Improving fuel economy and emissions performance of commercial goods transportation and mass transit vehicles using throttleless engines

METRANS Project #99-5

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FINAL REPORT

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TABLE OF CONTENTS

LIST OF FIGURES

DISCLOSURE STATEMENT

This work is part of a project cost-shared in conjunction with the following contract:

- Funding source: South Coast Air Quality Management District
- Names of principal investigator and co-principal investigators: Paul D. Ronney
- Dollar amount: $85,300 (ongoing; period of performance 9/1/99 – 8/31/02)
- Title of project: Reducing Vehicular Emissions Through Throttleless Engines Using Alternative Fuels
- Brief description of relationship to report: cost-shared, ongoing project

DISCLAIMER STATEMENT

ACKNOWLEDGEMENTS

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INTRODUCTION

Conventional premixed-charge engines employ a throttle to reduce power and torque when demand is low by reducing the pressure of the combustible mixture drawn into the cylinder. This results in the well-known "throttling loss." Under typical highway cruising conditions, this loss is typically 15% or more of the otherwise available power output of the engine. In mass transportation vehicles (e.g. urban buses) and goods transportation vehicles (e.g. delivery trucks) which operate primarily in urban areas with frequent stopping, starting and low-speed travel, this loss is even greater. This loss leads to reduced fuel economy and increased pollutant emissions.

What is needed is a means to provide the necessary range of engine output power and torque adjustment **without throttling.** Such a means is provided by the Throttleless Premixed Charge Engine (TPCE) concept developed previously by the Principal Investigator. The essence of the TPCE concept is the use of a combination of fuel-air mixture ratio control (stoichiometric and lean mixtures) and intake air preheat in order to obtain power and torque adjustment without throttling. Higher intake temperatures reduce the air density and thus power and torque. Leaner mixtures also reduce power and torque, and the intake air preheat substantially reduces the lean misfire limit. Thus *in the TPCE concept the synergistic use of preheating and lean mixtures is essential*; neither technique individually provides a sufficient range of power and torque adjustment for use in practical vehicles.

A detailed discussion of the concept, testing and implementation of the TPCE engine is given in our technical paper [1] that won the Institution of Mechanical Engineers Starley Premium Award for the best paper published in the Journal of Automobile Engineering in 1994. In this paper, we described experiments specially designed test the TPCE concept using 4-cylinder production engines using gasoline and natural gas fuel. These tests demonstrated the theoretically predicted improvement in brake thermal efficiency (up to 16% compared to the same engine operated using conventional throttle control at same power and engine speed) due to the absence of throttling loses. Also, because of lean operation, greatly reduced NO_x emissions are obtained – more than 10 times lower than the same engine operated using conventional throttle control at same power and engine speed. The observed NO_x level of less than 0.8 grams of NO_x per kW-hr (0.6 grams per hp-hr) at moderate and light loads corresponds to less than 0.2 grams per mile for a typical 15 hp road load at 55 mi/hr – **without the use of a reducing catalytic converter for NO_x removal.** This emission level is half of the 2001 California standard, and equal to the 1998 "Clean Fleet" standard required for 30% of new vehicles used by centrally-fuelled fleets in cities with poor air quality. CO and unburned hydrocarbon emissions in TPCE engines were found to be comparable to throttled engines, thus only inexpensive oxidizing catalysts for CO and UHC are needed for TPCE engines. Torque control via exhaust gas recirculation (EGR) was also tested in our study [1] but found to result in vastly inferior thermal efficiency and torque adjustment range.

The TPCE concept is ideal for applications in urban mass transit buses and goods transportation vehicles, which are the subject of the current solicitation, because these types of vehicles are constantly changing load and speed, especially on the roads in the LA metropolitan area, and are only infrequently operated at wide-open throttle. *The TPCE concept provides many of the best aspects of premixed-charge, spark-ignition engines (fast response time, high power to weight ratio, relatively low NO_s formation and negligible particulate emissions) with the best aspect of nonpremixed-charge compression-ignition (Diesel-type) engines (higher part-load thermal efficiency due to lean operation without a pressure-reducing throttle).* These advantages of the TPCE are particularly noteworthy considering that most Diesel engine technologies used in urban buses and goods transportation vehicles are unlikely to be able to meet future NO_x and particulate emission standards, especially those proposed by the EPA for the year 2004.

PROJECT OBJECTIVES

While the aforementioned results are very encouraging, there are two remaining issues to be addressed before the international award winning TPCE concept is put into practical application in real-world, urban mass transit buses and goods transportation vehicles. These issues and their solutions are discussed below.

I. Optimal strategies for torque and emissions control

In the TPCE and throttled engine experiments described above, the engine was operated in a manner compatible with vehicle applications in all aspects except one: for experimental convenience the air was preheated using an electrical heater, whereas in a practical application the air preheat must of course be accomplished via heat exchange with the exhaust gas. A practical means of providing rapidly controllable, variable air preheat is proposed for assessment in this work. In this scheme a diverter valve and branched intake duct, one branch passing through the heat exchanger and the other bypassing the heat exchanger, is used. By adjusting the diverter valve position, cold mixture is always available without delay when the torque demand (commanded by the driver or cruise control system) increases suddenly. Thus, good dynamic performance characteristic of throttled engines is maintained despite the unavoidable thermal lag associated with heat exchangers. An additional advantage of this scheme is that only one additional moving part (the diverter valve) is needed. In the proposed study the viability of the heat exchanger / branched manifold / diverter valve scheme for control of TPCE engines is assessed with respect to emissions performance, thermal efficiency, and dynamic response.

In the TPCE system, three engine operating parameters need to be controlled: fuel-air mixture ratio, intake air temperature and ignition timing. This wide control parameter space allows the engine performance to be optimized for lowest emissions while maintaining good fuel economy. For example, lean operation reduces NO_x emissions but may lead to unacceptably poor efficiency due to misfire if the engine is operated too lean. Also, elevated intake temperatures are advantageous because of the wider flammability limits and lower intake mixture density this entails, but too high intake temperatures will result in destructive engine knock (see issue II below). In the proposed work we determine the proper program of control parameters for both static and dynamic engine operation, including transient conditions such as acceleration and deceleration.

