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The 27th INTERNATIONAL ELECTRIC VEHICLE SYMPOSIUM & EXHIBITION
BARCELONA
17th-20th November 2013

The Optimal Choice of Operating Points in Large Series Hybrids

Qian Bui and Peter Bauer
Department of Electrical Engineering
University of Notre Dame

Organized by Fira Barcelona avele
Hosted by AVERE mea Ajuntament de Barcelona
In collaboration with EVAAP EDTA
Supported by European Commission

OUTLINE:

1. Introduction
2. Brake specific fuel consumption (BSFC) characterization
3. Results
4. Example
5. Conclusion and Interpretations

1. Introduction

- Environmental concerns: emissions
- Fossil fuel reserves: limited reserves
- Economic considerations: price of oil
- Focus here: Large Series Hybrids (Diesel ICE)

1. Introduction cont.

1. Introduction cont.

- Usually:
  Power generated(t) = power needed(t)

- Efficiency of ICEs is highly dependent on power output

- The efficiency problem in current day ICEs:
  - frequent load changes
  - operation away from bsfc optimum

1. Introduction cont.

Alternatives possible with hybrid power generation units:

- Generate power at “average” power levels and buffer power mismatch.
- Use a 2 operating point scheme, with one OP being the bsfc minimum.
- Use multiple operating points to follow power trajectory or LP filtered power request.

1. Introduction cont.

- Here: The 2 OP scheme, with one OP being the bsfc optimum
- The other OP needs to be found
- Many advantages over the “average power” approach:

  - can be significantly more efficient
  - less storage requirement
  - average power sometimes unknown apriori

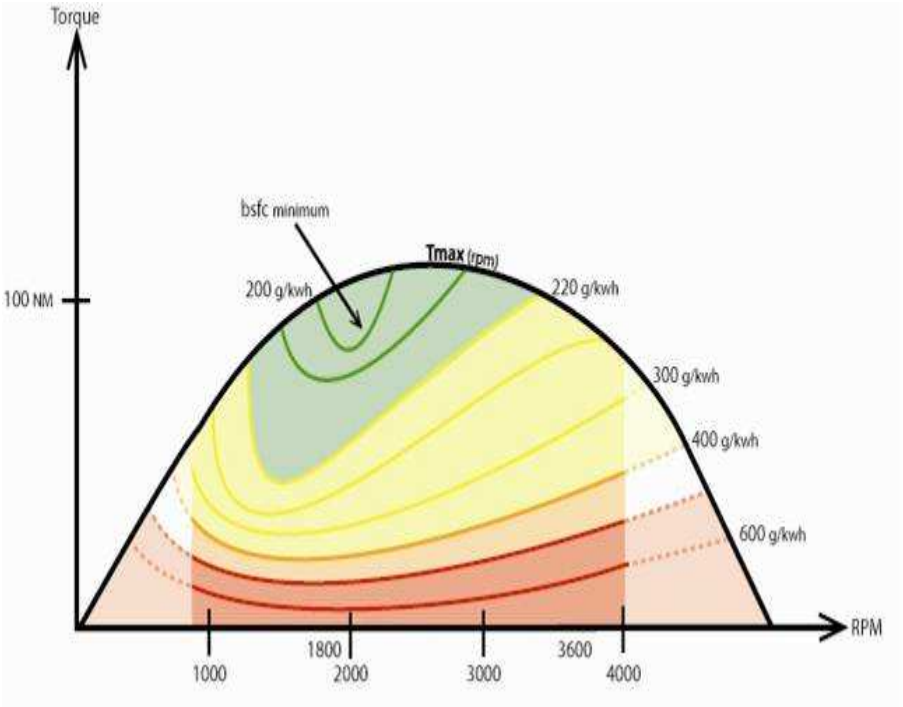
    making the approach difficult to apply

