

Optimal Use of E85 in a Turbocharged Direct Injection Engine

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ABSTRACT

Ford Motor Company is introducing "EcoBoost" gasoline turbocharged direct injection (GTDI) engine technology in the 2010 Lincoln MKS. A logical enhancement of EcoBoost technology is the use of E85 for knock mitigation. The subject of this paper is the optimal use of E85 by using two fuel systems in the same EcoBoost engine: port fuel injection (PFI) of gasoline and direct injection (DI) of E85.

Gasoline PFI is used for starting and light-medium load operation, while E85 DI is used only as required during high load operation to avoid knock. Direct injection of E85 (a commercially available blend of ~85% ethanol and ~15% gasoline) is extremely effective in suppressing knock, due to ethanol's high inherent octane and its high heat of vaporization, which results in substantial cooling of the charge. As a result, the compression ratio (CR) can be increased and higher boost levels can be used. The increased full load BMEP allows downsizing of the engine at equivalent or enhanced vehicle performance.

By enabling higher CR and engine downsizing, the use of E85 DI + gasoline PFI makes the engine more efficient in its use of gasoline, thereby leveraging the effect of the available ethanol in reducing the consumption of gasoline. This leveraging has a profound influence on ethanol's net energy balance and CO₂ reduction potential. The vehicle owner will realize high fuel economy because gasoline, with its high heating value per volume, is primarily used for most driving modes in a downsized, high CR engine.

In this paper, the concept of E85 DI + gasoline PFI is assessed using a Ford Motor Company 3.5L turbocharged direct injection "EcoBoost" engine. A PFI system was added to the engine and CR was increased

to 12:1. The amount of E85 required to avoid knock was quantified as a function of BMEP at various engine speeds on an engine dynamometer. A full load torque curve subject to the peak pressure and turbine inlet temperature constraints of the engine was also acquired. A vehicle simulation program was then used to quantify the amount of E85 required for various drive cycles, and to determine vehicle fuel consumption.

BACKGROUND

The US Energy Independence and Security Act of 2007 mandates the use of 36 billion gallons of biofuels by 2022. This law allows for 15 billion gallons of corn-based ethanol and 16 billion gallons of cellulosic biofuel, which is likely to be primarily comprised of cellulosic ethanol. Although 31 billion gallons of ethanol would be a significant fraction of the total gasoline used in the US (about 142 billion gallons in 2007), it represents only about 14% on an energy content basis. Thus, even if the ethanol mandate of the energy bill is fulfilled, the nation's automobiles and light trucks will still rely heavily on gasoline.

There is also much debate about the net energy value of corn-based ethanol. An authoritative and thorough analysis conducted by Shapouri, Duffield, McAloon, and Wang [1], based on input data from 2001, estimates an energy output-to-input ratio of 1.67 for corn ethanol produced in the US. (That is, an amount of ethanol with 1.67 MJ of energy content requires 1 MJ of energy for production.) Continued improvement in corn farming productivity and in the efficiency of ethanol producing facilities is expected to result in higher energy ratios [2]. However, other researchers have estimated energy ratios which are less favorable, as the results are sensitive to the input assumptions and boundary conditions [3,4,5].

Further, there has been a large amount of controversy about the effect of corn-based ethanol production on land use changes [6,7], and on the availability and price of the world's food supply. A recent study on the future availability of corn for ethanol production which accounts for the trend in improving corn farming productivity [8] indicates that this criticism of corn ethanol may be unfounded. Nevertheless, balancing ethanol production with perceived effects on land use and food availability constitutes a potential argument for limiting the supply of corn ethanol.

Although production of cellulosic ethanol holds the promise of dramatically increased energy ratios [3] and reduced impact on land use changes and the food supply, it has yet to reach a large commercial scale.

With this highly political and controversial backdrop, it is apparent that the supply of ethanol is constrained, and its favorable properties should be utilized in an optimal manner to reduce petroleum consumption and CO₂ emissions.

INTRODUCTION

It is well known that ethanol has a high octane but low heating value compared to gasoline. Table 1 shows fuel properties of pure ethanol (E100) and gasoline [9].

A conventional flexible fuel vehicle (FFV) is capable of running on either gasoline or E85 or a mixture of the two fuels. Some FFV calibrations adjust the spark timing with E85 to take advantage of the higher octane of ethanol. For example, for the Ford 5.4L-3V in the 2009

Table 1: Properties of ethanol and gasoline

Property	Fuel	
	Ethanol (E100)	Gasoline
Octane (RON)	107	91-98
Heat of vaporization (kJ/kg)	840	~350
Stoichiometric A/F	9.0	~14.6
Heat of vaporization of stoichiometric fuel quantity (per mass of air)	3.9 x base	base
Lower heating value (MJ/kg)	26.9	~44
Heating value of stoichiometric fuel quantity (per mass of air)	0.99 x base	base
Density (kg/L)	0.785	~0.75
Heating value – volumetric basis (MJ/L)	0.64 x base	base

F-150, peak torque is increased from 365 ft lbs with 91 RON gasoline to 390 ft lbs with E85, and peak power is increased from 310 hp to 320 hp [10].