II. Application of TPCE technology to alternative fuels and fuel blends

Since the TPCE concept requires the use of lean mixtures and preheating of the intake air, TPCE engines are in general limited by lean-limit fuel performance and engine knock (sometimes called "autoignition," "detonation" or "pinging") which is more prevalent at elevated intake temperatures [2]. For these reasons conventional fuels such as gasoline, which have relatively poor lean-limit performance and knock characteristics, do not perform well in TPCE engines [1]. However, by using natural gas fuel, which has excellent lean-limit performance and anti-knock properties even at elevated temperatures, we expect to obtain the required range of torque adjustment in TPCE engines without throttling.

As a result of these findings, we propose to examine the performance of alternative fuels such as natural gas, methanol, ethanol and hydrogen in TPCE engines. These fuels also have greatly enhanced lean limit and/or anti-knock performance relative to gasoline and thus are likely candidates for TPCE operation in urban buses and goods delivery vehicles. In particular, methanol and ethanol have much higher octane ratings than gasoline blends, and hydrogen has the lowest lean misfire limit of any fuel. Consequently, the TPCE studies will be extended to evaluate the performance of these alternative fuels and fuel blends. These results will be compared to the performance of natural gas fuel, which has already proven to be an excellent choice for TPCE engines.

The tasks performed are as follows:

Task #	**Description**
1 - 2	Design, fabricate and assemble heat exchanger, branched intake manifold and diverter valve. Integrate into existing engine test facility
3	Using natural gas fuel, determine optimal intake air temperature, mixture strength and spark ignition timing for best emissions performance and thermal efficiency
4	Determine dynamic response of TPCE to changes in torque demand, *i.e.* determine the time lag between change in torque command input and engine torque output
5	Compare optimized emissions and thermal efficiency to conventional throttled engines operating at the same torque loadings and engine RPM
6	Repeat second through fourth items using methanol, ethanol and hydrogen fuels
7	Assess data to determine the optimal means to integrate the TPCE concept into real-world practical motor vehicles

PROJECT RESULTS

Tasks 1 and 2 (Design, fabricate and assemble heat exchanger, branched intake manifold and diverter valve; integrate into existing engine test facility) were completed. Initially we attempted to out-source the fabrication to a commercial heat exchanger manufacturer (NREC) but eventually (after many discussions and much time lapse) they declined to bid on the project. Consequently, we fabricated our own heat changer using 20 stainless steel tubes, each bent into a U-shape (Figures 1 – 7). This apparatus was integrated into the exhaust system of our existing engine test apparatus and plumbing installed to allow a controllable portion of the intake air to flow into this system, thereby enabling control over the intake air temperature.

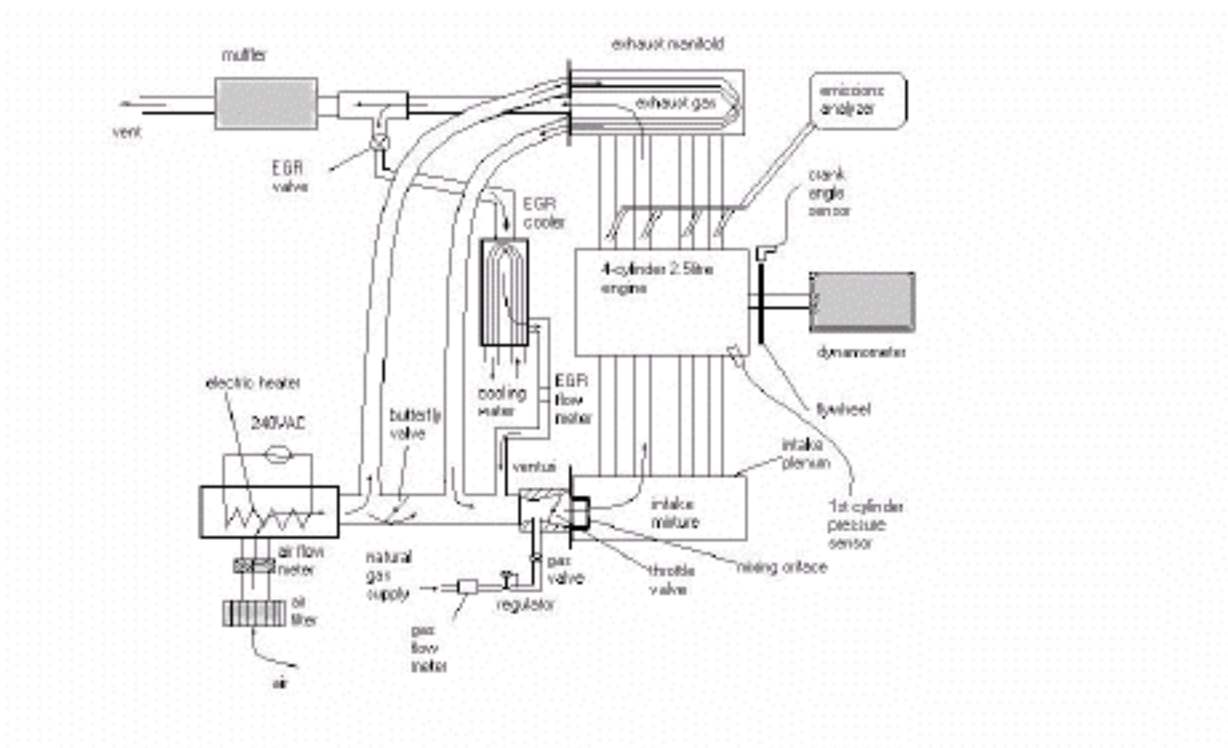

Figure 1. Schematic diagram of engine test setup including exhaust/intake heat exchanger.

