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Ultrasonic gasoline evaporation transducer — reduction of internal combustion engine fuel consumption using axiomatic design

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Abstract

The possibilities of improving fuel combustion efficiency have been studied deeply, for environmental as well as economic reasons. It is well known that better combustion is linked to consistent fuel droplet size that is as small as possible. In this paper ultrasonic fuel atomization is investigated as an alternative to traditional fuel systems which are highly coupled and complex. The proposed design is the Ultrasonic Gasoline Evaporation Transducer (UGET), devised using Axiomatic Design principles. The UGET replaces a standard carburetor's highly sensitive venturi mechanism by vaporizing the fuel with piezoelectric crystals that oscillate at a high frequency (1.7 MHz). The UGET produces much finer, more even fuel vapor compared to that of a standard carburetor, expect to result in a more complete combustion by an internal combustion engine. Due to the absence of small apertures, the UGET is less vulnerable to congestion risks than a fuel injection system or a carburetor. The current prototype vaporizes up to 40 g min^{-1} of fuel to operate a 170 cc 4-stroke engine with performance comparable to a normal carburetor.

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Keywords: axiomatic design, ultrasonic, carburetor

1. Introduction

Efficiency of small off-road engines (SORE) is becoming more important as the EPA Phase 3 legislation [1] takes effect: 100 million SORE are manufactured on a yearly basis [2]. EPA phase 3 rules for class 1 engines, *i.e* <225 cc, limit the amount of HC + NO_x to 10 g kW^{-1} h^{-1} and CO to 549 g kW^{-1} h^{-1} [1]. One well-known method of improving efficiency is optimizing the air-fuel mix quality in the fuel system. Standard carburetors (SC) and fuel injection systems (FIS) are the options available. SC is commonly used with small engines since FIS is more expensive: production cost of a FIS for small internal combustion engines (ICE) is ≈ 35 USD compared to ≈ 5 USD production cost of a SC (Ómarsson, Kristján. Conversation with: Jónsson, Garðarsson, Pétursson, Hlynsson, and Foley. 2014 Sep 23.).

The first patented carburetor was invented by Karl Benz when building his first automobile [3]. Though SC have not been used in the automobile industry since the 90's [4], most small engines utilize SC. A SC adds fuel to the air stream in the engine's intake manifold with a network of small orifices (nebulizers). Inconsistent atomization of the nebulizers reduces the engine's combustion efficiency (Figure 1)[5].

Nomenclature

AFR	Air-fuel ratio
EPA	Environmental Protection Agency
FIS	Fuel Injection System
HVAC	Heating, ventilation and air conditioning
ICE	Internal Combustion Engines
PLC	Programmable logic controller
SC	Standard Carburetor
SORE	Small Off-Road Engines
UGET	Ultrasonic Gasoline Evaporation Transducer

The first gasoline FIS was introduced in automobiles by Mitsubishi in 1996 [6]. FIS is a computer controlled, high pressure system which injects a predetermined amount of fuel through a nozzle directly into the combustion chamber when the piston has completed compression. Precise control of pressure and nozzle geometry results in high efficiency combustion from consistent atomization. The amount of fuel injected must be determined by measurements of airflow to the engine, throttle position and exhaust gas temperature [7].

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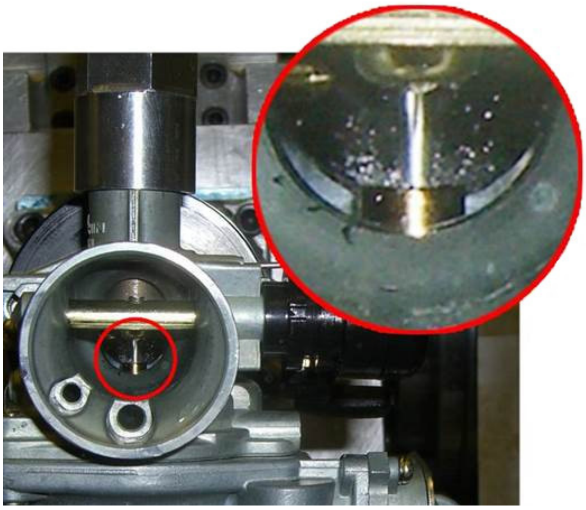

Fig. 1. Inconsistent droplet formation in a standard carburetor's nebulizer. Source: Fjolblendir ehf.

