POWER & MOBILITY

Extension of Diesel Engine Power via Electrically Assisted Turbocharger

Sang-Guk Kang[1], Erik S. Schroen[1], Jonathan M. Mattson[1], Kenneth S. Kim[1], Kyle D. Hepp[1], Kurt M. Kruger[1], Peter J. Clerkin[1], Chol-Bum M. Kweon[1], Joseph A. Gibson[2], Rik D. Meininger[2], and Marshall R. Musser[3]

[1] DEVCOM Army Research Laboratory, Aberdeen Proving Ground, MD
[2] DEVCOM Aviation & Missile Center, Redstone Arsenal, AL
[3] US Army PEO Aviation, Redstone Arsenal, AL

Introduction

- Diesel engines
- High reliability, fuel efficiency, and power density
- Used for many unmanned ground vehicles and unmanned aircraft systems

- Power demand ever growing to meet power requirements
- Forced air induction system such as turbochargers
- Mild hybridization technologies using electric machines

Army unmanned aircraft systems

Introduction – cont'd

- Mild hybridization
- Supplement conventional engines with electrification technologies
- Motor-generators, electrically assisted turbochargers, and e-turbocompound
- Partial energy recovery and increased usable power output

- Typical usage of electrically assisted turbocharger (EAT)
- Low engine load:
  - Motoring turbo shaft increasing boost pressure
  - Faster transient response minimizing turbo lag
- High engine load:
  - Reducing turbo speed
  - Producing surplus electrical energy

- **No research to extend engine power using EAT**

Electrically assisted turbocharger

Research Objective and Scope

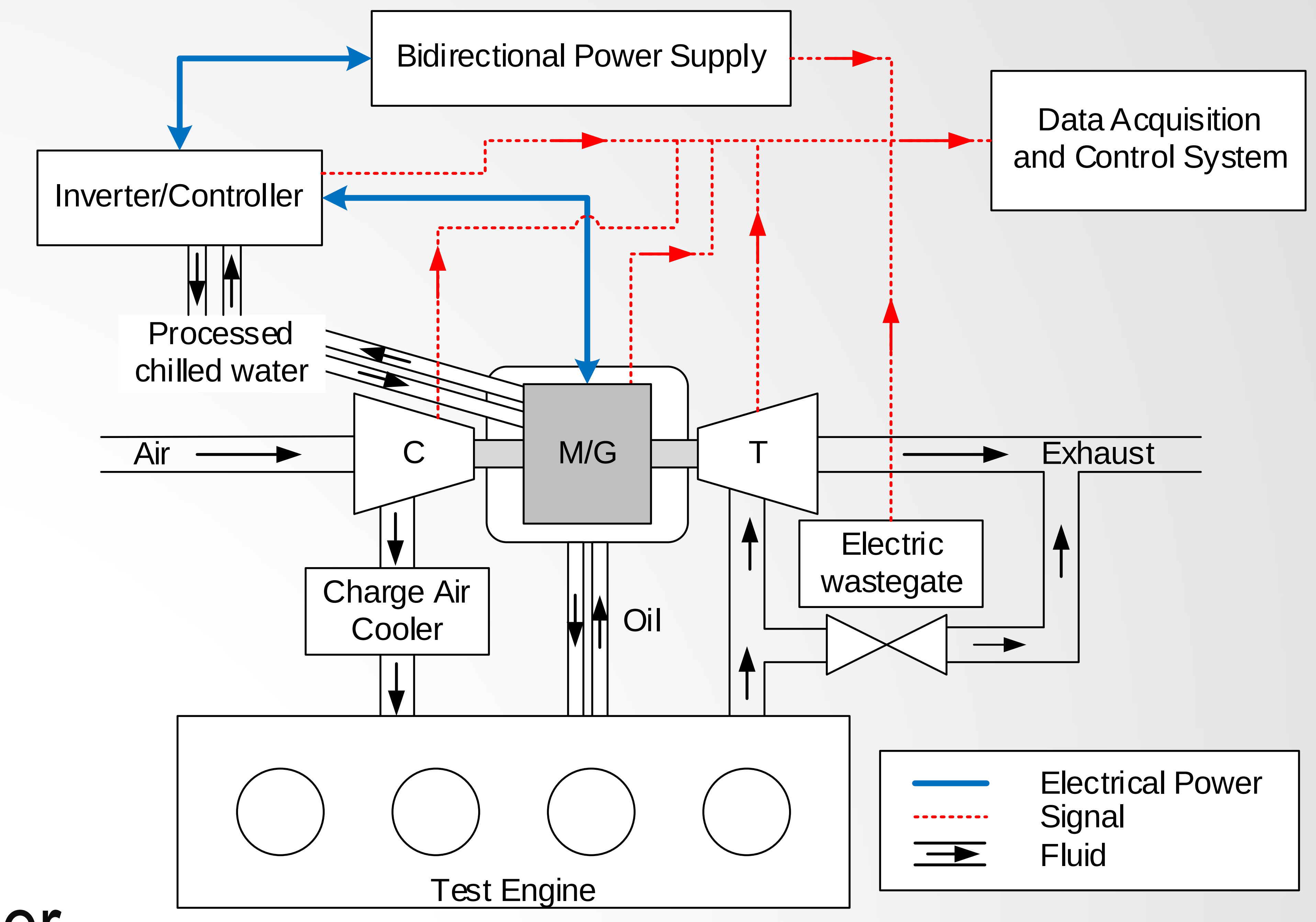
- Research Objective
- Investigate a capability of EAT to enable additional power of diesel engine

