DEVELOPMENT OF THE UTEP E85-FUELED VEHICLE

E. Acedo, O. Acosta, D.G. Holloway, F. Jasso, J. Perez, M. Perez, J.A. Villalobos, R. B. Wicker*
***Faculty Advisor and Contact Author**

The University of Texas at El Paso Department of Mechanical and Industrial Engineering El Paso, Texas 79968-052

ABSTRACT

UTEP has developed a dedicated E85 vehicle with superior emissions and cold starting characteristics when compared to the original gasoline vehicle, and with no apparent differences in performance and driveability. All fuel system components that were not E85 compatible have been replaced or modified. Cold start characteristics are improved by incorporating a high frequency multiple spark ignition system and a high-pressure fuel delivery circuit, successfully extending the lean flammability limit of E85. The stock ECM is utilized for engine control and provides sufficient control during all normal driving conditions. To account for differences in fuel characteristics, increased mass flow rate injectors are used. An ethanol-specific light-off and main catalyst are being utilized for emissions reductions. To further reduce required warm up time, the exhaust manifold is coated with a ceramic material up to the exhaust catalyst. There have been no internal engine modifications to maintain fuel flexibility. However, the intake manifold has been honed, which provides an approximate 15 horsepower increase.

INTRODUCTION

The 1998 Ethanol Vehicle Challenge (EVC) involves fourteen schools from across the United States and Canada. The challenge for the teams is to convert a 1997 Chevrolet Malibu with a 3.1L V6 engine to dedicated operation on E85 (85% denatured ethanol and 15% gasoline) according to the competition rules [3]. The University of Texas at El Paso (UTEP) team consists of ten students from the Engines & Alternative Fuels Research Laboratory (EAFRL) located within the Mechanical and Industrial Engineering Department. The EAFRL occupies approximately 2,500 square feet of floor space and has research equipment that includes an engine test cell and engine dynamometer, flow rate measurement bench, chassis dynamometer, continuous emissions monitoring equipment, cold start test facility, and various additional equipment. This laboratory provided an adequate facility for the conversion of the vehicle.

UTEP has participated in a number of vehicle challenges including the 1993 CNG Vehicle Challenge, the 1995 Hybrid Electric Vehicle Challenge and the 1996 and 1997 Propane Vehicle Challenges. Numerous educational benefits are derived from participation in these challenges.

For example, this year, the student team has designed and built a fully instrumented engine stand, specified and installed a cold start test facility, and performed numerous engine dynamometer and cold start tests.

The 1998 EVC is the first year for ethanol as the motor fuel. Ethanol is an attractive fuel and has many advantages compared to other alternative fuels. One of the primary advantages when compared to other alternative fuels is that ethanol is a renewable fuel. The majority of the ethanol in the U.S. is made from the fermentation of grain, primarily corn, biomass, and sugarcane. Additionally, ethanol has the potential for lower emissions than many other fossil fuels because of its low carbon to hydrogen ratio. The high octane rating of ethanol allows the use of higher compression ratios, thus increasing the thermal efficiency of the engine. Finally, the storage and dispensing of ethanol is similar to gasoline since it is a liquid fuel [1].

Despite the numerous advantages, there are also some difficulties encountered when using ethanol as a motor fuel. For example, ethanol is corrosive and electrically conductive, and thus, the components used in the fuel system of a traditional gasoline powered vehicle may not be compatible with ethanol. Ethanol also has a low vapor pressure, making engines difficult to start when cold. This particular fuel characteristic presents the most significant challenge for this year’s competition.

The UTEP strategy has always been to combine simplicity and sound engineering practices with the effective use of experimentation for design validation. Using this principle, the UTEP team focused on five basic areas for the 1998 EVC. These areas are described briefly below.

1. Fuel System Compatibility: Fuel system components that are not ethanol compatible have been replaced or modified.

2. Cold Start Strategy: UTEP focused much energy on the cold start problem. For cold starting, a multiple spark discharge ignition system combined with a higher pressure fuel delivery system successfully extend the lean flammability limit of the E85.

3. Engine Management: The OEM ECM is used along with higher flow rate fuel injectors. The OEM ECM maintains the vehicle in closed-loop control during all expected closed-loop conditions, as determined by an FTP test.