In this work the feasibility of using ultrasonic sound waves to achieve air-fuel mixture is investigated. When piezoelectric crystals are subjected to high-frequency, high-voltage oscillations, the crystals and an attached metal plate rapidly change shape, emitting high frequency sound waves. By passing the sound waves through a liquid phase medium, the liquid atomizes into a fine mist.

The rate of evaporation which the transducer supplies is dependent on the liquid medium thickness it is surrounded with, making the Ultrasonic Gasoline Transducer (UGET) concept limited to stationary class 1 engines on level ground, *e.g* electric generators and pumps.

The concept is to pass air through a customized chamber, fitted to an engine's intake manifold, where an ultrasonic transducer evaporates fuel and supplies air-fuel mixture to the engine's combustion chamber. The resulting air-fuel mixture should contain more consistently sized, finer fuel droplets than a SC can produce and less complexity than a FIS. Finer droplets result in more complete combustion, as the amount of expelled hydrocarbon chains decreases at higher temperatures. The smaller droplet's core burns closer in temperature of the outer layer [8], resulting in increased overall efficiency of the engine.

Ultrasonic atomization should result in more complete combustion, causing better fuel efficiency and less polluting gases coming from the engine exhaust. The consistently fine droplets created and the absence of small apertures vulnerable to clogging makes this concept distinctive from the SC and the FIS.

This concept has been explored in numerous amateur online videos [9–13] and patents [14,15]. There are few scientific references to ultrasonic carburetors, primarily focused on diesel systems [16].

2. Requirements

Constraints are listed in Table 1 The functional requirements (FR) are mapped to corresponding design parameters (DP) in Table 2 on page 3. The decomposed design matrices are in Eq. 1–2. A full design matrix is in Eq. 3.

Table 1. Industry-driven fuel system constraints.

	Constraint
1	Maximum in-production price 40 USD
2	Operate without intervention or maintenance for 300 h
3	No changes to the engine it is attached to

$$\begin{Bmatrix} FR_1 \\ FR_{1.1} \\ FR_{1.2} \end{Bmatrix} = \begin{bmatrix} X & & \\ & X & 0 \\ & X & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_{1.1} \\ DP_{1.2} \end{Bmatrix} \quad (1)$$

$$\begin{Bmatrix} FR_2 \\ FR_{2,1} \\ FR_{2,2} \end{Bmatrix} = \begin{bmatrix} X & & \\ & X & 0 \\ & 0 & X \end{bmatrix} \begin{Bmatrix} DP_2 \\ DP_{2,1} \\ DP_{2,2} \end{Bmatrix} \quad (2)$$

$$\begin{Bmatrix} FR_1 \\ FR_{1.1} \\ FR_{1,2} \\ FR_2 \\ FR_{2,1} \\ FR_{2,2} \\ FR_3 \end{Bmatrix} = \begin{bmatrix} X & & & 0 & 0 & 0 & 0 \\ & X & 0 & 0 & 0 & 0 & 0 \\ & X & X & 0 & 0 & 0 & 0 \\ X & X & X & X & & & 0 \\ X & X & 0 & & X & 0 & 0 \\ 0 & 0 & 0 & & X & X & 0 \\ X & 0 & X & 0 & 0 & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_{1.1} \\ DP_{1.2} \\ DP_2 \\ DP_{2,1} \\ DP_{2,2} \\ DP_3 \end{Bmatrix} \quad (3)$$

The target air-fuel ratio (AFR) of 14.7 is the optimal stoichiometric mix based upon the chemical composition of gasoline and air. That level of precision is beyond the capabilities of this initial investigation: our ratio is expected to lie in the range 14–16.

The design matrix indicates that this design is decoupled and feasible for implementation. It must be noted that the creation of the correct fuel mix (DP_2) is challenging to separate from the airflow rate ($FR_{1.2}$). The correct airspeed ($FR_{1.2}$) requires knowledge of the engine's load ($DP_{1.1}$) and the piston geometry. Efficient atomization ($FR_{2.1}$) requires the level control system to be operating properly ($DP_{2.2}$). Other elements have been uncoupled by careful modularization.

