

Optimizing ICE Efficiency through Cycling: Methods for Evaluating Achievable Gains

J. Campanaro¹, M. Ruof, P. Bauer, J. Murillo²

¹J. Campanaro (M. Ruof, P. Bauer), University of Notre Dame, 275 Fitzpatrick Hall, jcampan1@nd.edu

²J. Murillo, Rovira i Virgili University, 26 Pasos Catalans Avenue, 43007 Tarragona, jenny.murillo.a@gmail.com

Abstract

This paper introduces evaluation methods for fuel efficiency gains that are obtainable through cycling of large ICEs in a series hybrid powertrain. The presented concepts allow for a fast and simple decision making process in determining whether cycling is advantageous for a particular engine. The paper also answers the question of the optimal number of discrete operating points and how to choose them. Artificially generated polynomial representations of *bsfc* curves as well as the *bsfc* curve of a production engine are used to illustrate the results. While the obtained methods are applicable to any series hybrid powertrain system, they are especially suited for systems powered by large Diesel engines.

Keywords: efficiency, optimization, ICE, heavy duty, HEV

1 Introduction

It is well known that engine cycling can provide improved overall engine efficiency, or equivalently, reduced overall fuel consumption [1, 3, 4, 7, 8, 9]. This is a particularly attractive option for series hybrid architectures, since there are few constraints on the relationship between power generation and power dissipation levels [1, 6, 7]. Whether the advantages of cycling are actually realizable depends on a number of factors and, in practice, can be quite a difficult task to determine. Two of the most critical factors are the characteristics of the engine *bsfc* field and the choice of the discrete operating points (OPs). While it is almost always beneficial to cycle an engine between the *bsfc* optimal power and the engine off state - depending on transient fuel consumption effects caused by the cycling frequency [1] - this type of cycling is often not feasible in large engines. While generally the benefits of cycling are well known, a detailed analysis of the amount of fuel savings and conditions for advantageous cycling has not been conducted, even though some initial results were recently published [3,8]. The topic of cycling large Diesel engines in series hybrid configuration is particularly important and timely for the design of future hybrid drivetrains of large vehicles, i.e. trucks, earth moving equipment, etc. The Diesel-electric powertrain has been the choice of configuration for large powertrain systems, and in a sense can be considered a “relative” to the series hybrid class of powertrain systems.

This paper is structured as follows: section 2 introduces some preliminaries on brake specific fuel consumption and basic relationships between *bsfc*, burned fuel mass, power and time spent at an OP. Section 3 investigates the number and location of optimal OPs purely from a simulation point of view using polynomial approximations of the *bsfc* function. Some theoretical insights on optimal OPs are provided in section 4 using basic calculus. Section 5 introduces and discusses in detail the first analysis tool: break-even *bsfc* for the low power OP. These results can be viewed as defining the boundary case where cycling and constant operation yield the same fuel efficiency. Section 6 for the first time introduces the concept of cycling induced *bsfc*, i.e. an average power dependent *bsfc* resulting from averaging fuel consumption

over the two OPs. Finally in section 7, the introduced methodology is applied to a production engine, a Cummins Diesel. Section 8 offers some final conclusions.

2 Preliminaries

In this section we will define some of the key quantities and relationships that will later be used in the analysis. The fuel mass M burned to produce brake power P for a time period of T is given by:

$$M = P \cdot T \cdot bsfc(P), \quad (1)$$

where $bsfc(P)$ is the minimal achievable brake specific fuel consumption at power level P of the engine. Denoting P_1 and P_2 as two different levels of brake power that define two OPs given by $bsfc(P_1)$ and $bsfc(P_2)$, and α as the fraction of time T spent at P_1 , the realization of average power output P_{avg} over time T through cycling using P_1 and P_2 can be expressed as [3]:

$$P_{avg} = \alpha \cdot P_1 + (1 - \alpha) \cdot P_2 \quad \text{and} \quad P_1 < P_{avg} < P_2 \quad (2)$$

$$M_{cycle} = \alpha \cdot T \cdot P_1 \cdot bsfc(P_1) + (1 - \alpha) \cdot T \cdot P_2 \cdot bsfc(P_2) \quad (3)$$

where M_{cycle} is the fuel mass burned over a time period T , when cycling between P_1 and P_2 .