4. Emissions: Quick catalyst heat-up is important for minimizing hydrocarbon emissions after a cold start. The exhaust system from the engine to the catalyst has been ceramically coated to minimize catalyst light-off time. Also, an ethanol-specific light-off and main catalyst have been placed in the exhaust system.

5. Performance: For the same compression ratio engine, there is a performance penalty when converting from gasoline to E85. In order to maintain fuel flexibility (not a competition requirement), no internal modifications have been made to the engine. However, engine performance has been improved by polishing the intake manifold

runners.

The following more fully describes the five areas of the UTEP conversion. Results of experiments conducted during the course of the conversion are also included.

FUEL SYSTEM COMPATIBILITY

The team identified various modifications to the fuel system that were required prior to E85 operation. Ethanol is corrosive and not compatible with some of the gasoline fuel system components. Ethanol is not compatible with most plastics, rubber seals, and aluminum. General Motors (GM) informed the teams that the gas tank, flexible lines, body lines, strainer, lubricating oil, level sensor and the in-tank fuel pump reservoir did not need to be replaced. The gas tank is steel coated with zinc-nickel epoxy, which is ethanol compatible. The flexible fuel lines, pump reservoir, and body lines are constructed of nylon or steel. The strainer is constructed with Saran and the level sensor is mounted on a ceramic card. These components are ethanol compatible and have not been replaced or modified.

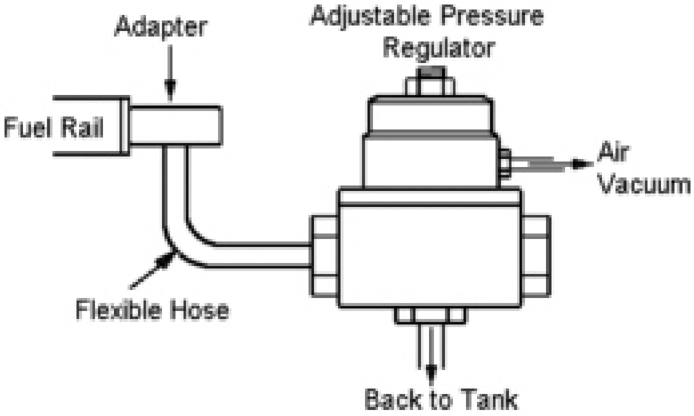


Figure 1. Schematic of adjustable pressure regulator and fuel rail adapter to replace stock fuel pressure regulator.

Fuel system components that were replaced include the fuel pump, fuel regulator and the fuel injectors. Fuel system modifications include anodizing the aluminum fuel rail and the addition of a filler neck flame arrester. The fuel pump has been replaced with an electrically shielded pump provided by GM. This in-tank pump has been placed in the original tank location. The aluminum fuel rail has been coated with a gold alodine coating. The pressure regulator attached to the fuel rail has been replaced with an adjustable pressure regulator that is ethanol compatible. The Paxton 800-1690 regulator (adjustable from 0 psi to 70 psi for the Malibu fuel pump), is placed in the fuel system as shown in Figure 1. This pressure regulator allowed for extensive testing of fuel rail pressure effects on cold starting.

The fuel injectors have also been replaced. For the required increased mass flow rate difference between E85 and gasoline, the stock injectors have been replaced with MSD 2019 saturated 24 lbs/hr (at 45 psi) injectors (details of the injector selection procedure are provided in the Engine Control section). These injectors combined with an increased fuel delivery pressure allowed the OEM ECM to effectively control the fuel flow rate. In addition, all the O-rings on the injectors and fuel rail have been replaced with Viton-B O-rings.

COLD START STRATEGY

The most significant challenge addressed by the 1998 UTEP EVC team has been the cold start strategy. Ethanol does not readily ignite in a cold engine due to its low vapor pressure and high heat of vaporization. For these reasons, the UTEP team focused on two strategies for cold start improvement. Cold start characteristics were improved by incorporating a high frequency multiple spark ignition system and a high-pressure fuel delivery circuit. A prototype multiple spark ignition system for the 3.1L engine with a Distributorless Ignition System (DIS) was acquired from Autotronic Controls Corporation. The improved ignition system combined with a high-pressure fuel delivery circuit successfully extended the lean flammability limit of E85 [as described in reference 4] to provide superior cold starting characteristics.