3. Design

The inspiration for the UGET concept originated from discussions with the chief designer of the Total Combustion Technology (TCT) fuel system Kristján B. Ómarsson (Ómarsson, Kristján. Conversation with: Jónsson, Garðarsson, Pétursson, Hlynsson, and Foley. 2014 Sep 23.) The venturi design consists of an ultrasonic transducer fitted to the bottom of a small, cylindrical fuel container, which is adapted to an engine's air-intake manifold. Upstream air is bled into the chamber, and a narrowing at the UGET output creates the pressure difference to draw fuel vapor into the engine's combustion chamber (Fig. 2). The environment is always assumed to be stationary and on level ground, appropriate for applications such as generators (Section 4.1).

This design requires integration into the air intake manifold of the engine, violating Constraint 3. Moving the venturi before the manifold was not considered because it might significantly affect the airflow.

The current design is an in-line chamber as can be seen in Fig. 3. This design is more complicated to control the AFR, but does not significantly impact the airflow to the manifold.

Table 2. Functional Requirements (FRs) and Design Parameters (DPs) mapping.

	FRs	DPs
0	**Produce consistent fuel & air mixture for engine combustion.**	**Ultrasonic transducer atomization controlled by engine state.**
1	Match fuel-air mixture airflow to demand.	Evaluation of engine state
1.1	Detect engine load.	Engine load sensor
1.2	Adjust air-speed	Servo flapper valve
2	Create desired air:fuel ratio of 14.7:1.	Ultrasonic transducer excitation of fuel in chamber
2.1	Atomize fuel at desired rate.	Transducer input amplitude
2.2	Maintain optimal transducer fuel interface.	Gravity-driven fuel level control system
3	Transport fuel-air mixture to engine.	Standardized SORE carburetor coupling

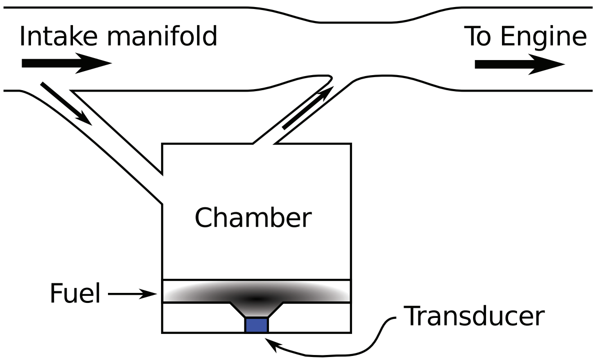

Fig. 2. UGET venturi concept. Arrows show direction of air flow.

The lack of small apertures means that clogging due to fuel contaminants is not a concern. This design was implemented as a proof-of-concept to validate a basic level of operation without precise FAR control needed for a complete system as per the design matrix. This capability is to be implemented later.

3.1. Body

The body of the UGET prototype consists of a hollow cylinder, an aluminum base panel, an acrylic top panel, an air intake pipe and an air/fuel outlet pipe that leads to the engine. This design allows the device to be adapted to an engine's intake manifold only by making minor alterations to it, and in turn asserts the UGET as an essential part of the engine's air-fuel system. A DSS Solidworks™ model of the body can be seen in Fig. 3.

Polycarbonate was chosen as the building material for the cylindrical container as its transparency is ideal for evaluation purposes. This material was discovered to be incompatible for long term operation due to the destructive interaction of gasoline and ultrasonic vibrations, but the visualization capability was extremely valuable at this phase. Future implementations will be constructed of metal or a gasoline-compatible polymer.

3.2. Ultrasonic transducer

The ultrasonic transducer, insulated with a nitrile seal ring, is located at the bottom of the chamber and clamped to the base with a brass bracket (Fig. 4). A local HVAC company pro-

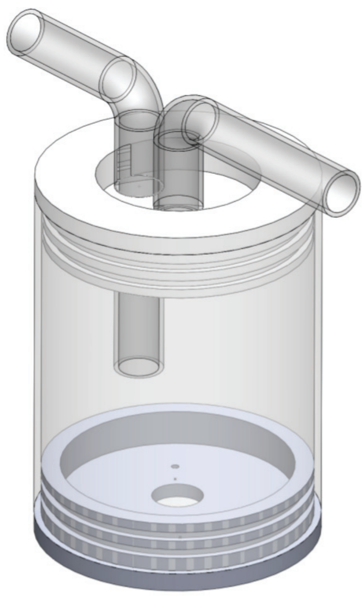

Fig. 3. CAD model of the in-line UGET. This configuration is used in the current prototype.