3 Optimal Number of Operating Points

In this section we will shed some light on the efficiency optimal choice of OPs and the optimal number of OPs. At first we will address the optimal location in the two OP case, and subsequently analyze the case of three and more OPs through simulations.

3.1 The Case of Two Operating Points

It was shown through massive simulations of artificial $bsfc$ curves, that fuel consumption is minimized if one OP is at the $bsfc$ minimum and the other is close to zero power. This of course assumes that the $bsfc$ curves are such that an efficiency maximum exists (using cycling) and that the average power level is between the $bsfc$ minimum power P_{opt} and P_1 . Also, the exact location of P_1 , i.e. the low power operating point close to zero, depends highly on the shape of the $bsfc$ curve and the way the $bsfc$ function tends to infinity at zero brake power. The simulations that were performed always used polynomial approximations of $bsfc$ curves. For example, Figure 1 shows the results of optimal power levels P_1 (10KW), P_{opt} (245KW), and P_{avg} (165 KW). Generally, all results pointed to the same fact: One operating point should be chosen to be at or close to P_{opt} , i.e. the $bsfc$ minimum power, and the other should be close to zero power.

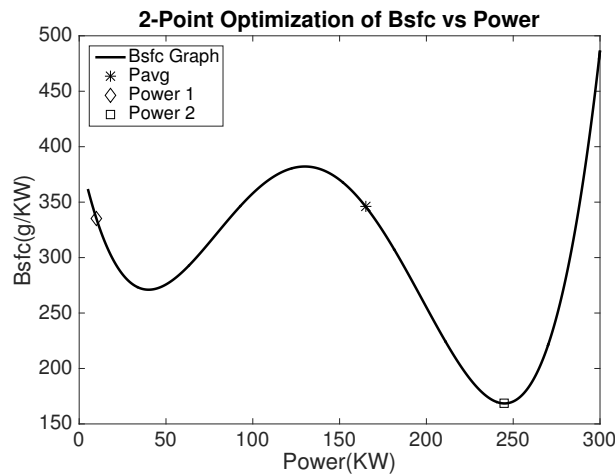


Figure 1: Two point optimization of a fourth order polynomial $bsfc$ graph.

3.2 The Case of Three and Four Operating Points

Massive simulations using three and four OPs show, that efficiency is maximized when the same two OPs are used as in section 3.1 for the two OP case, i.e. the additional points coincide with either P_1 or P_{opt} . The fact that multiple OPs always collapse to the optimal OPs of the two OP case shows, that nothing can be gained from employing more than two discrete operating points when cycling an engine. This is illustrated in Figure 2, which shows the same 4th order *bsfc* curve as in Figure 1. One can clearly see that two OPs collapse to the point of P_1 of the two OP case, and another two OPs collapse to the point P_{opt} . Therefore we can conclude, that using more than two OPs has no advantage with regard to efficiency.

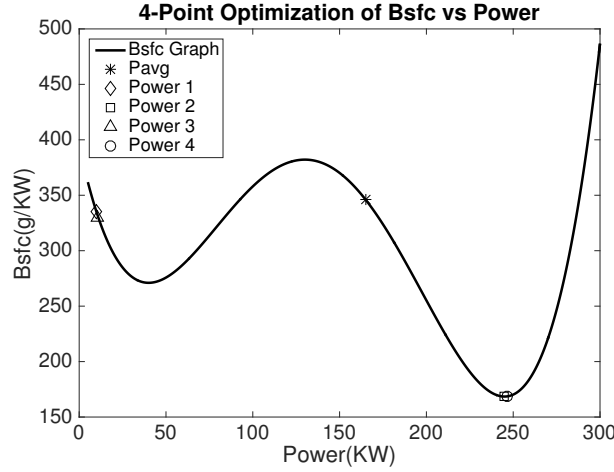


Figure 2: Four Point Optimization of a Fourth Order Polynomial *Bsfc* Graph.