Figure 2. Photograph of the Engine Cold Start Test Facility.

For cold start testing, the team purchased and installed a freezer in the EAFRL (see Figure 2). The additional engine provided by GM was to be placed inside the freezer for cold start testing. However, the team could not identify the source of an engine misfire in the additional engine for several months, and as a result, no cold start tests were performed within the new Engine Cold Start Test Facility.

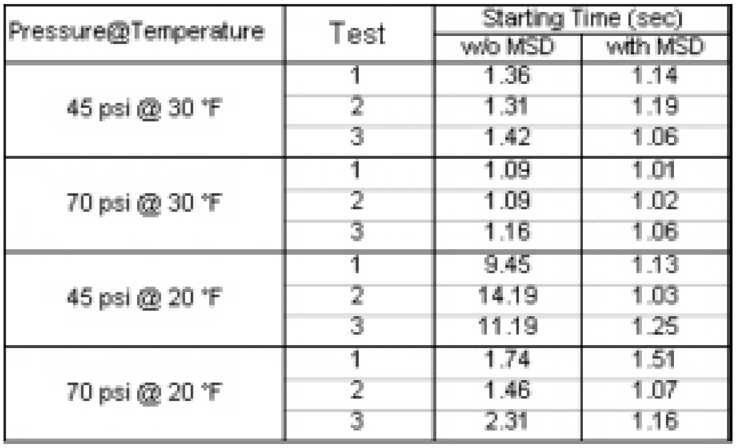
Despite the difficulties with the additional engine, cold start tests were performed using the UTEP vehicle. For the tests, the entire vehicle was placed inside a refrigerated trailer (see Figure 3) that was rented for one month from a local company. A series of tests were performed at various temperatures, using both gasoline and the E85 competition fuel, with and without the multiple spark ignition system, and for various fuel rail pressures. These tests allowed for the optimization of the UTEP cold start strategy.

Figure 3. EVC vehicle inside refrigerated trailer for cold start testing.

The multiple spark discharge (MSD) ignition system used in the UTEP strategy is capable of supplying high energy, high frequency multiple sparks of 105-115 milli-Joules per spark. This series of sparks increases the probability of igniting a flammable mixture in the combustion chamber, and has been shown to extend the lean flammability limit in gasoline [4].

Results from cold start tests at different temperatures, fuel rail pressures, and with and without the MSD ignition system are provided in Table 1. The fuel rail pressure was adjusted using the adjustable pressure regulator shown in Figure 1. The two pressures shown in Table 1 are the stock fuel rail pressure of 45 psi and the maximum pump head of 70 psi. The starting time of the stock gasoline vehicle at 20 ºF was measured as 1.4 seconds. Thus, as is shown in Table 1, a high pressure fuel delivery circuit, combined with the multiple spark ignition system provides excellent cold starting characteristics.

A final fuel rail pressure of 60 psi was selected for the vehicle. This pressure was the minimum pressure that provided reliable and repeatable engine starts at 20 ºF. Finally, the team used low viscosity synthetic oil and a high cranking amperage battery for improved cold starting.



Pressure@Temperature	Test	Starting Time (sec)	
		w/o MSD	with MSD
45 psi @ 30 °F	1	1.36	1.14
	2	1.31	1.19
	3	1.42	1.06
70 psi @ 30 °F	1	1.09	1.01
	2	1.09	1.02
	3	1.16	1.06
45 psi @ 20 °F	1	9.45	1.13
	2	14.19	1.03
	3	11.19	1.25
70 psi @ 20 °F	1	1.74	1.51
	2	1.46	1.07
	3	2.31	1.16

Table 1. Starting times for cold starts with and without MSD ignition system at different fuel rail pressures.

ENGINE CONTROL

The UTEP team originally planned to use a MOTEC programmable controller for engine control. However, after the vehicle was converted to E85, it was observed that the stock ECM provided adequate engine control during operation (as measured with the Tech–II Scan Tool and an FTP emissions test). As a result, the stock ECM was retained for the conversion. This strategy maintained fuel flexibility and lead to a very cost-effective conversion.

