

In summary, The improved ECU provides facilities for the mechanics who are performing the EFI Tune up process, especially supposed to cope with decayed injectors to moderate the Injector Pulse pattern according to the readings, specifically the HC amount of the exhaust gas analyzer in order to minimize the emissions and fuel waste without modifying the EFI circuit, that is ensuring the enhanced easiness of EFI Tune Up process.

Challenges Encountered and Future Developments

One of the major problem encountered when implementing the system was the heat dissipation of switching devices. The system was initially designed with power transistors, then MOFETs, but none of them could survive in flow of high currents in long hours. Solid state relays were the ideal solution to overcome the situation.
In future development, rather than using a series of PIC microcontrollers, a single comprehensive microprocessor can be used to perform the computations. The crucial requirement is such a processor must possess four PWM modules enabling to generate four injector pulse patterns for the individual injectors simultaneously. It was noticed that some advanced models of Atmel AVR microcontrollers are able to satisfying this requirement. Direct communication with the existing ECU instead of reading the output injector pulse may enhance the efficiency further. The feasibility of implementing a self-calibrating mechanism for the device is another possible approach to evolve the system.

Conclusion

The research has concluded with outstanding results with regard to reduction of fuel wastage and pollutant emission control. This significant achievement was gained by the improved ECU relying on the HC content in exhausted gas which is used as a feedback value to complete the closed loop. Closed loop control systems those consider the produced output to perform due adjustments in successive iterations of the process cycles in order to minimize the deviation of the output from expected value(s), are always better than open loop systems. In addition, a remarkable deduction of other toxic emissions such as CO was also resulted.

Experimental results have proven that employment of the improved ECU could reduce the major emissions up to 84.92 % and with an average of 75.8%. And most excitingly, the improved ECU has capable of cut-offing the fuel wastage due to decayed fuel injectors up to 76.63 % while maintaining an average over 70 %.

Finally, by examining the obtained results analyzed with statistical artifacts, conveys that the research has produced remarkable outcomes and carrying a very high potential in contribution to unearthing of sustainable solutions for emerging energy crisis and environmental conservation.

References

Cunlei, W., Jianlong, Z., Cunlei, W., Jianlong, Z., & Chengliang, Y. (2014). Novel Application-oriented Transient Fuel Model of a Port Fuel Injection S. I. Engine. *Chinese Journal of Mechanical Engineering, Vol. 27, No. 2,* 384.

DeCastro, J.A. (2003). *Design and Validation of High-Bandwidth Fuel Injection Systems for Control of Combustion Instabilities.* Masters dissertation, The University of Virginia.

Ommi, F., Movahednejad, E., & Nekofar, K. (2008). Study of Injection Parameters on Performance and Fuel Consumption in a Port-Injected Gasoline Engine with Experimental and Theoretical Methods. *Annals of The Faculty of Engineering Hunedoara – Journal of Engineering, Tome VI, Fascicule 2.*

Research Designs and Standards Organization Lucknow India. (2011). *Development of an Electronic Fuel Injection System for a 4-stroke Locomotive Diesel Engine of Indian Railways.* Retrieved September 15, 2016, from http://www.iitk.ac.in/erl/Index_files/Popular%20Publication/Direction%20Article%20Development%20of%20EFI%20for%204-stroke%20locomotive%20diesel%20engine.pdf.

Sebok, M., Jurcik, J., Gutten, M., Korenciak, D., Roj, J., & Zukowski, P. (2015, August). *Diagnostics and measurement of the gasoline engines injection System.* Paper presented at Przegląd Elektrotechniczny, Warszawa, Poland.

Yukumatsu, N., Sakamaki, K., Ikezoe, A., Tarumoto, T., & Uno, Y. (2001). Development of power train ECU for AZ line engine. *Fujitsu Ten Technical Journal, No.16.*