4 Optimal Operating Points for P_1 and P_2 - A Theoretical Analysis

In the previous sections we addressed through simulations how optimizing fuel consumption it is best to cycle between two powers, one at the left most power allowable and one at the global minimum.

$$m(P_1, P_2) = P_1 \cdot bsfc(P_1) \cdot t_1 + P_2 \cdot bsfc(P_2) \cdot (1 - t_1) \quad (4)$$

This equation can then be rearranged to give a form that replaces time, with P_1 and P_2 , as seen below.

$$m(P_1, P_2) = bsfc(P_1) \cdot \frac{P_{avg} - P_2}{1 - \frac{P_2}{P_1}} + bsfc(P_2) \cdot \frac{P_{avg} - P_1}{1 - \frac{P_1}{P_2}} \quad (5)$$

This equation allows for exploration of whether optimal OPs always follow the conclusion made in section 3.

4.1 Finding Optimal P_1 and P_2 Points

From (5), taking the partial differentials with respect to P_1 and P_2 results in (6) and (7). To find OPs (6) and (7) are added to obtain (8).

$$\begin{aligned} \frac{\partial m(P_1, P_2)}{\partial P_1} = & -\frac{P_2 \cdot (P_{avg} - P_2) \cdot bsfc(P_1)}{P_1^2 \cdot (1 - \frac{P_2}{P_1})^2} - \frac{bsfc(P_2)}{1 - \frac{P_1}{P_2}} + \frac{(P_{avg} - P_1) \cdot bsfc(P_2)}{(1 - \frac{P_1}{P_2})^2 \cdot P_2} \\ & + \frac{(P_{avg} - P_2) \cdot bsfc'(P_1)}{1 - \frac{P_1}{P_2}} = 0 \end{aligned} \quad (6)$$

$$\begin{aligned} \frac{\partial m(P_1, P_2)}{\partial P_2} = & -\frac{P_1 \cdot (P_{avg} - P_1) \cdot bsfc(P_2)}{P_2^2 \cdot (1 - \frac{P_1}{P_2})^2} - \frac{bsfc(P_1)}{1 - \frac{P_2}{P_1}} + \frac{(P_{avg} - P_2) \cdot bsfc(P_1)}{(1 - \frac{P_2}{P_1})^2 \cdot P_1} \\ & + \frac{(P_{avg} - P_1) \cdot bsfc'(P_2)}{1 - \frac{P_1}{P_2}} = 0 \end{aligned} \quad (7)$$

$$\begin{aligned} 0 = & (P_1 + P_2 - P_{avg}) \cdot bsfc(P_2) - (P_1 + P_2 - P_{avg}) \cdot bsfc(P_1) + P_1 \cdot (P_{avg} - P_2) \cdot bsfc'(P_1) \\ & + P_2 \cdot (P_1 - P_{avg}) \cdot bsfc'(P_2) = 0 \end{aligned} \quad (8)$$

Different cases were studied to examine if P_1 and P_2 should always be at the left most allowable OP and the global $bsfc$ minimum, respectively. From (8) it was found that there are cases in which it is not optimal to have the two OPs at the left most allowable power and at the global $bsfc$ minimum. These cases satisfied (6-8) when P_{avg} was very close to the global $bsfc$ minimum, resulting in P_1 being slightly smaller than the P_{avg} , and P_2 being slightly to the right of the $bsfc$ global minimum. However, in these cases the fuel savings seen in contrast to operating at the left most allowable power point and at the global $bsfc$ minimum were very slight, showing minimal advantage.