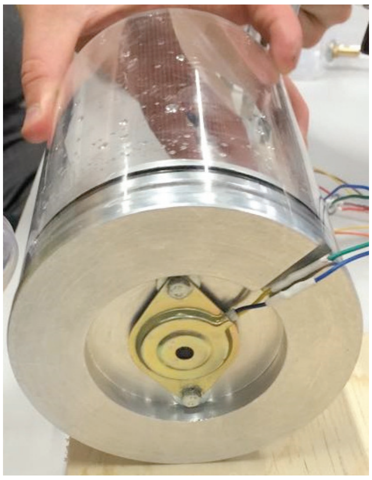

Fig. 4. Bottom of chamber. Ultrasonic transducer is mounted on aluminum base panel.

Fig. 5. Float switch configuration. The upper float is for fuel addition and the lower float signals emergency shutoff if triggered.

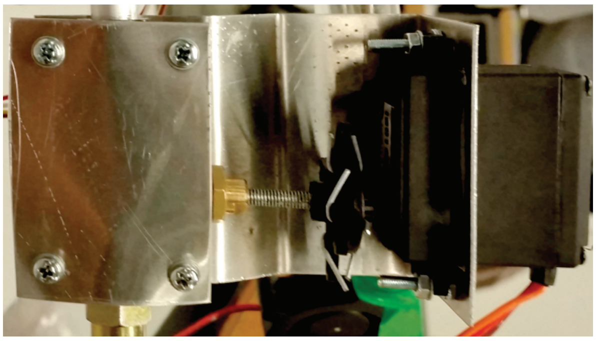

Fig. 6. Fuel addition servo-motor configuration. The rotary valve (left) is between an elevated fuel reservoir and the chamber.

vided a high power ultrasonic transducer and oscillator, but no specifications nor documentation were available, making it unsuitable for further investigation. Instead, an ultrasonic transducer and oscillation circuit were adapted from a Wilfa HU-3W household humidifier [17]. This appliance was not designed for interfacing with a micro-controller: a servo-motor was employed to adjust the amplitude via an existing potentiometer (Section 3.4). Transducer operation requires a peak-to-peak voltage of $V_{p-p} = 50\,\text{V}$ and an input frequency of $f = 1.7\,\text{MHz}$.

3.3. Fuel level monitoring

To ensure that the unit can operate safely with an even layer of fuel above the transducer the design utilizes float switches (Fig. 5). An upper float switch sends a signal to a main module to actuate the fuel addition servo when the fuel level (h) goes below a predetermined height currently set at 4 cm (Table 3 and Section 5). In a future implementation, the top level float switch will be replaced with a digital level monitor to provide a better control loop signal. If the fuel reservoir runs out, the lower float controlled switch triggers the main module to shut off power to avoid a fire hazard and damage to the transducer.

3.4. Servo-motor control

The servo-motor system includes two 6 V Power HD-1501MG High Torque servos. The power control servo (Fig. 6) is mounted to the main module (Fig. 7) and rotates a potentiometer to control the power trim output (P_ϵ) of the ultrasonic transducer based on engine demand. The fuel addition servo adjusts the fuel addition valve based on the current fuel layer height (h). A future configuration will use a digitally controlled proportional valve.

3.5. Main module

The system is controlled using an 8-bit micro-controller called the SparkFun RedBoard. A final product would be controlled by an integrated micro-controller or PLC as the control logic is straightforward.

The controller processes signals from all sensors and controls the fuel addition servo or triggers the critical fuel level safety switch based on those readings. The controller also receives commands from the user about desired evaporation rate and translates them into commands for the power control servo.

An air-way flapper valve and engine load sensor were to be integrated into this design. Unfortunately, due to supplier complications, they had to be omitted at this phase.

The oscillation circuit is used to send an alternating current to the ultrasonic transducer as instructed by the controller. The main module also includes an LCD display that displays the status of the sensor readings and power level states. The main module can be seen in Fig. 7.