To retain the stock ECM, the gasoline fuel injectors had to be replaced with higher flow rate injectors suitable for E85. The OEM injectors are saturated type and have a static mass flow rate of approximately 21 lbs/hr. To determine a suitable mass flow rate fuel injector for E85, the following analysis was performed.

The performance of an engine can be described by the engine brake power. The engine brake power, *bp*, is the power output of an engine as measured by an engine dynamometer with the engine running at constant speed. The brake power can be written:

$$bp = \eta_{ti}\eta_c\eta_V\eta_m \frac{\rho DN}{x} LHV_p FA \qquad \text{(Eq. 1)}$$

where η_{ti} is the indicated thermal efficiency, η_c is the combustion efficiency, η_V is the volumetric efficiency, η_m is the mechanical efficiency, ρ is air density, *D* is engine displacement, *N* is engine rpm, *x* is the number of engine revolutions per power stroke, LHV_p is the constant pressure lower heating value, and *FA* is the fuel air ratio [2]. If the four engine efficiencies can be determined, the performance of an engine can be specified. Using the definitions for the volumetric efficiency and the fuel air ratio, Equation 1 can be rearranged in terms of the mass flow rate of the fuel.

$$\dot{m}_{fuel} = \frac{bp}{\eta_{ti}\eta_c\eta_m LHV_p} \quad \text{(Eq. 2)}$$

Assuming (as a first approximation) that the efficiencies in Equation 2 remain the same for E85 and gasoline, the E85 fuel flow rate can be related to the gasoline fuel flow rate for the same brake power. The resulting relationship becomes

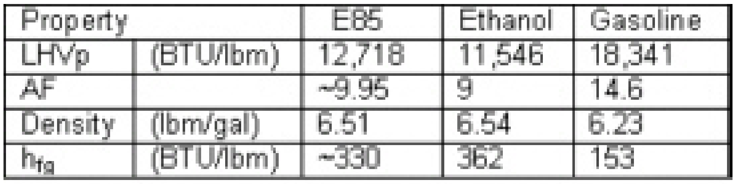
$$\dot{m}_{Ed85} = \frac{LHV_p(gas)}{LHV_p(Ed85)}\dot{m}_{gasoline} \quad \text{(Eq. 3)}$$

Equation 3 shows that the required E85 mass flow rate can be related to the gasoline mass flow rate and the ratio of gasoline and E85 constant pressure lower heating values. Properties of gasoline, ethanol, and E85 are provided in Table 2. Using the LHV_p values in the table, the required E85 fuel flow rate becomes:

$$\dot{m}_{Ed85} = 1.44 \times \dot{m}_{gasoline} \quad \text{(Eq. 4)}$$

Thus, as a first approximation, it appears that approximately 44% more E85 is required for the same brake power.

Using this value as a baseline, the team identified potential injectors for replacement. The injectors available on the market had a limited selection of flow rates. The two available sizes that could simply "plug" into the existing fuel rail were 24 lbs/hr and 38 lbs/hr (static flow) injectors. As a result, the 24 lbs/hr ethanol compatible MSD 2019 12v saturated injectors were chosen for testing.



Property		E85	Ethanol	Gasoline
LHVp	(BTU/lbm)	12,718	11,546	18,341
AF		~9.95	9	14.6
Density	(lbm/gal)	6.51	6.54	6.23
h_{fg}	(BTU/lbm)	~330	362	153

Table 2. Various properties of E85, Ethanol, and Gasoline (E85 from competition organizers, ethanol and gasoline from [1]).

Since the available fuel injectors were specified for static flow conditions, the team designed a dynamic flow fuel injector test rig. However, before the team finished the fuel injector test rig, it was found experimentally (by placing the injectors in the vehicle) that the stock ECM could very effectively control the fuel injection timing. Thus, these injectors performed satisfactorily and were used in the final conversion.

EMISSIONS

For exhaust emissions reduction, the stock ECM control system was combined with an ethanol-specific light-off and main catalyst from Allied Signal and ceramic coating of the exhaust manifold up to the catalyst. The light-off and main catalysts are combined in a single canister that was canned by Delphi. The exhaust manifold was coated with a ceramic material to reduce required catalyst warm up (or light-off) time.