5 The Break Even Bsfc Method

This method is based on a hypothetical $bsfc$ curve which shows the $bsfc$ of the low power OP P_1 that will result in the same fuel consumption as continuous operation at P_{avg} . The $bsfc$ of an engine as a function of P_1 can be calculated by the following equations [3]:

$$bsfc(P_1) = A + B \cdot \frac{1}{P_1}, \quad \text{where} \quad (9)$$

$$A = \frac{bsfc(P_{avg}) \cdot P_{avg} - bsfc(P_{opt}) \cdot P_{opt}}{P_{avg} - P_{opt}} \quad \text{and} \quad B = \frac{P_{avg} \cdot P_{opt} \cdot [bsfc(P_{opt}) - bsfc(P_{avg})]}{P_{avg} - P_{opt}} \quad (10)$$

where P_{avg} is the average power, $bsfc(P_{avg})$ is the $bsfc$ at the average power, P_{opt} is the power at the global $bsfc$ minimum, and $bsfc(P_{opt})$ is the minimum attainable $bsfc$. Figure 3 provides examples of break even $bsfc$ for the low power OP for various values of P_{avg} .

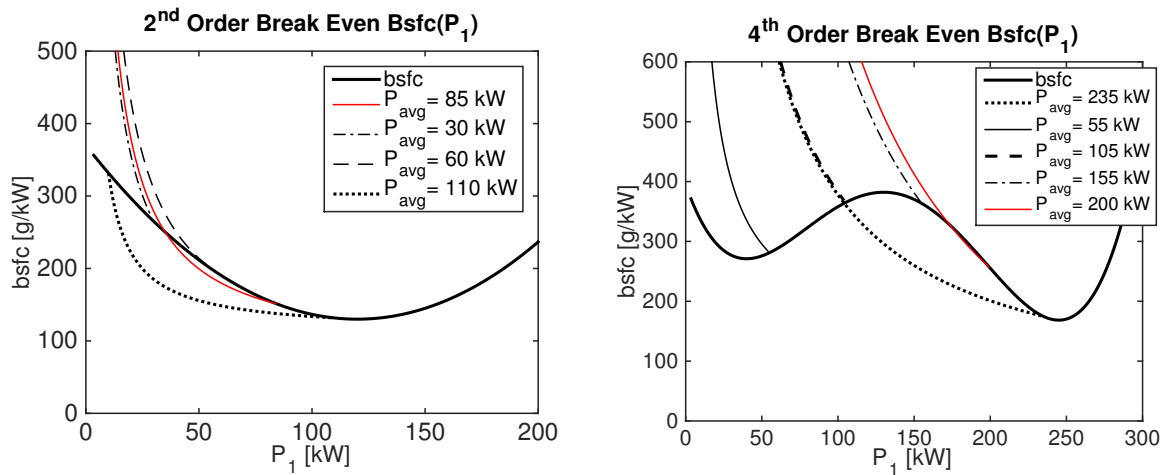


Figure 3: Break even $bsfc$ as a function of low power operating point ($P_1, bsfc(P_1)$)

The curves $bsfc(P_1)$ are referred to as break even $bsfc$ curves [3] because they show whether or not cycling with a certain low power OP P_1 will beat the engine $bsfc$ for a given average power P_{avg} . At an

OP P_1 where the break-even $bsfc$ curve is above the uncycled $bsfc$ curve, cycling at the given average power will have better fuel efficiency than the uncycled engine. On the contrary, it is more costly to cycle when the break-even $bsfc$ curve is below the uncycled $bsfc$ curve.

Notice from Figure 3 it is almost always more fuel efficient to cycle because the break-even $bsfc$ curves are almost always above the uncycled $bsfc$ curve. The exception to this occurs when P_{avg} becomes too close to P_{opt} . For example, observe the fourth order break-even $bsfc$ curves in Figure 3. For each P_{avg} except $P_{avg} = 235$ kW, the break-even $bsfc$ curve is at or above the uncycled $bsfc$ curve; however, because $P_{avg} = 235$ kW is too close to $P_{opt} = 250$ kW, the break-even $bsfc$ curve drops below the uncycled $bsfc$ curve between 110 kW and 235 kW. Therefore cycling with an OP P_1 in this region where $P_{avg} = 235$ kW would not be fuel efficient.

It is also evident from Figure 3 that a lower power level OP P_1 leads to a higher $bsfc(P_1)$, increasing the ceiling on how large the uncycled $bsfc$ can be to still attain fuel savings. A lower P_1 thereby increases the fuel efficiency of cycling. This supports our previous conclusion from Section 3.2 that it is best to choose an OP P_1 as low as possible.