4. Experiments

4.1. Feasibility

To determine the feasibility of the UGET, the system needs to fulfill the fuel consumption requirements of a mass produced engine in the category of <225 cc. The Honda GX-160 motor was chosen as reference in this purpose. Its fuel demands range from $\approx 2.5\,\text{g}\,\text{min}^{-1}$ in idle running up to $\approx 25\,\text{g}\,\text{min}^{-1}$ at 10 N m torque load [18]. A test of the evaporation rate of a Wilfa HU-3W humidifier was conducted in order to determine it's evaporation rate. Results of these tests can be found in Table 3 on tests 1 and 2.

4.2. Fuel layer evaporation rate

An experimental setup was conducted to determine the effect of fuel layer thickness above the transducer on fuel evaporation rate. The setup consisted of the UGET prototype operating at different fuel layer thicknesses, at the transducer amplifier's minimum and maximum settings using a fan to provide constant air circulation in the system. Results can be seen in Table 3 on tests 3–5.

4.3. Engine operation

A Honda GX-160 or equivalent engine was to be provided by Fjolblendir, but did not arrive in time due to shipping complications. The UGET was instead attached to the air intake manifold of a 170 cc, 4-stroke gasoline powered pull-start engine dedicated for experiments.

The experiment's main objective is to prove the UGET is capable of supplying fuel to already running engine. A standard

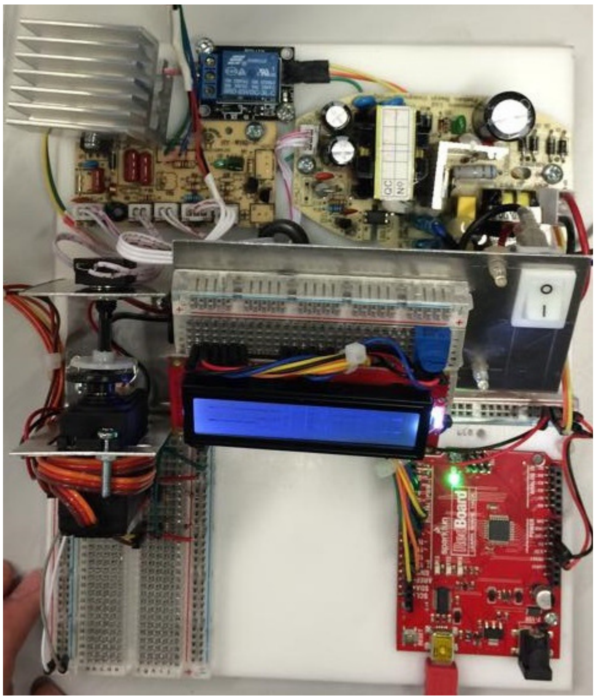

Fig. 7. Main module. Micro-controller on the bottom right, power control servo on the bottom left, LCD display in the middle and an oscillation circuit on the top.

carburetor was used to start a cold engine. The engine was operated for 15 min to thermally stabilize it. Once stabilized, the fuel feed to the carburetor was blocked and the UGET powered on. Initially, the engine stalled. Additional air was bled parallel into the air/fuel mixture from the UGET, and the engine ran continuously. Unfortunately, this change makes the AFR ratio uncertain because previous evaporation measurements can not be used for calibration.

Another experiment was conducted to see if a cold engine would start using the UGET. The UGET was energized then a experimenter pulled the starter cord. In our tests, the engine was successfully able to start each time.

4.4. Fuel efficiency of UGET versus standard carburetor

An experiment is conducted to determine the fuel consumption of a 170 cc engine using the UGET fuel system to comparing to that of a standard carburetor. The UGET system is weighed prior to the test and again after a three minute run of the engine with an applied torque load of 7 N m. Due to an oversight, rotational speed was not measured during this test.

To evaluate the fuel consumption of the standard carburetor, mass measurements were taken of the test engines fuel chamber, before and after a three minute run of the engine operating at the same applied load. These measurements are adapted to the weight measurements of the UGET with the density of gasoline (0.73 g mL^{-1}).

Table 3. Evaporation rate tests of a Wilfa HU-3W humidifier's ultrasonic transducer [17]. T is the test number. P_ϵ was the trim power setting on the ultrasonic oscillator (0–1). m_n is the mass of the fuel container before ($n = 0$) and after ($n = 1$) the experiment. t is the duration of the test. h is liquid layer thickness. $\dot{m}$ is the calculated fuel evaporation rate. Tests 1–2 were conducted using the Wilfa humidifier's chamber, the remainder with the prototype's.