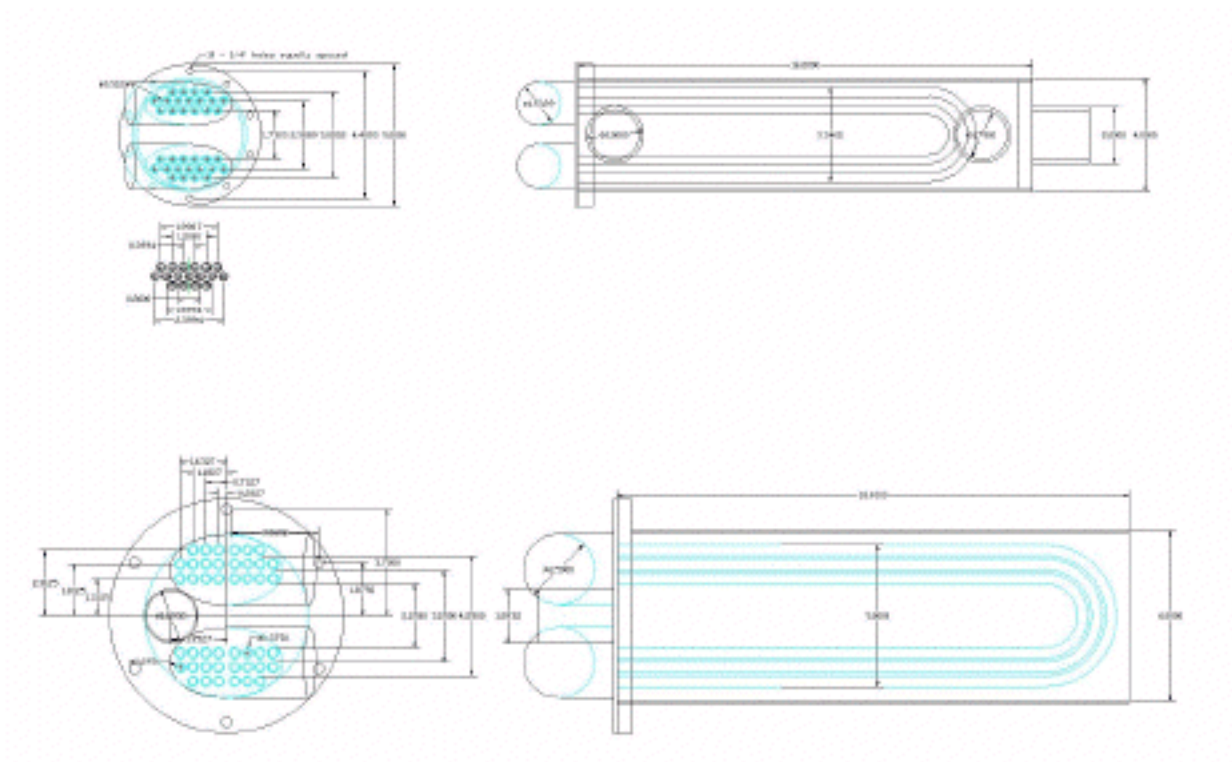

Figure 2. Detail drawing of exhaust/intake heat exchanger.

Figure 3. Photograph of interior of heat exchanger. Intake air flows through U-shaped tubes.

Figure 4. Photograph of assembled exhaust/intake heat exchanger.

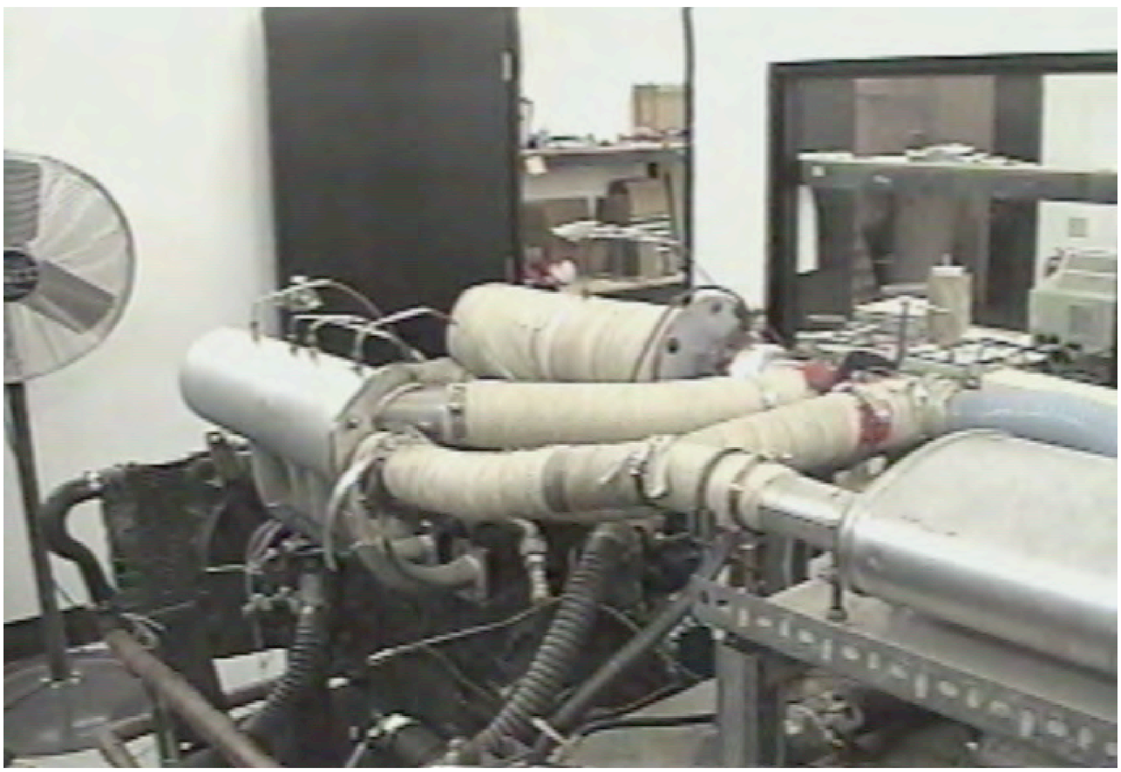

Figure 5. Photograph of engine with installed intake / exhaust heat exchanger (3/4 view).