- Research Scope
- Characterization of an EAT-attached diesel engine for all engine loads
- Extension of the engine power using the EAT at full engine load

Experimental Setup

- Engine
  - 2-liter, 4 cylinder, 4 stroke, turbocharged compression ignition diesel engine
  - F-24 jet fuel
  - Controlled by full authority digital engine controller (FADEC) including the fuel map

- EAT
  - Integrated motor-generator system
  - Replaced the legacy turbocharger
  - Matched to the boundary conditions of the legacy turbocharger
  - Cooling: Mechanical parts (oil), Electrical parts (water)
  - Electrical wastegate
  - Fiber optical speed sensor to prevent M/G overspeed



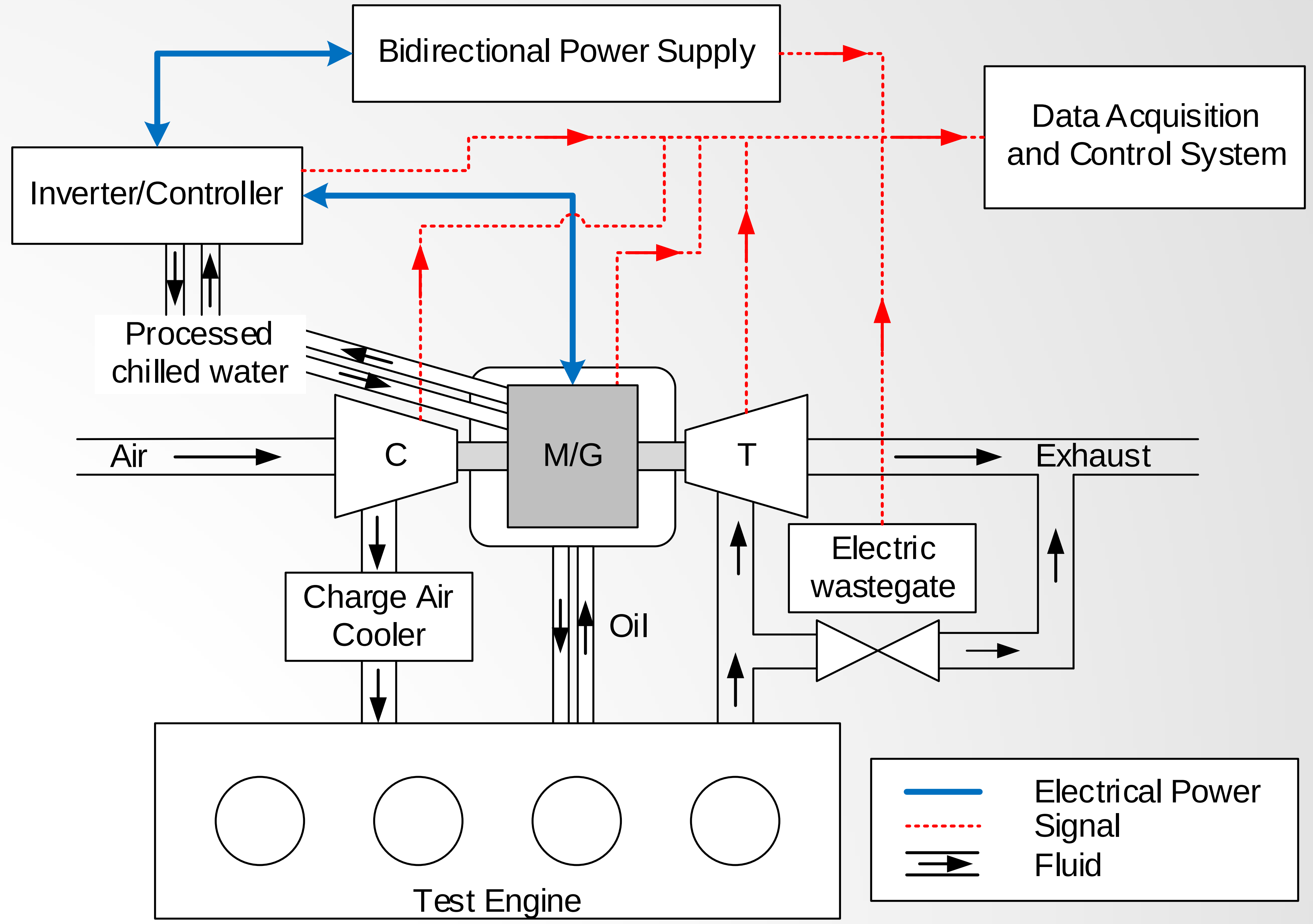
Schematic of EAT System

Experimental Setup – cont'd

- EAT controller/inverter
  - Power stage: SiC-MOSFETs
  - Bus voltage: 400 VDC
  - Cooling: water