Recently, turbocharging has been applied to the basic technology of direct injection gasoline engines, giving rise to the gasoline turbocharged direct injection (GTDI) engine which enables downsizing of the engine to improve fuel economy for a particular vehicle application. For example, the 2010 Lincoln MKS will use a 3.5L V6 “EcoBoost” GTDI engine instead of a larger displacement V8. The increasing application of these turbocharged direct injection engines has provided a further opportunity to increase engine performance with E85 by adjusting boost levels and spark timing to take advantage of ethanol's high octane. For example, the peak power of the Saab 9-5 BioPower 2.0t is increased by 30 horsepower with E85 compared to gasoline [11].

However, even in these engines, which take advantage of ethanol's high octane to some extent, FFVs operating on E85 suffer from a dramatic reduction in range and volumetric (mpg) fuel economy due to ethanol's low heating value. Starting at cold temperatures is also problematic due to ethanol's boiling point of 78.5°C, high heat of vaporization, and low saturated vapor pressure at low temperatures [12,13]. To mitigate this issue, the percentage of gasoline components is typically increased to approximately 30% in winter blends of “E85” which are distributed in cold climates. Direct injection also shows promise for improving starting characteristics at cold temperatures on ethanol, but requires high injection pressure during cranking to be effective [14,15].

The use of E85 DI + gasoline PFI in principle overcomes these disadvantages of FFVs. The purpose of the work described in this paper is to assess E85 DI + gasoline PFI and quantify its benefits.

CONCEPT DESCRIPTION

First proposed by Cohn, Bromberg, and Heywood of MIT [16], the basic premise of E85 DI + gasoline PFI is that ethanol (or another lower alcohol such as methanol) suppresses knock due to the large evaporative cooling effect it has on the air-fuel mixture when it is injected directly into the cylinder, supplemented by ethanol's high inherent octane number [17,18,19,20]. It is widely accepted that direct injection engines benefit from an improved knock limit as a consequence of cooling of the fresh charge due to the heat of vaporization of the fuel [21]. As shown in Table 1, the heat of vaporization of ethanol is approximately four times higher than that of gasoline for a stoichiometric mixture.

The concept combining gasoline PFI with E85 DI in the same engine is illustrated in Figure 1. The concept requires separation of E85 and gasoline, which is accomplished most readily with a separate storage tank for each of the two fuels. Gasoline PFI is used for starting and low to medium load operation. The amount

of directly injected E85 is increased as a function of load, but only in the amount required to prevent knock. In this way, an E85 DI + gasoline PFI engine utilizes the full octane benefit of E85 while minimizing the negative effects of low heating value and poor cold start capability.

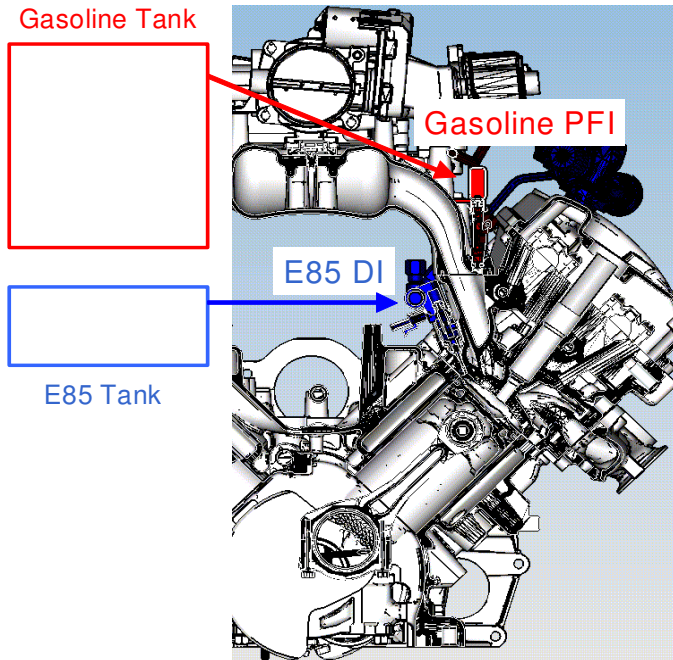


Figure 1: Cross section illustrating E85 DI + gasoline PFI

Because knock is suppressed, the compression ratio can be increased, and in a turbocharged or supercharged engine higher boost pressures can be used. The resulting higher BMEP levels allow downsizing of the engine displacement at equivalent vehicle performance. Operation at high loads with the spark timing at or close to MBT results in lower turbine inlet temperatures and consequently enrichment is reduced or eliminated. These factors result in broad regions of low BSFC in the speed/load map. In the vehicle, this enables the use of lower numerical gear or axle ratios, so that the engine operates at a lower engine speed and higher BMEP for a particular vehicle condition. This is referred to as downsizing. Both downsizing and downsizing move the operating regime of the engine to a more efficient part of the speed/load map.