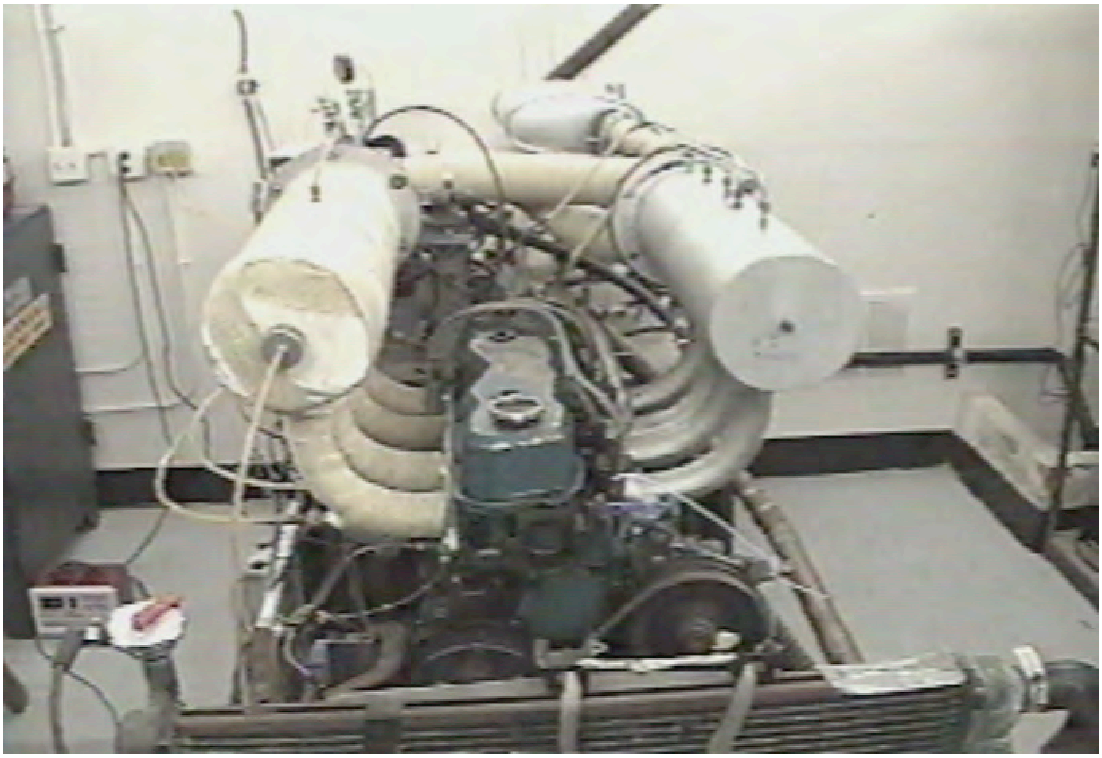

Figure 6. Photograph of engine with installed intake / exhaust heat exchanger (front view).

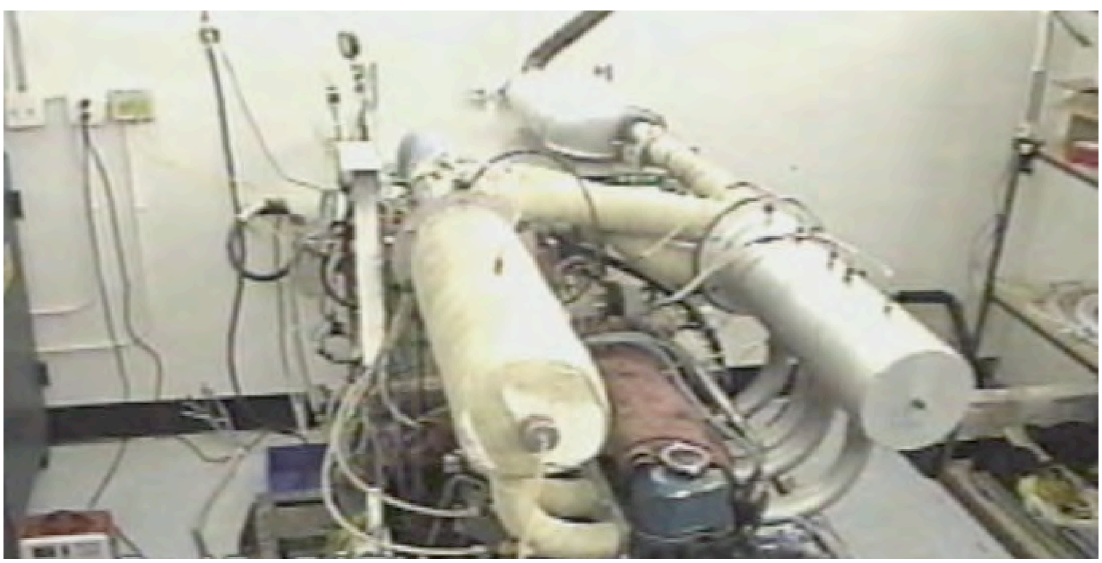

Figure 7. Photograph of engine with installed intake / exhaust heat exchanger (rear view).

Task 3 (operate of TPCE engine on natural gas) was completed. Results are shown in Figures 8 - 12. The effect of ignition timing was investigated and in all cases the timing corresponding to the data shown in Figures 8 - 12 correspond to maximum brake power. These data show the expected improvement in fuel efficiency and emissions performance obtainable with the throttleless engine system. These data generally show that for a given power level, the most advantageous mode of operation is to use the leanest possible mixture with the least preheating in order to minimize NO_x formation. UHC emissions show the opposite trend. CO emissions are not substantially affected by the choice of mixture strength and intake temperature for a given preheat level. Somewhat unexpectedly, lean mixtures exhibited excellent resistance to engine knock compared to stoichiometric mixtures [2]. This is significant because the intake charge preheating used in the TPCE concept might have worsened knock problems, but for lean mixtures our research has shown that this is not the case. An important implication of these results is that optimal fuels for TPCE engines may be different from those of conventional stoichiometric-burning throttled engines.

The observed pre-catalyst NO_x level of less than 0.8 grams of NO_x per kW-hr (0.6 grams per hp-hr) at moderate and light loads corresponds to less than 0.2 grams per mile for a typical 15 hp road load at 55 mi/hr – **without the use of a reducing catalytic converter for NO_x removal.** This emission level is half of the 2001 California standard, and equal to the 1998 "Clean Fleet" standard required for 30% of new vehicles used by centrally-fuelled fleets in cities with poor air quality.