6 The Cycling Induced Effective Bsfc

A new $bsfc$ curve for an engine can be generated under the assumption that the engine will be cycled. In other words, if we assume an engine will be cycled with one OP at power level P_1 close to zero power and the other OP at the global $bsfc$ minimum power level P_{opt} , then using [3] and (1-5) we can create a $bsfc$ function for cycling according to the following equation:

$$bsfc(P_{avg}) = \frac{P_1 \cdot (P_{avg} - P_{opt}) \cdot bsfc(P_1) + P_{opt} \cdot (P_1 - P_{avg}) \cdot bsfc(P_{opt})}{P_{avg} \cdot (P_1 - P_{opt})}, \quad (11)$$

where P_1 is the low power OP, $bsfc(P_1)$ is the $bsfc$ at the low power OP, P_{opt} is the power at the global $bsfc$ minimum, and $bsfc(P_{opt})$ is the $bsfc$ at the global $bsfc$ minimum. A function $bsfc(P_{avg})$ curve, also known as a cycling induced $bsfc$ curve, for a cycled engine shows the minimum fuel consumption for a certain engine that can be obtained from cycling with a given power level P_1 , as shown in Figure 4.

The shape of each cycling induced $bsfc$ curve appears to be almost identical for both the second and fourth order polynomial $bsfc$ curves examined. It also appears that the largest differences between cycling induced $bsfc$ curves occur between $P_1 = 5$ kW and $P_1 = 10$ kW rather than $P_1 = 15$ kW and $P_1 = 20$ kW because P_1 is optimal when it is as small as possible. Therefore, the differences at the lower power levels P_1 are more significant than the differences at higher power levels P_1 . This is further evidence it is always important to choose a power level OP P_1 as low as possible because even minuscule power level P_1 differences cause significant differences in fuel savings. These cycling induced $bsfc$ curves also provide visual confirmation that cycling with lower power levels P_1 leads to more fuel efficiency.

In the case of the second order polynomial $bsfc$ curve shown in Figure 4, the steep drop in the cycling- $bsfc$ curve implies that maximum fuel savings from cycling will occur at an average power slightly larger than the given P_1 . For example, when $P_1 = 5$ kW, maximum fuel savings appear to occur at a P_{avg} of approximately 20 kW. This characteristic is not true in the case of the fourth order polynomial $bsfc$ curve because a local $bsfc$ maximum exists. The P_1 value corresponding to this local maximum becomes the location of maximum fuel savings because it is much more efficient to generate these average powers by cycling through two low- $bsfc$ power points rather than by running the engine directly at these local $bsfc$ maximum power points.

Finally, these cycling induced $bsfc$ curves illustrate that local extrema do not affect cycling. Fuel savings are indeed significantly larger at points of local $bsfc$ maxima, however the shape of cycling induced $bsfc$ curves themselves are not affected by these local maxima. Therefore, we may once again conclude that, regardless of the presence of local extrema in an engine's $bsfc$ curve, it is almost always better to choose a low power OP P_1 as low as possible rather than a low power OP P_1 at a local minima.