2. Brake Specific Fuel Consumption Characterization

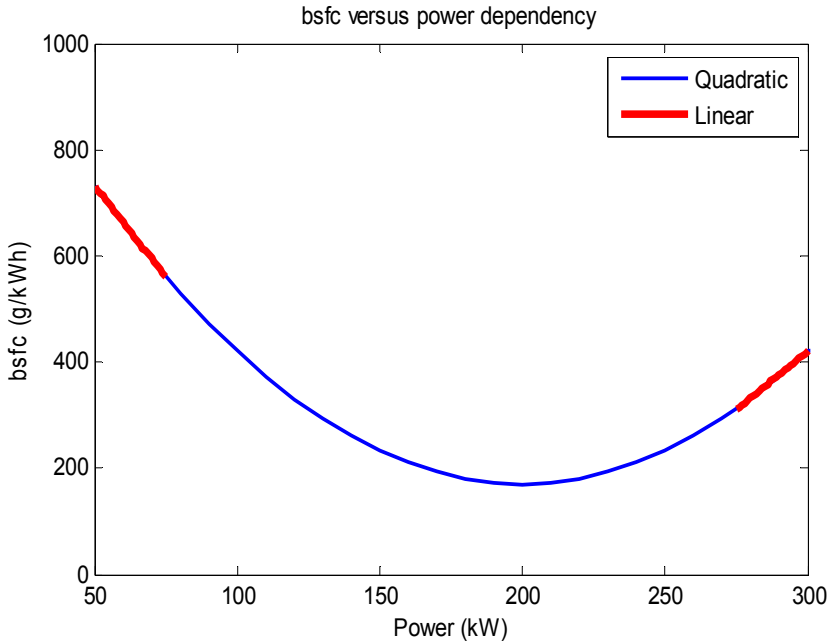
- BSFC are often given as isoclines of constant values in a torque-speed or power-speed diagram
- There exist infinitely many operating points that produce the same amount of power
- The function bsfc(P) maps P to the minimal achievable bsfc value for that power P
- Typical functions bsfc(P) have a pronounced minimum at mid power levels and are continuous and differentiable in power

2. BSFC Characterization cont.

Typical bsfc Representation



BSFC(P)



2. BSFC Characterization cont.

Assumptions made:

- Quadratic bsfc dependency around bsfc minimum
- Linear dependency at very low and very high power
- No transient fuel consumption effects between Ops, i.e. long stay times.
- Many assumptions will be relaxed later

3. Results

Fuel mass consumed using a weighted average between average power OP and the two OP scheme:

$$M = T(q\ P1\ bsfc(P1) + q\ Popt\ bsfc(Popt) + (1 - 2q)\ Pav\ bsfc(Pav))$$

Where $0<q<0.5$

- P1: low operating point power
- Popt: optimal operating point power
- Pav: average power
- M: fuel mass
- T: engine run time

3. Results

- For the two OP scheme to burn less fuel we need:

$$dM/dq < 0$$

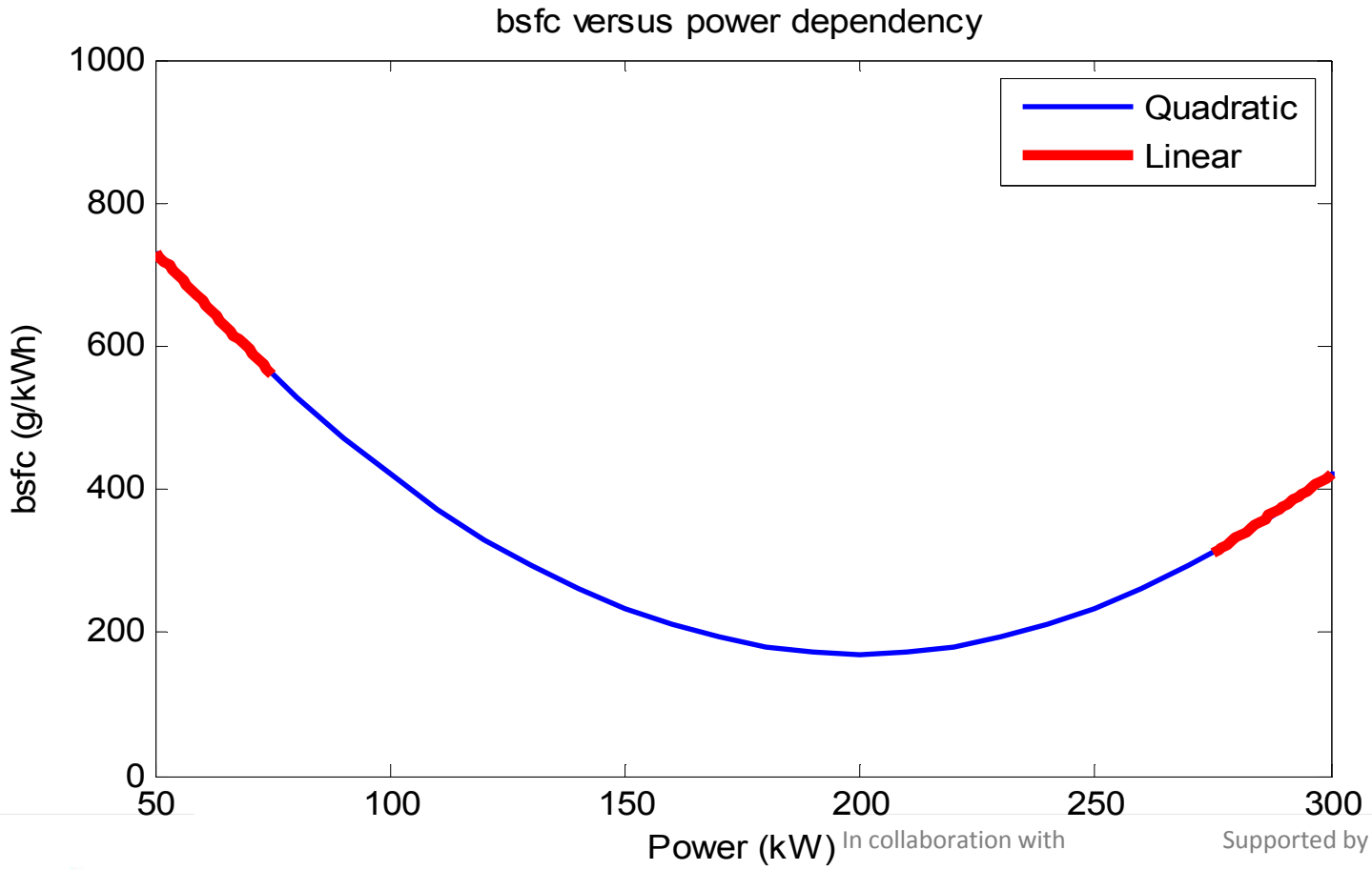
- Remember:

q=0 means only Pav is used

q=0.5 means only (Popt,P1) used

Also: $P1 < Pav < Popt$

3. Results – BSFC Approximation



3. Results – Linear BSFC Approx.

- The Linear Case:

  $dM/dq < 0$ if $P1 - Popt < 0$

  which by definition is always satisfied.

=> If (P1, Pav, Popt) lie on a line with negative slope (linear case), cycling using P1 and Popt is always advantageous.

3. Results – Quadratic BSFC

- The quadratic case:

  $dM/dq < 0$ if $2P1 - Pav < 0$

- This implies:

  $P1 < Pav/2$ and $Popt - Pav > P1$

Under these conditions cycling using (P1 and Popt) is advantageous.

3. Results – Other Dependencies

- The sub-linear case:

  meaning that P1 is below the line of negative slope given by Popt and Pav.

  => Results are the same as for linear case – it is always advantageous to cycle !

- The sub-quadratic case:

  meaning that P1 is below the quadratic dependency and above the linear one.

  => Quadratic case results still hold!

4. Example (Sub-quadratic case) 650KW Diesel Genset

- Pav = 210KW, bsfc= 240 g/Kwh
- Popt=400KW, bsfc= 180 g/Kwh
- P1=20KW, bsfc= 320 g/Kwh
- Fuel consumption per hour at Pav: 50.4 Kg
- Fuel consumption per hour cycling between P1 and Popt: 39.2Kg
- Fuel savings in one year (operating 80% of year): 78490 kg = approx. 95000 liter of Diesel => between $100,000 and $3,000,000 depending on application

5. Conclusion and Interpretations

- Conditions under which cycling in large series hybrids is advantageous
- In the linear negative slope bsfc case, it is always advantageous to cycle.
- In the quadratic case, cycling is advantageous if the low power OP is sufficiently small in power.
- Other dependencies were also investigated

5. Conclusion.....

- Note that “quadratic” and “linear” does not mean that the entire bsfc curve or even a part of it needs to be quadratic or linear, only the 3 points P1, Popt and Pav need to have this relationship!!
- Transient fuel consumption effects were not considered – long stay times assumed!
- Fuel savings can be large, typically 20 - 30%
- The results also apply to slowly time-variant average power

5. Conclusions

Open Problems and Questions:

⇒Considering transient OP phenomena and their effects on fuel savings

⇒Comparison with low pass filtered power request

⇒A cost analysis of fuel savings versus hardware cost for storage.

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Questions? Preguntas?

- For questions, comments or ideas:

  (Comentarios, preguntas, ideas?)

Peter Bauer

pbauer@nd.edu

(001) 574 631 8015