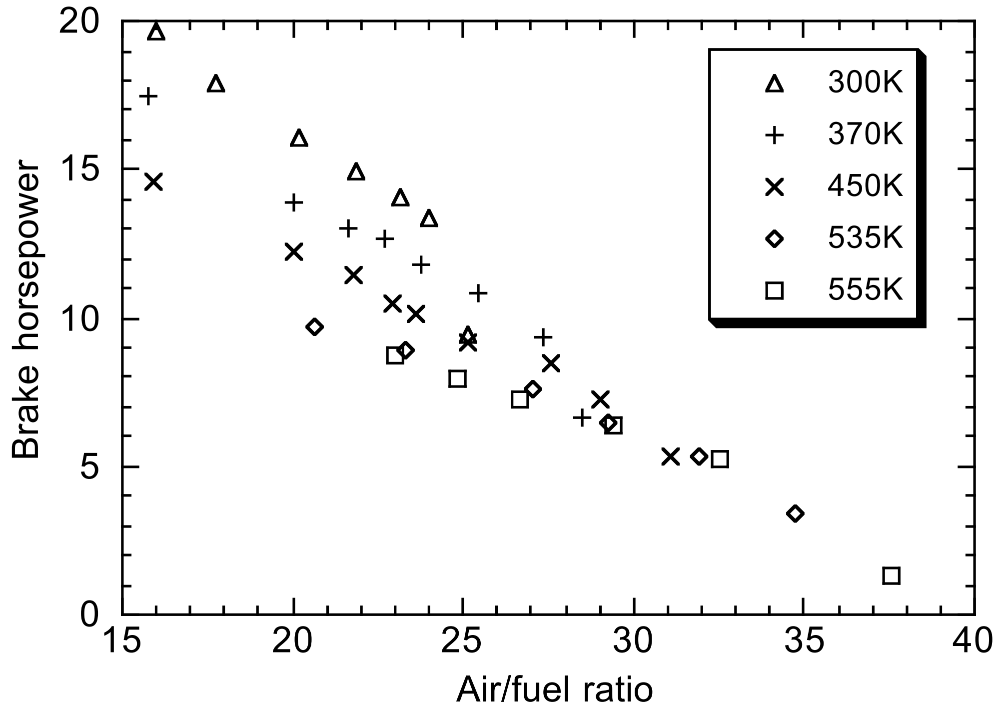

Figure 8. Effect of air/fuel ratio and intake air temperature on brake horsepower output of TPCE engine operating on natural gas.

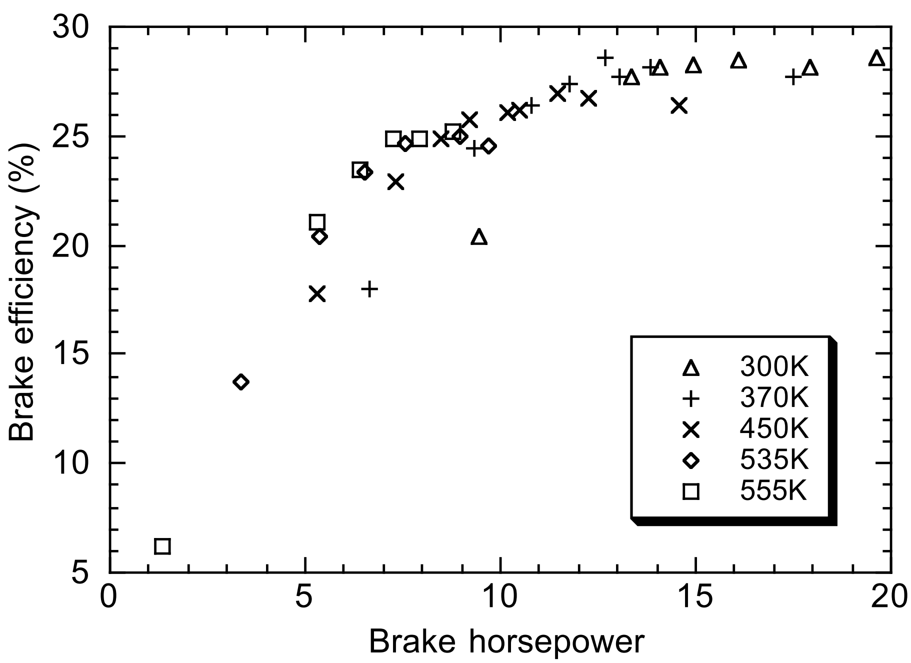

Figure 9. Effect of engine load (in terms of brake horsepower) and intake air temperature on brake thermal efficiency of TPCE engine operating on natural gas.

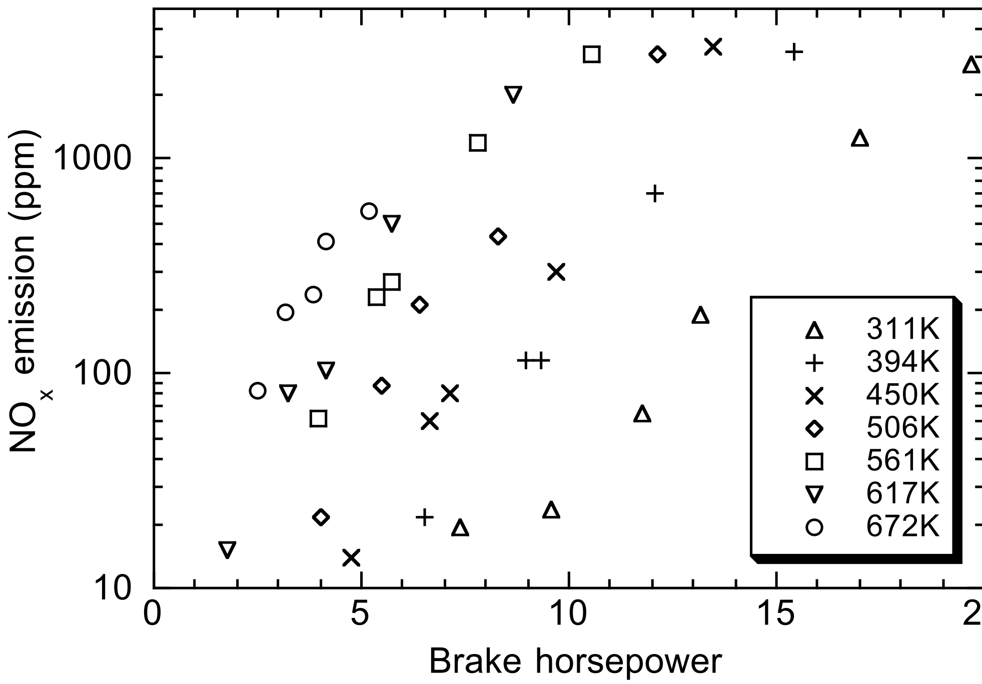

Figure 10. Effect of engine load (in terms of brake horsepower) and intake air temperature on NO_x emissions of TPCE engine operating on natural gas.