The vehicle owner will realize high fuel economy because gasoline, with its greater heating value per volume, is the fuel that is primarily used for most driving modes. Furthermore, by enabling higher CR, downsizing, and downsizing, E85 DI + gasoline PFI makes the engine more efficient in its use of gasoline. Improved engine efficiency leverages the effect of the limited supply of E85, compared to simply displacing gasoline as in an FFV. As will be shown in a later section of this paper, this leveraging can be very substantial, and has the effect of dramatically improving the net energy balance of ethanol, and therefore its beneficial impact on reducing petroleum consumption.

CONCEPT ASSESSMENT

ENGINE DYNAMOMETER DATA - As a preliminary step to quantify the knock benefit of directly injected E85 on a modern turbocharged engine, an early prototype 3.5L EcoBoost engine at 9.8:1 CR was used to compare the knock-limited combustion phasing of E85 to that of 98 RON gasoline. A BMEP sweep was performed at 2500 rpm with the spark timing set to borderline knock or MBT, or as limited by the peak pressure constraint of the engine. As shown in Figure 2, with 98 RON fuel the spark timing must be progressively retarded as BMEP is increased above about 8 bar. With E85, the spark can be held at MBT until the peak pressure limit of the engine structure is reached. As expected, maintaining combustion phasing at MBT results in much lower turbine inlet temperatures compared to the retarded combustion phasing with 98 RON fuel. This can have a significant effect on the amount of fuel enrichment required and/or the cost of materials for the turbine.

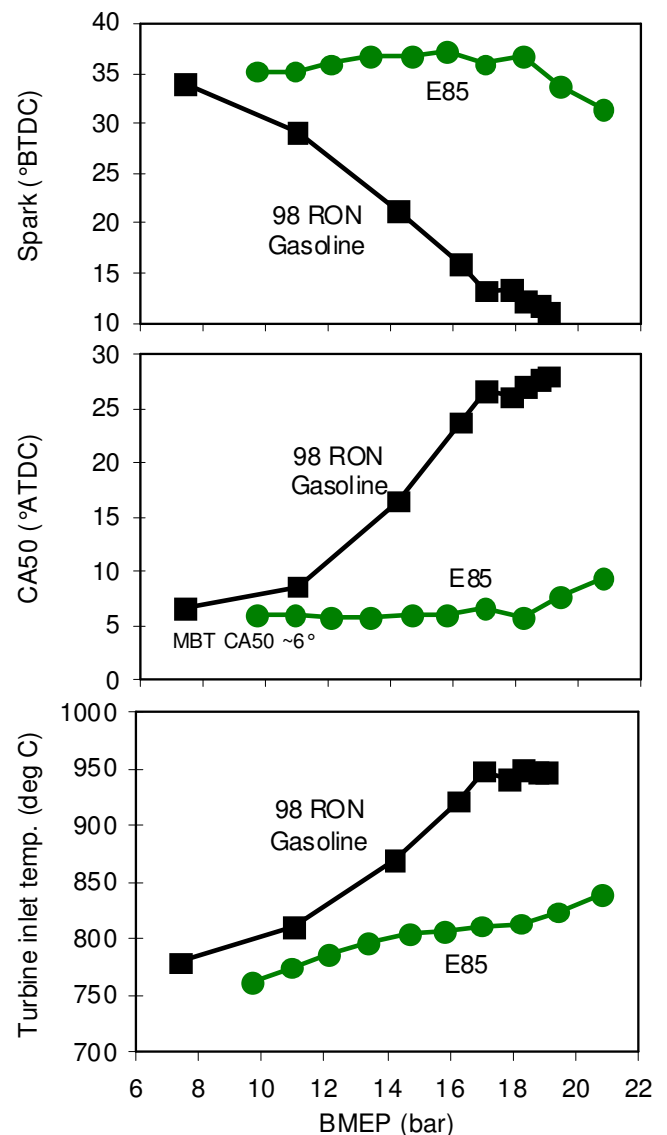


Figure 2: E85 vs. gasoline BMEP sweeps at 2500 rpm

Following this initial data which substantiated the improvement in knock with direct injection of E85, an early prototype 3.5L EcoBoost engine was outfitted with PFI, and CR was increased to 12:1 by using modified pistons. The PFI system was supplied with 91 RON gasoline, and the DI system was supplied with E85. Properties of the fuels used are shown in Table 2.