T	P_ϵ	m_1 [g]	m_2 [g]	Δm [g]	t [min]	h [cm]	$\dot{m}$ [g min^{-1}]
1	1	1197	1165	32	1	N/A	32
2	0	1266	1248	18	2	N/A	9
3	0	2490	2470	20	1	5.2	20
4	0	2830	2800	30	1	4.0	30
5	1	2800	2760	40	1	3.7	40

5. Results and discussion

The fuel layer thickness h above the transducer has an impact on the rate of evaporation of the UGET. According to our experiments the optimum liquid layer thickness is ≈ 4 cm. The fuel addition float switch (Section 3.3) is calibrated to maintain that level.

The prototype was used to supply an internal combustion engine in the university's Energy Lab, a demonstration 170 cc 4-stroke model. With a few adjustments to the prototype, it performed as a functioning fuel system to operate the engine.

Preliminary results of the comparison experiment in Section 4.4, suggest that a 170 cc engine's fuel consumption operating with a UGET fuel system is 20 g min^{-1} compared to a 16 g min^{-1} of the same engine using a standard carburetor. While this shows a 20% increase over the existing technology, it is within the error margins of our limited testing environment. Another possibility is that the UGET may have been rotating faster at the same load and providing higher power output, but due to the lack of rotational data this cannot be evaluated. Additional testing under more controlled conditions is needed.

5.1. System capabilities

The current prototype has these capabilities:

- Vaporizing around 40 g min^{-1} of gasoline at full power which is enough to meet the fuel consumption of a typical <225 cc engine (Honda GX-160 as a reference) which is up to 25 g min^{-1} at 10 N m torque [18].
- Maintaining a constant fuel layer thickness of 4 cm as long as the fuel reservoir is not empty.
- Delivering a very fine and even mist of fuel into the intake manifold of an engine.
- Safely shutting down as the fuel level goes too low to prevent overheating and fire hazards.
- Running a 170 cc engine without intervention.

5.2. Evaluation of functional requirements

FR0 The UGET is capable of mixing air and fuel to start and run a 170 cc engine that was operated without intervention for 3 min.

FR1 Due to part availability, fuel-air airflow was not directly controlled. It will be easy to fulfill this requirement with additional resources, but may run into the cost constraint.
   FR1.1 The engine demand sensor was not used due to availability. To emulate this function in the prototype, demand was set manually on the micro-controller.
   FR1.2 Airspeed was also not determined to be important in the initial prototype, so this functionality was not implemented. (Section 4.3)

FR2 The UGET is capable of vaporizing around 40 $\mathrm{g\,min^{-1}}$ of gasoline at full power and modulating that to a lower amount.
   FR2.1 Evaporation rate of the transducer is controlled by rotating a potentiometer using a servo. The servo is controlled by serial inputs from the user through the micro-controller serial monitor.
   FR2.2 Fuel control system can maintain a fairly constant fuel layer thickness of 4 cm for consistency.

FR3 An adapter was manufactured to connect the output of the UGET to match a SORE coupling

6. Conclusion

The simplified prototype was successful at meeting the majority of the requirements derived. The elements that were omitted will be implemented in future work.

Regarding performance, at our fuel efficiency test, the UGET consumed 20% more fuel than the standard carburetor. It was not expected that this prototype would decrease fuel consumption, nor was that the focus; it is to be considered an operational proof of concept using proper design methodology. In that context, it was successful.

6.1. Future work

These are elements that need further investigation on the path to a complete system:

- Testing to determine if gasoline liquid evaporates evenly, that is if some hydrocarbons in gasoline evaporate more rapidly than others, leaving behind a more concentrated mixture of certain elements.
- Further development to determine how to synchronize AFR accurately when engine is subjected to various loads and conditions. This would require the actively adjustable air path (DP1.2) and engine load sensor (DP1.1).
- Replace polycarbonate chamber with more gasoline and ultrasonic-compatible material.
- Reduce the size of the UGET to properly integrated with a <225 cc class engine.
- Reduce the electronics to a single board for compactness.

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