Ethanol-specific catalytic converters were utilized to help reduce the emission of aldehydes, and specifically acetaldehyde, characterisitic of alcohol fuels [5]. The palladium light-off catalyst occupied the first third of the can while the main catalyst occupied the remaining two thirds of the can. Care was taken to minimize the light-off time (for reduced cold start emissions of ethanol) by placing the catalyst in the stock catalyst location (36 inches from the exhaust manifold) and coating the exhaust manifold up to the catalyst.

Two Federal Test Procedure (FTP) emissions tests were performed prior to the competition to compare gasoline baseline exhaust emissions with those produced by the E85 conversion. The closest Federally certified emissions test facility is in San Antonio, Texas which is 600 miles from El Paso. Southwest Research Institute located in San Antonio performed two FTP tests prior to the competition.

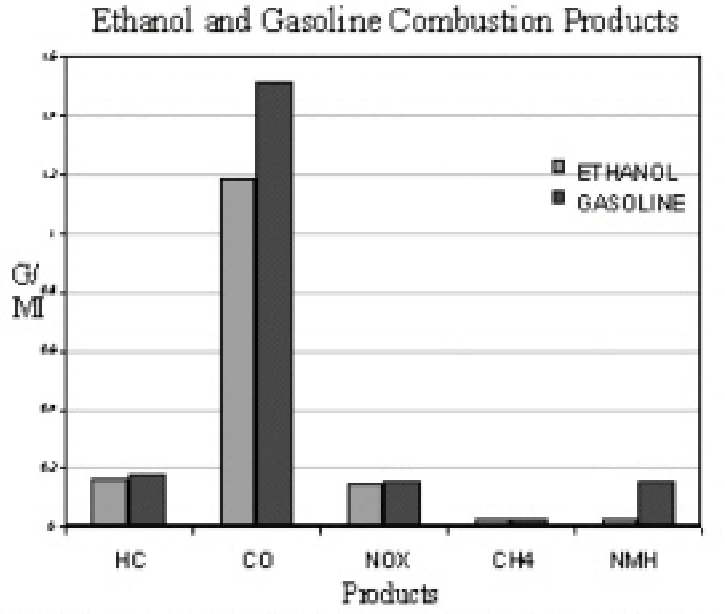


Figure 4. Combustion Products from Gasoline and E85 FTP.

Results of the two FTP tests performed by Southwest Research Institute are provided in Figure 4. In Figure 4, gasoline baseline FTP results are provided along with results for the vehicle operating on E85. The E85 results represent the emissions measured for the converted vehicle with the stock ECM, E85 compatible fuel system and fuel injectors, and ethanol-specific catalyst. However, these results are without the performance improvements (to be described in the next section) and without the exhaust manifold ceramic coating.

The results in Figure 4 illustrate that the E85 emissions are superior to gasoline. However, more detailed analysis of the FTP results (modal analysis results are not shown here) show that a significant fraction of hydrocarbon emissions occur in Bag 1. Furthermore, it was observed that the vehicle required 52 seconds to begin closed-loop operation. Thus, in order to reduce the catalyst light-off time and oxygen sensor warm-up time, the exhaust manifolds were coated with a ceramic material up to the catalyst. This modification should help reduce Bag 1 emissions. Emissions tests with the modified exhaust system were not conducted until the competition.

PERFORMANCE

Ethanol has a higher octane rating than gasoline, but has a lower LHV as discussed previously. The lower LHV has a detrimental effect on the fuel economy of the vehicle. For example, since more fuel has to be utilized to provide equivalent gasoline power and torque [see equation 1], the vehicle range is decreased by approximately 30% [2]. There are various modifications, which can be made to the engine to increase the brake power. The UTEP team considered increasing the compression ratio, supercharging, and making simple modifications to the intake and exhaust systems to minimize pressure drops.

The UTEP team did not increase the compression ratio so that the vehicle would have fuel flexibility (a good marketing strategy for ethanol but not necessarily a good strategy for maximizing points in the competition). Furthermore, the team experienced financial and ultimately time constraints that did not allow the incorporation of a supercharger. As a result, the only modification to enhance performance of the UTEP vehicle was a modification to the engine intake.