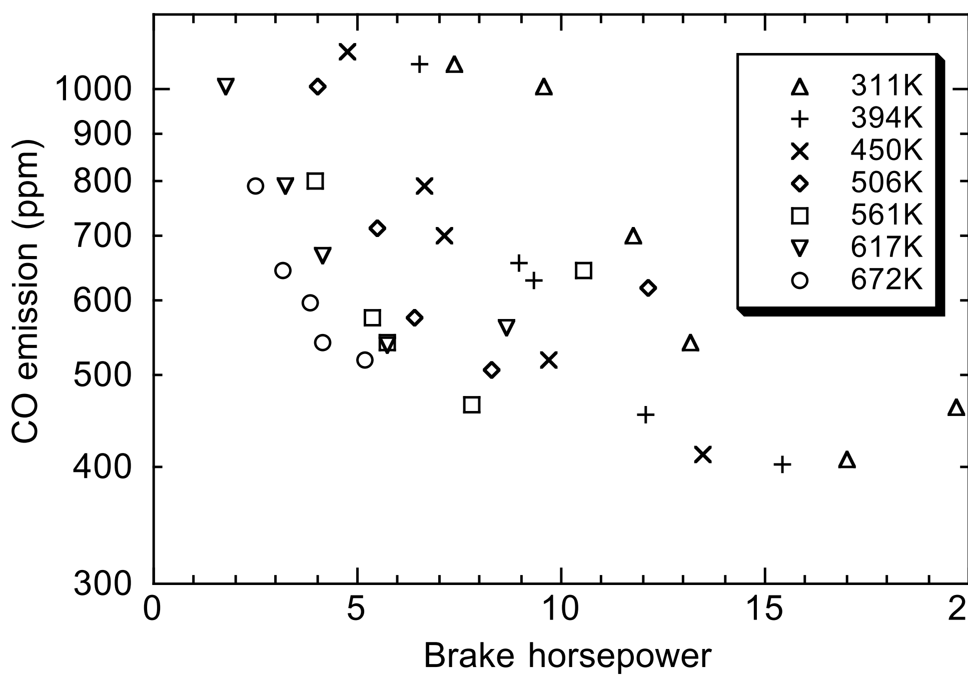

Figure 11. Effect of engine load (in terms of brake horsepower) and intake air temperature on CO emissions of TPCE engine operating on natural gas.

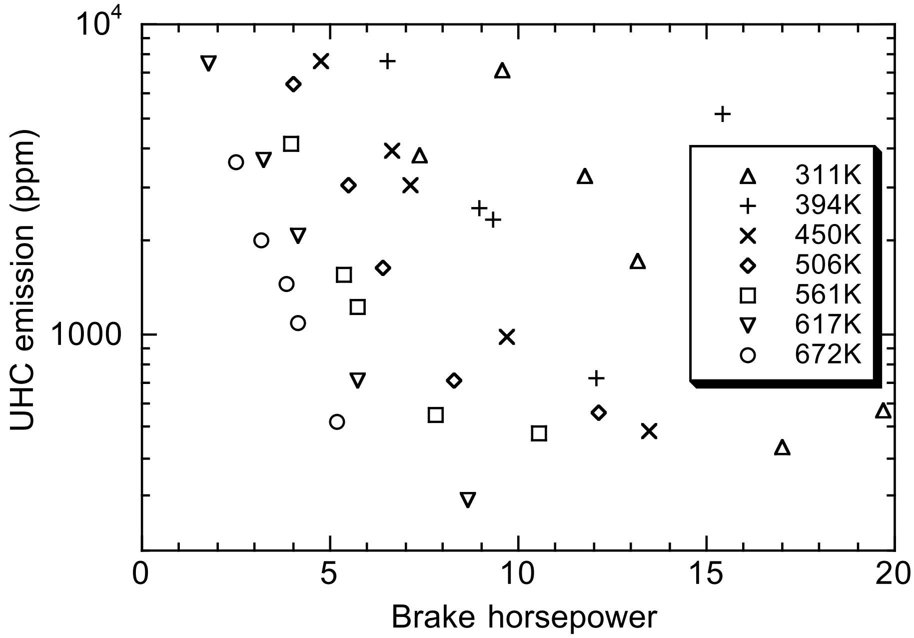

Figure 12. Effect of engine load (in terms of brake horsepower) and intake air temperature on unburned hydrocarbon emissions of TPCE engine operating on natural gas.

Task 4 (Determine dynamic response of TPCE to changes in torque demand, *i.e.* determine the time lag between change in torque command input and engine torque output) was completed. Results are shown in Figures 13 - 16. The typical response time for either increases or decreases in torque demand is 1 - 2 seconds. It should be noted, however, that these times are for a non-optimized heat exchanger design and with an optimized design (in particular, tubes with thinner walls) this time could easily be reduced.

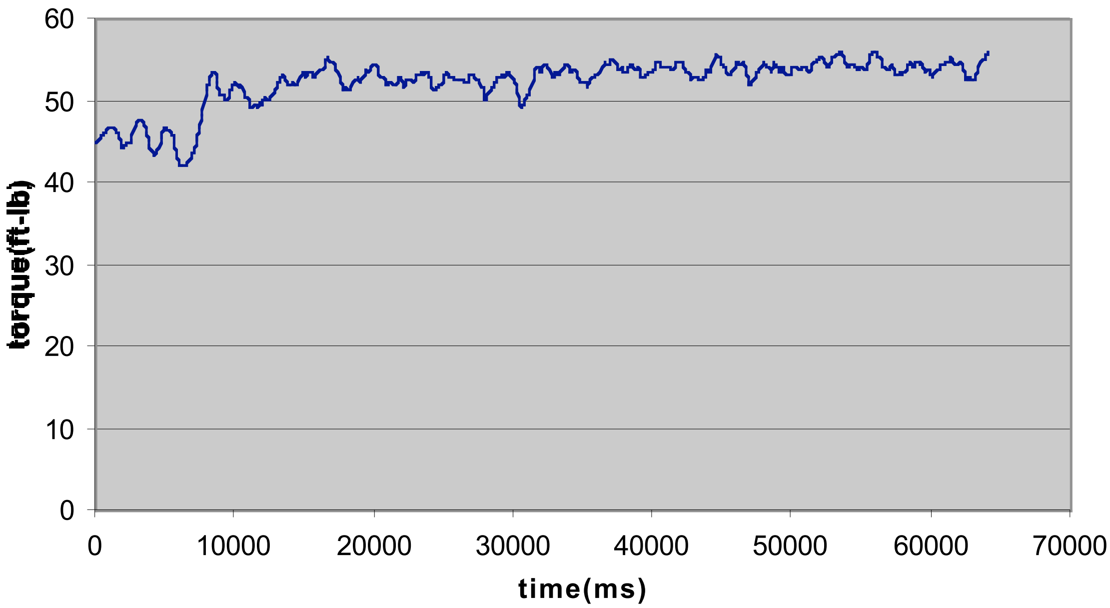

Figure 13. Change in engine torque as a function of time for 1500 RPM engine speed, butterfly valve from full close (minimum torque) to full open (maximum torque).