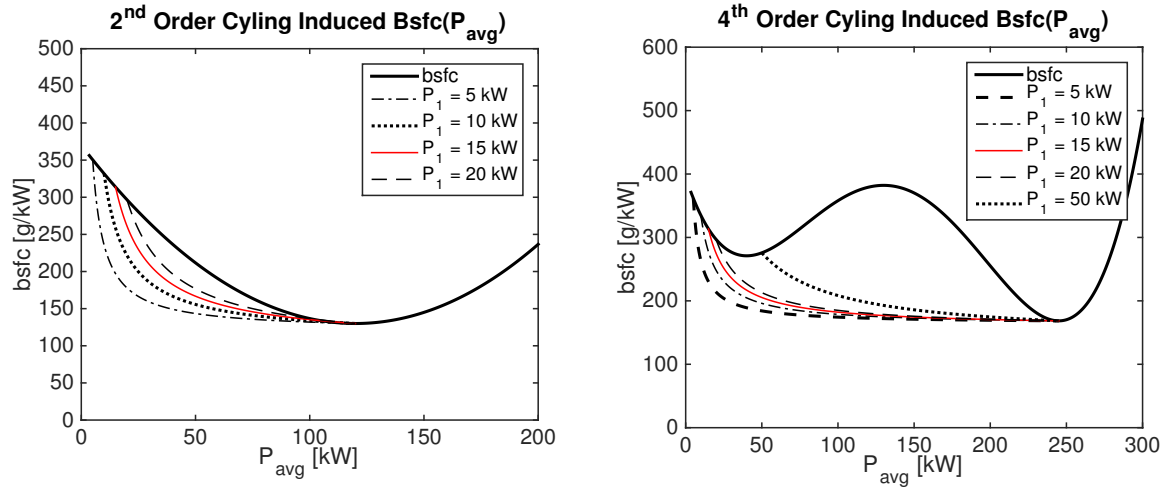


Figure 4: Cycling induced $bsfc$ curves

7 A Realistic Case: The Cummins EQB235-20 Diesel Engine

A piecewise $bsfc$ curve approximation was used for the Cummins B-Series EQB235-20 Diesel Engine for vehicle applications in order to test our theories and simulations on an existing engine [2]. The EQB235-20 has a piecewise $bsfc$ function with a gradually decreasing slope from low to optimum P_{avg} , as can be seen in Figure 5. Notice that around $P_{avg} = 75 \text{ kW}$ the curvature of the $bsfc$ curve changes from convex to concave (then back to convex). It is this paramount characteristic which allows the Cummins EQB235-20 engine to serve as an example of a case in which cycling does result in fuel savings.

From Figure 5, it is evident the cycling induced $bsfc$ curves are lower than the uncycled piecewise $bsfc$ function at every average power for every lower power OP P_1 . Because the cycling induced $bsfc$ curves are always lower than the uncycled piecewise $bsfc$ function, cycling the Cummins EQB235-20 engine is always beneficial. It must be noted that the dashed extension of the piecewise $bsfc$ function indicates a projected $bsfc$ outside the range of attained data. The cycling induced $bsfc$ curve of $P_1 = 10 \text{ kW}$ is particularly significant because it illustrates lower P_1 values correspond to cycling induced $bsfc$ curves with steeper initial slopes and therefore lower $bsfc$ values with more fuel savings. This also validates the conclusions from Section 3.2.

It is important to consider the fuel mass savings through cycling. For each P_{avg} , the mass of fuel consumed while cycling is within 3% of the mass consumed without cycling. Though fuel savings do exist in this case, they are relatively minuscule and may not be large enough to justify cycling - especially when the realistic cost of switching between OPs is considered. However, the case of the Cummins EQB235-20 engine still proves that cycling an existing engine can be beneficial. Considering that the Cummins EQB235-20 engine was not designed to be cycled yet fuel savings can still be achieved through cycling, we claim that much greater fuel savings can be achieved by an engine specifically designed for cycling with two OPs.