Industry experts informed the UTEP team that engine horsepower could be increased by approximately 15 horsepower by simply polishing the intake manifold runners. Furthermore, the industry experts also informed the team that the exhaust side of the engine could not be improved significantly. Thus, the intake manifold has been polished by ExtrudeHone. The polishing process removes core shift casting marks, enlarges internal passageways with consistent stock removal, blends areas between hand porting and CNC machining, and improves overall air flow through the intake manifold.

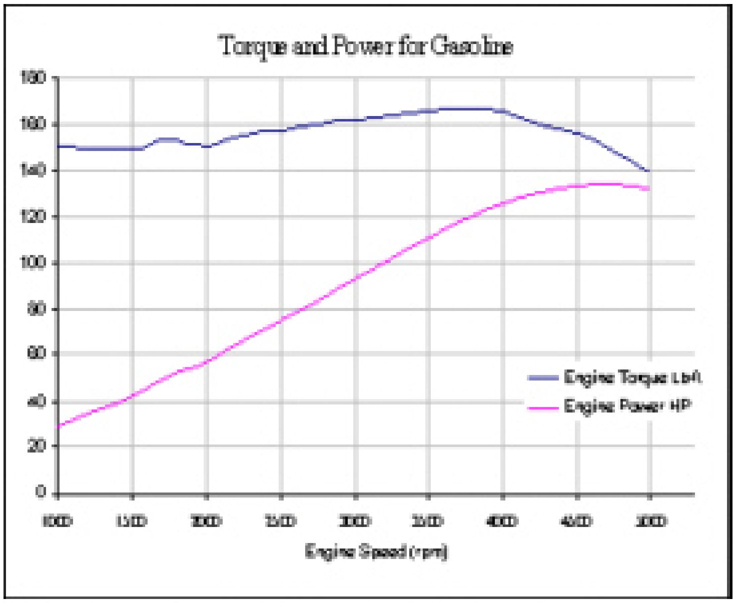


Figure 5. Engine Torque and Power for gasoline without the MSD ignition system.

Unfortunately, engine dynamometer testing was limited prior to the competition because of an engine misfire condition that occurred on the additional 3.1L V6 engine provided by GM. This condition required several months to identify and eliminate. As a result, engine dynamometer testing was only performed for gasoline baseline with the stock ignition system. As shown in Figure 5, the results obtained from the dynamometer testing show that the maximum measured torque was 167 Lb-ft at 3750 rpm and the maximum power was 134 HP at 4750 rpm. Again, the polished intake manifold is expected to provide an increase of approximately 15 horsepower over these values.

CONCLUSIONS

A team of ten UTEP students converted a 1997 Chevrolet Malibu with a 3.1L V6 engine to dedicated E85 as part of the 1998 Ethanol Vehicle Challenge. The UTEP design strategy combines simplicity and sound engineering practices with the effective use of experimentation for design validation. The dedicated E85 vehicle has superior emissions and cold starting characteristics when compared to the original gasoline vehicle, with no apparent differences in performance and driveability.

Cold-start characteristics were improved by incorporating a high frequency multiple spark ignition system and a high-pressure (60 psi) fuel delivery circuit. This strategy successfully extended the lean flammability limit of E85 to provide superior cold starting characteristics.

Engine management is provided by the stock ECM. To account for differences in fuel characteristics, increased mass flow rate injectors are used. The fuel control system remains in closed-loop operation during all expected closed-loop conditions.

Emissions reductions are provided by an ethanol-specific light-off and main catalyst placed in a single canister and in the original exhaust system. To reduce required light-off time, the exhaust manifold is coated with a ceramic material up to the exhaust catalyst.

Performance improvements focus on the intake of the engine. There have been no internal engine modifications to maintain fuel flexibility. However, the intake manifold has been honed, which provides an approximate 15 horsepower increase.

The UTEP vehicle provides an excellent demonstration of the benefits derived from an E85 system. Although the system could be further optimized for dedicated E85, the system demonstrates benefits derived from a low-cost conversion of a gasoline vehicle to a dedicated E85 vehicle.

ACKNOWLEDGMENTS

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competition are gratefully acknowledged. All the support for this project has been appreciated.

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