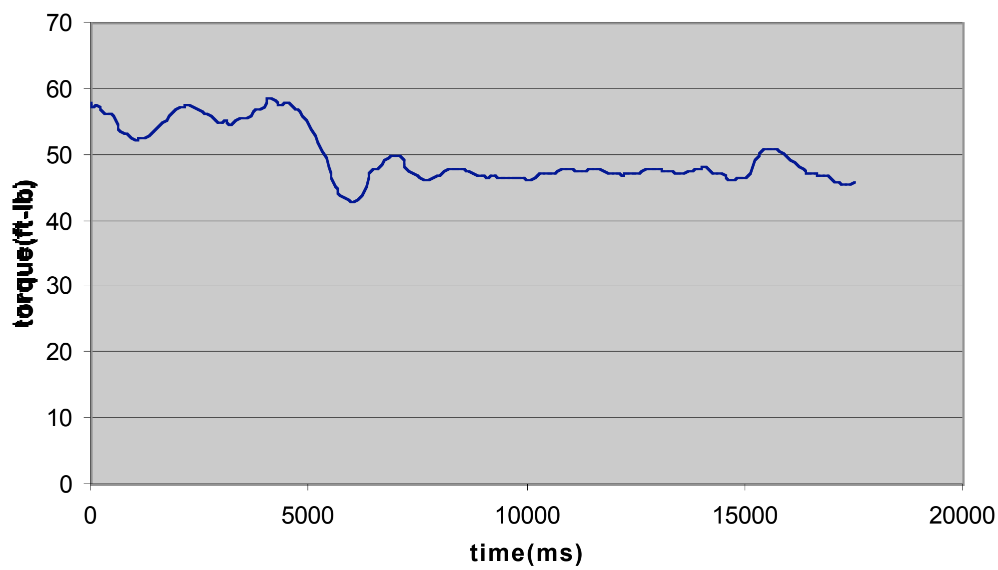

Figure 14. Change in engine torque as a function of time for 1500 RPM engine speed, butterfly valve from full open (maximum torque) to full close (minumum torque).

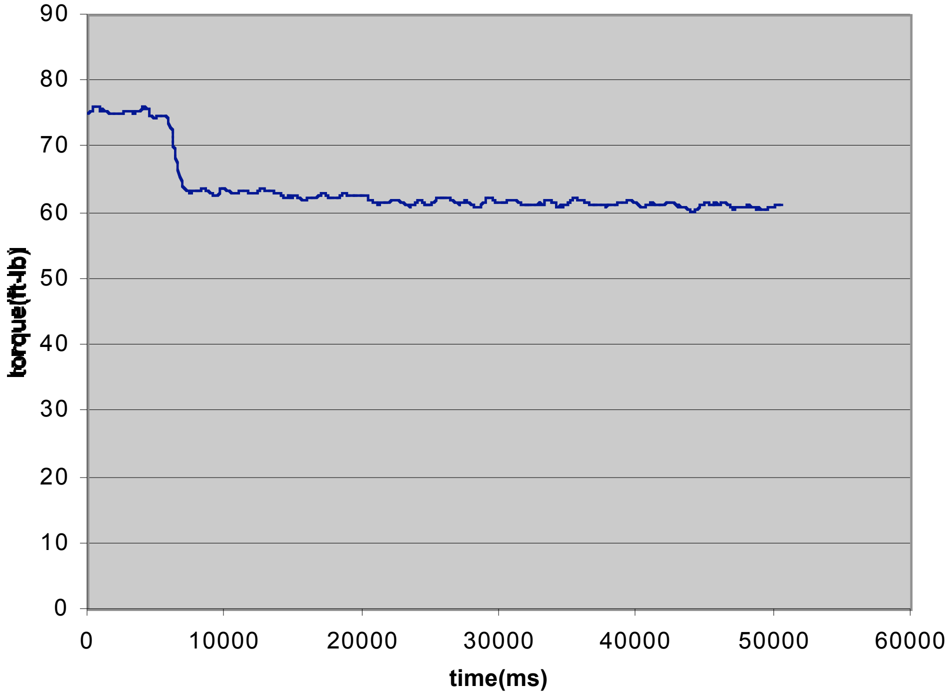

Figure 15. Change in engine torque as a function of time for 1200 RPM engine speed, butterfly valve from full open (maximum torque) to full close (minumum torque).

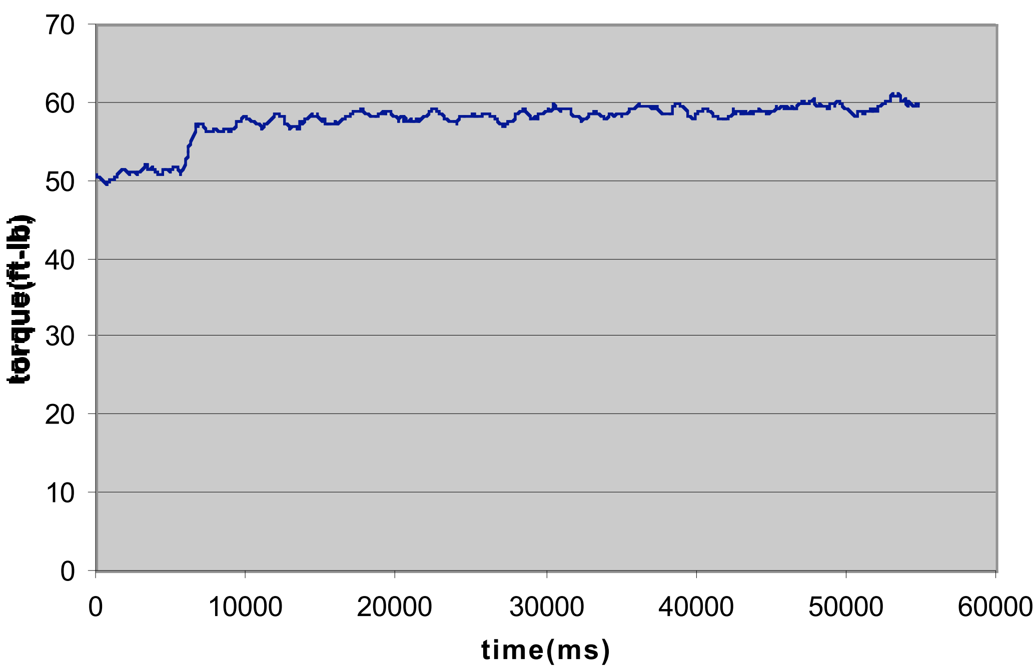

Figure 16. Change in engine torque as a function of time for 1200 RPM engine speed, butterfly valve position change corresponding to 206˚C (lower torque) to 127˚C (higher torque).