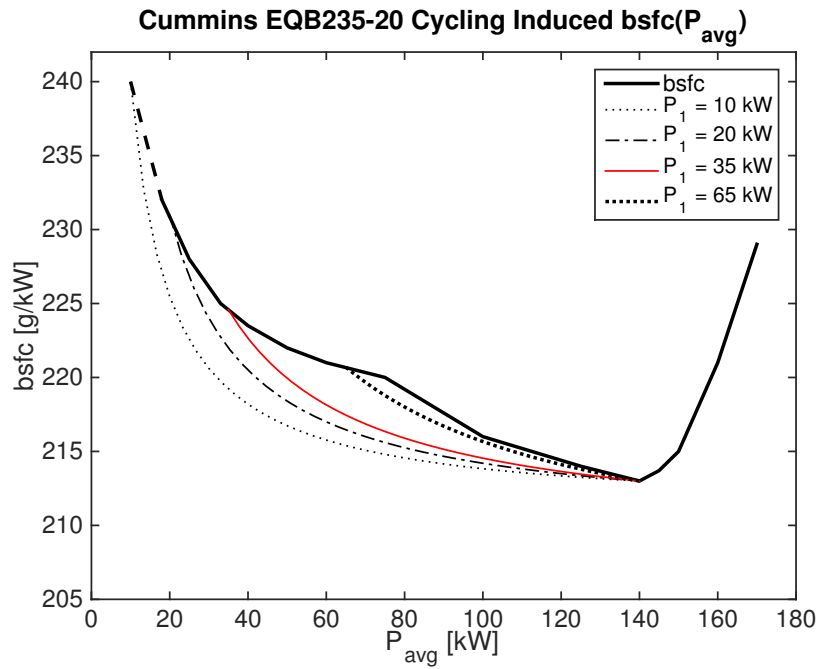


Figure 5: Induced $bsfc$ curves for the Cummins EQB235-20 Diesel Engine

8 Conclusion

This paper introduces new tools for analyzing efficiency gains in large ICEs achievable through cycling. It was shown that if cycling between two OPs results in better efficiency than the average power OP, then two OPs are sufficient and cannot be improved upon by adding additional OPs. Several methods to find the optimal OPs were introduced, most notably the cycling induced $bsfc$. The concept of break-even $bsfc$ for the low power OP was also demonstrated. Furthermore a theoretical analysis was performed that shed some more light on the choice of two optimal OPs, which in turn confirmed the simulation results. In summary, this paper provides a tool set that allows to easily evaluate the efficiency gains in ICEs obtained through cycling. The results were illustrated using examples of polynomial representations of artificial $bsfc$ curves as well as $bsfc$ data of production engines.

The introduced concept is particularly important for Diesel Series Hybrid configurations, which will most likely find applications in heavy duty machinery and large trucks. While it was shown, that with current production engines, fuel savings are relatively small, large savings are possible if the $bsfc$ field of the engine has certain characteristics, i.e. is customized for series hybrid architectures and cycling. It has been shown previously [3] that functions $bsfc(P)$ that have an approximately constant negative slope (between the low power operating point and the minimum $bsfc$ operating point) result in large efficiency gains and hyperbolic $bsfc$ dependencies often result in little or no gain. Therefore, future work on tailoring the $bsfc$ field to optimize fuel savings in series hybrid configurations appears to be a promising path towards large, highly efficient and hybridized propulsion systems.

References

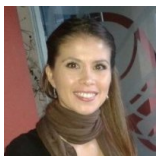
- [1] M. Ehsani, Y. Gao, A. Emadi, and S. Gay, *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles*, ISBN 0-8493-3154-4, CRC Press, 2005
- [2] FD Power Company, *CUMMINS EQB235-20 Diesel Engine For Vehicle Application*, <http://www.diesel-engine.cn/CUMMINS/EQB235-20.htm>, accessed on 2015-04-27.
- [3] P.H. Bauer and J. Murillo, *An Analysis of Conditions for Efficiency Gains in Large ICEs Using Cycling*, ICHEV 2015, Istanbul, January 2015.

- [4] P.H. Bauer and E. Perez-Bernabeu. "The Effect of the Operating Point Choice on Fuel Economy in Series Hybrids." IEEE Xplore. EVS27 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium, 17 Nov. 2013. Web. 27 Apr. 2015.
- [5] K. Mollenhauer. Handbook of Diesel Engines. N.p.: Springer, 2010. Print.
- [6] D.S. Crumbez, P.J. Curran, S.L. Napier, "Method and apparatus for reducing engine cycling in hybrid electric vehicles." Publication Number EP 1231092 B1, USA, 2008.
- [7] C.E. Whitney, L. Scavone, A. H. Heap, and C. Heisler, "Diesel engine steady state and transient hybrid optimization." Publication Number US9073545 B2, USA, July 2015
- [8] P.H. Bauer and Q. Bui, "On the optimal choice of operating points in large series hybrids", Proc. of the EVS 27, Nov. 17-20, Barcelona, 2013.
- [9] J. Halme and J. Suomela, "Optimal efficiency based gen-set for a series hybrid work machine", 8th IEEE VPPC, Oct 9-12, 2012, Seoul, South Korea.