Table 2: Selected properties of E85 and 91 RON fuels

Property	Fuel	
	E85	Gasoline
% Ethanol	80.8	0
Net heating value (MJ/kg)	28.84	43.36
Specific gravity @ 60°F	0.78	0.74
H:C Ratio	2.77	1.88
O:C Ratio	0.375	0
Stoichiometric A/F ratio	10.0	14.62
RON	N/A*	91
MON	N/A*	83
Vapor Pressure (kPa)	38-59	48-56

*Fuel property not available.

BMEP sweeps were performed at various engine speeds to determine the amount of directly injected E85 required to avoid knock. Results from this testing at 2500 rpm are shown in Figure 3. In this paper, the amount of E85 is expressed as a percentage of the total mass of fuel flow, since fuel flow was measured on a mass basis in the engine dynamometer test cell.

For this early prototype EcoBoost engine, the peak pressure (mean + 3 sigma variation) was constrained to 100 bar due to engine structural limitations. As shown in Figure 3, the peak pressure limit was reached at 15 bar BMEP, requiring spark retard to control peak pressure at higher BMEP.

The spark retard results in later combustion phasing and higher turbine inlet temperature. To protect the prototype hardware, turbine inlet temperature was limited to 900°C, which is relatively conservative compared to the state-of-the-art for spark ignition engine turbochargers. The 900°C limit required enrichment with additional gasoline above 20 bar BMEP.

As shown in the bottom graph of Figure 3, the amount of E85 required to avoid knock increased with load up to 15 bar BMEP. Spark timing was limited by the peak pressure above 15 bar BMEP, and hence the required amount of E85 started to decrease with load.

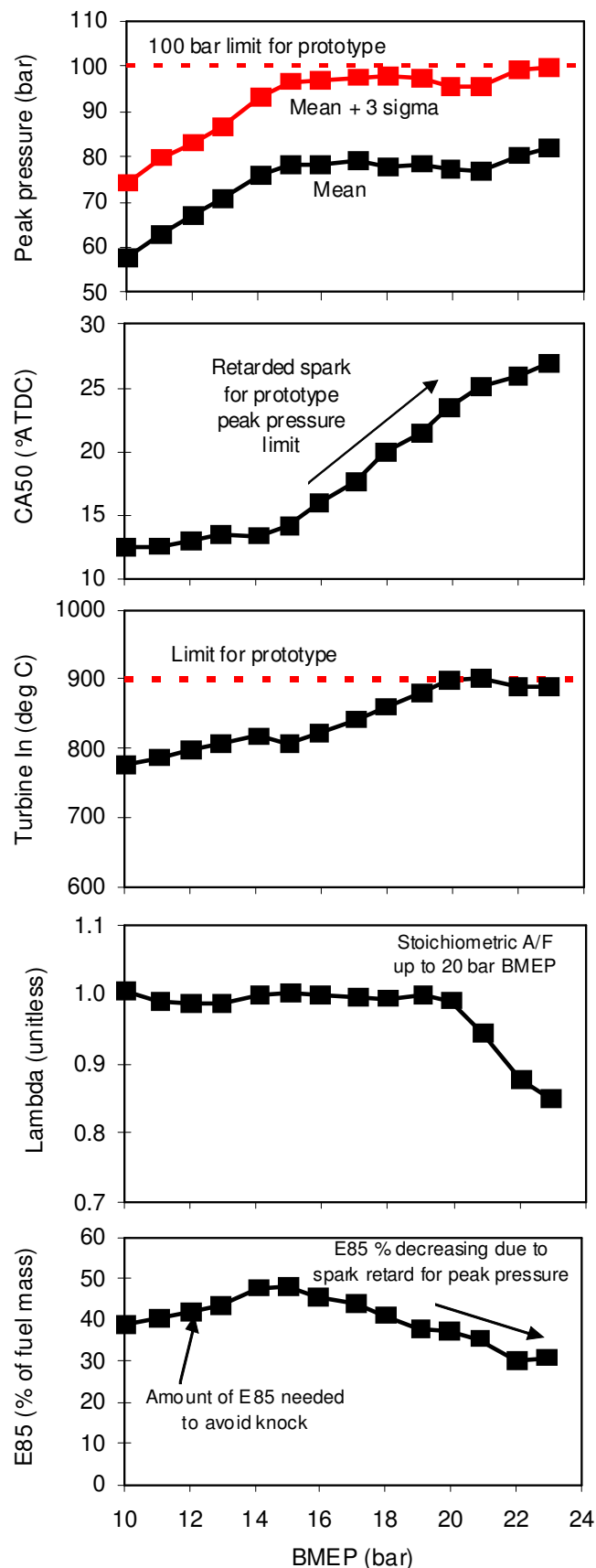


Figure 3: BMEP sweep at 2500 rpm