Tasks 5 – 7 were not completed during the project period. This was because of technical problems associated with the construction and modification of the building in which the new engine lab is located. The high-pressure natural gas supply line has recently been completed, so that natural gas testing can be completed soon. Also, at high engine power levels the room ventilation was not sufficient and so the room would get too warm for testing with liquid fuels due to pre-vaporization. Sufficient ventilation and/or cooling to the engine lab is being added now and will be completed in the next few months, leaving plenty of time to complete the project by August 3, 2002, with no additional SCAQMD project costs. (This METRANS project was part of a cost-sharing effort funding by SCAQMD (South Coast Air Quality Management District), and the portion of the effort supported by SCAQMD will continue until that time.)

IMPLEMENTATION

The TPCE concept is simple and inexpensive to implement since it requires only one additional moving part compared to a conventional engine – a diverter valve in the intake stream. Moreover, it is easy to retrofit to existing engines because only a change of the intake, exhaust, and engine control systems is required. No changes to the major engine mechanical parts (cylinder heads, cylinder block, valve train, etc.) are needed. A block diagram of how the TPCE concept can be implemented is shown in Fig. 17, which is similar to the test setup shown above. The intake manifold is branched into preheated and non-preheated sections. The preheated section obtains thermal energy from the exhaust gases through a heat exchanger. The amount of preheat is controlled by a diverter valve in the intake manifold. The heated air is then mixed with fuel (if carbureted) and fed into the combustion chambers. The fuel:air ratio and level of preheating employed depend on the power or torque required. Since many combinations of fuel:air ratio and intake temperature will provide the same power or torque output, there is flexibility to optimize performance depending upon the application. For most applications low NO_x emissions are required, but the improvements in thermal efficiency that are possible with the TPCE must not be compromised substantially. Our test results indicate that for these criteria, the optimal operating condition is to use the leanest mixture that does not produce significant misfire and the corresponding reduction in thermal efficiency. If the power output is larger than desired at this condition, greater preheat should employed and fuel:air ratio reduced to the new lean misfire limit. For vehicle applications, a rapid response to changing power or torque demand is required. Much of the dynamic performance of throttled engines is maintained in the TPCE system despite the presence of the heat exchanger and its unavoidable thermal lag time. This is achieved through the use of the diverter valve and the branched intake manifold. By this means cold, non-preheated reactants are available without delay when the power or torque demand increases suddenly. Moreover, in most implementations of the TPCE concept, an auxiliary throttle would be useful under some conditions such as: (a) shortly after startup, when the heat exchanger is cold and thus unable to provide sufficient preheating; (b) at very low power or torque demand, that is below the capabilities of the use of low fuel:air ratio and high intake temperatures; (c) in vehicles when engine braking is desired, for example when coasting downhill; and (d) when a transient response faster than the capabilities of the baseline TPCE is desired.

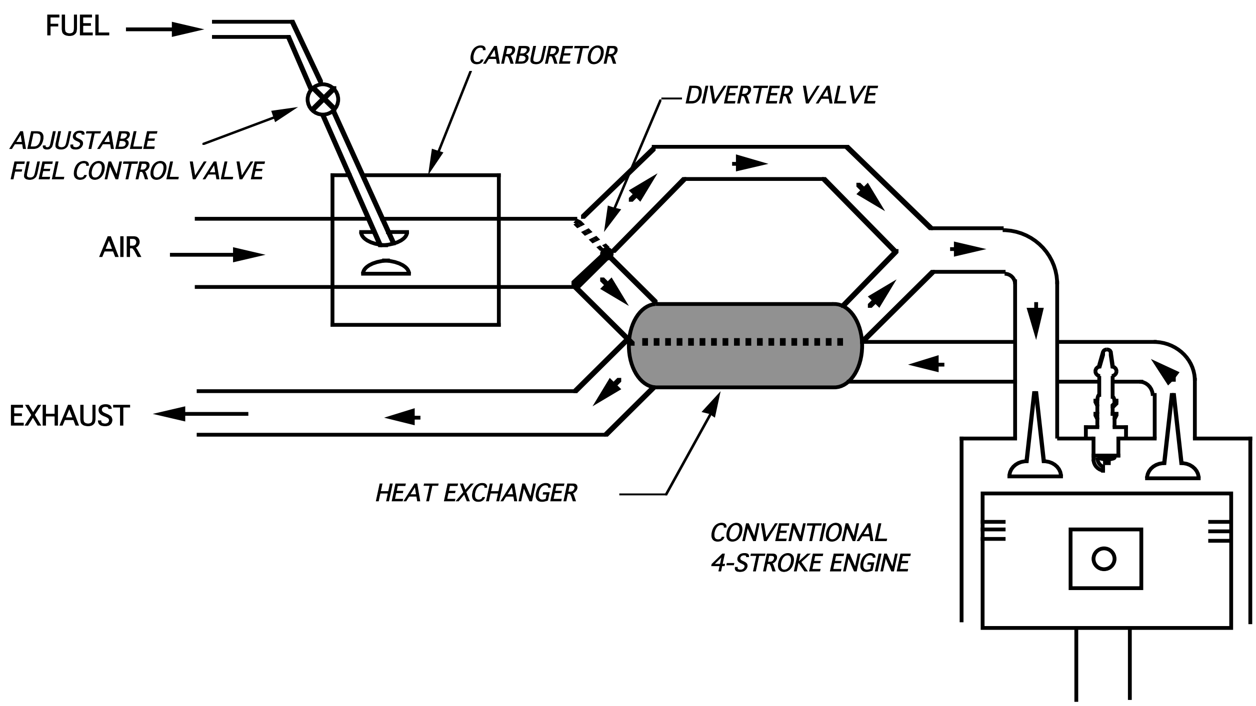

Figure 17. Possible implementation of TPCE using heat exchanger and diverter valve to control inlet temperature and thus torque output. (Carbureted gaseous fuel system shown; liquid fuel system would likely employ fuel injection system).

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