Authors



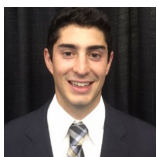
Peter Bauer is currently Professor in the Dept. of Electrical Engineering at the University of Notre Dame. His area of specialization includes control and DSP systems, multi-dimensional systems and stability theory, and efficiency optimization in power generation with applications in (hybrid) electric vehicles and renewables. He has authored and co-authored more than 180 technical papers and is a Fellow of the IEEE.



Jenny Murillo received a BS and MS degree in Mechanical Engineering from the University Rovira i Virgili (URV) Tarragona, Spain. Mrs. Murillo worked as an Assistant Professor at the same university in 2013/2014 in the Dept. of Mechanical Engineering. Her interests include energy efficient buildings and vehicles, green technologies, and hybridization approaches for power generation.



Justin Campanaro came to The University of Notre Dame from Irvine, CA in 2013. He is currently a third year undergraduate mechanical engineering student at Notre Dame in pursuit of a B.S. degree in ME. His research interests include energy engineering and efficiency, particularly in relation to the automotive industry. He began researching under Professor Peter Bauer in the Spring of 2015.



Michael Ruof came to The University of Notre Dame from Fresno, CA in 2013. He is currently a third year undergraduate mechanical engineering student at Notre Dame in pursuit of a B.S. degree in ME. His research interests include energy engineering, thermal systems and control systems particularly in relation to the automotive industry. He began researching under Professor Peter Bauer in the Spring of 2015.

9 Appendix

EQB235-20

General

Displacement	5.9L
Bore	102mm
Cylinders	6
Stroke	120mm
Fuel System	BOSCH Pump

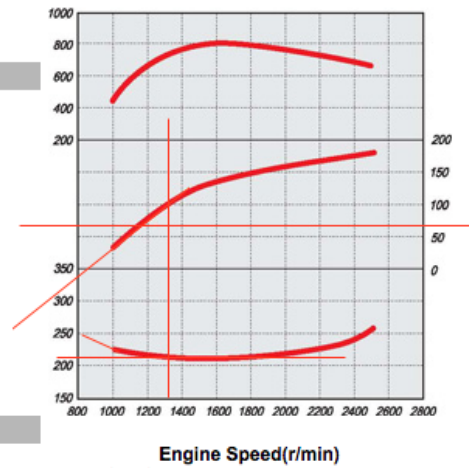
Technical Specification

Aspiration	Turbocharged & Aftercooled
Certification	Euro II
Weight Dry(with flywheel and alternator, but less starter and air compressor)	413kg
Weight Wet	437kg
Center Of Gravity Distance From Front End Of Cylinder Body	328mm
Center Of Gravity Distance Above Crank Centre Line	155mm
Maximum Bending Moment At Behind End Of Cylinder Body	1356N.m
Thrust bearing load limit	
Maximum intermittent	3781N
Maximum continuous	1780N

Performance Data

Idle Speed	750±100r/min
Maximum no load governed speed	2800r/min
Maximum overspeed capability (15 secs max)	4200r/min
Maximum altitude for continuous operation	2000m
Clutch engagement torque at 800r/min When using exhaust brakes	400N.m
Exhaust pressure,at 2720r/min,at turbocharger outlet,must not exceed	414kPa
Approximate engine retardation	112kW
Advertised Power	155kW@2500r/min
Peak Torque	700N.m@1500r/min

Power Curve



■ Torque(N.m)
■ Power(kW)
■ BSFC(g/kW.h)

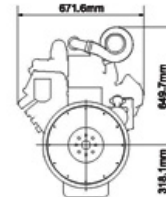
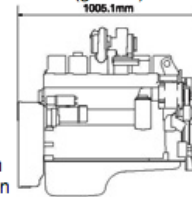


Figure 6: *Bsfc* data for the Cummins EQB235-20 Engine [2] used to derive the Cummins EQB235-20 piecewise *bsfc* function.