- Bidirectional power supply
  - Energy storage emulation
  - Transmission of electrical power to/from M/G system

- Master data acquisition and control (DAC) system
  - FADEC tuned for legacy turbocharger ➔ EAT controlled separately by master DAC
  - Control of either spool speed or electric wastegate position to achieve the MAP targets (legacy data)



Schematic of EAT System

EAT Characterization: Procedure

- EAT baseline performance
- M/G system deactivated
- MAP controlled by wastegate only
- Power lever angle (PLA) ranged from 0% to 100%

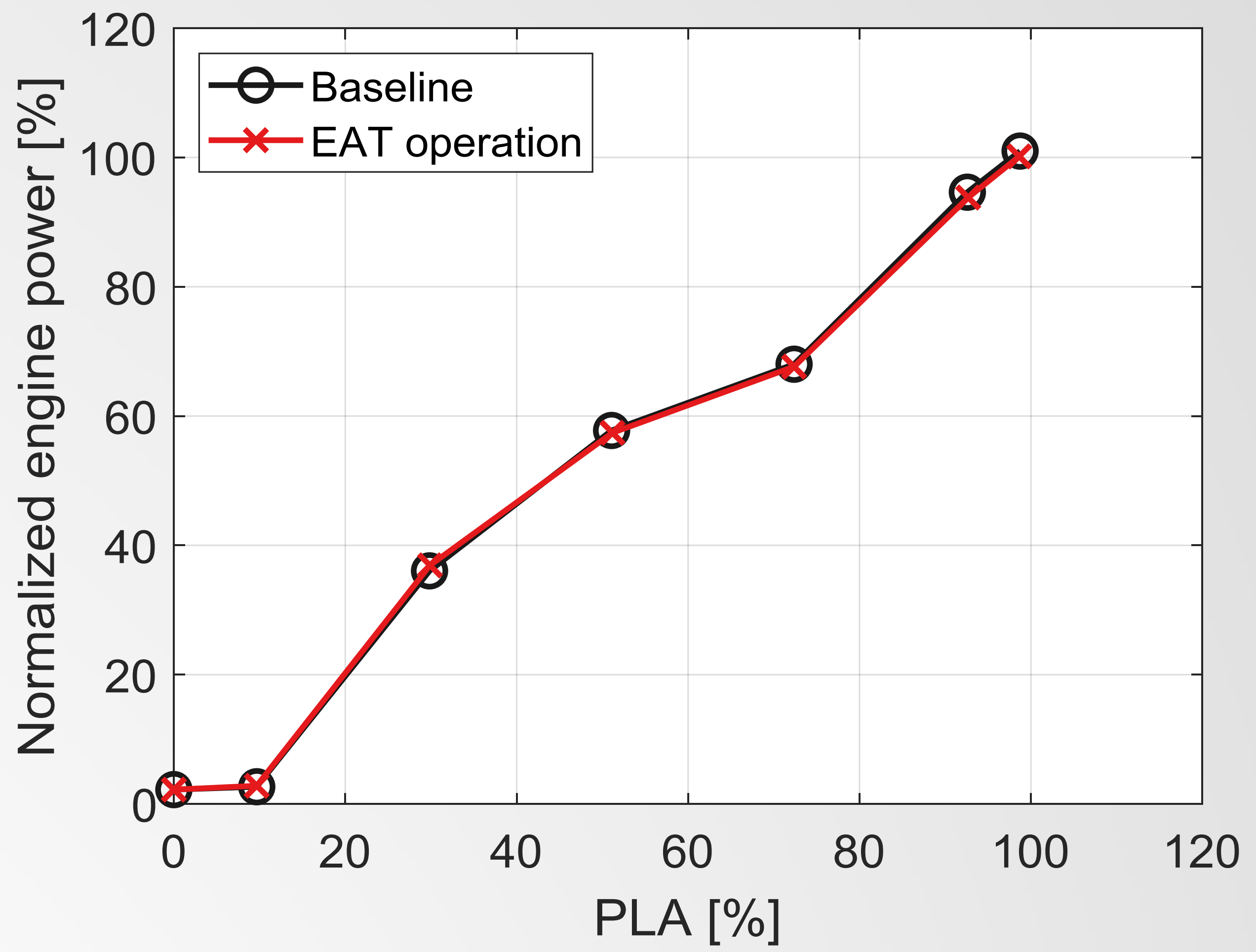
- EAT operation
- M/G system activated
- MAP controlled by EAT speed
- Wastegate fully closed
- Power lever angle (PLA) ranged from 0% to 100%

EAT Characterization: Results

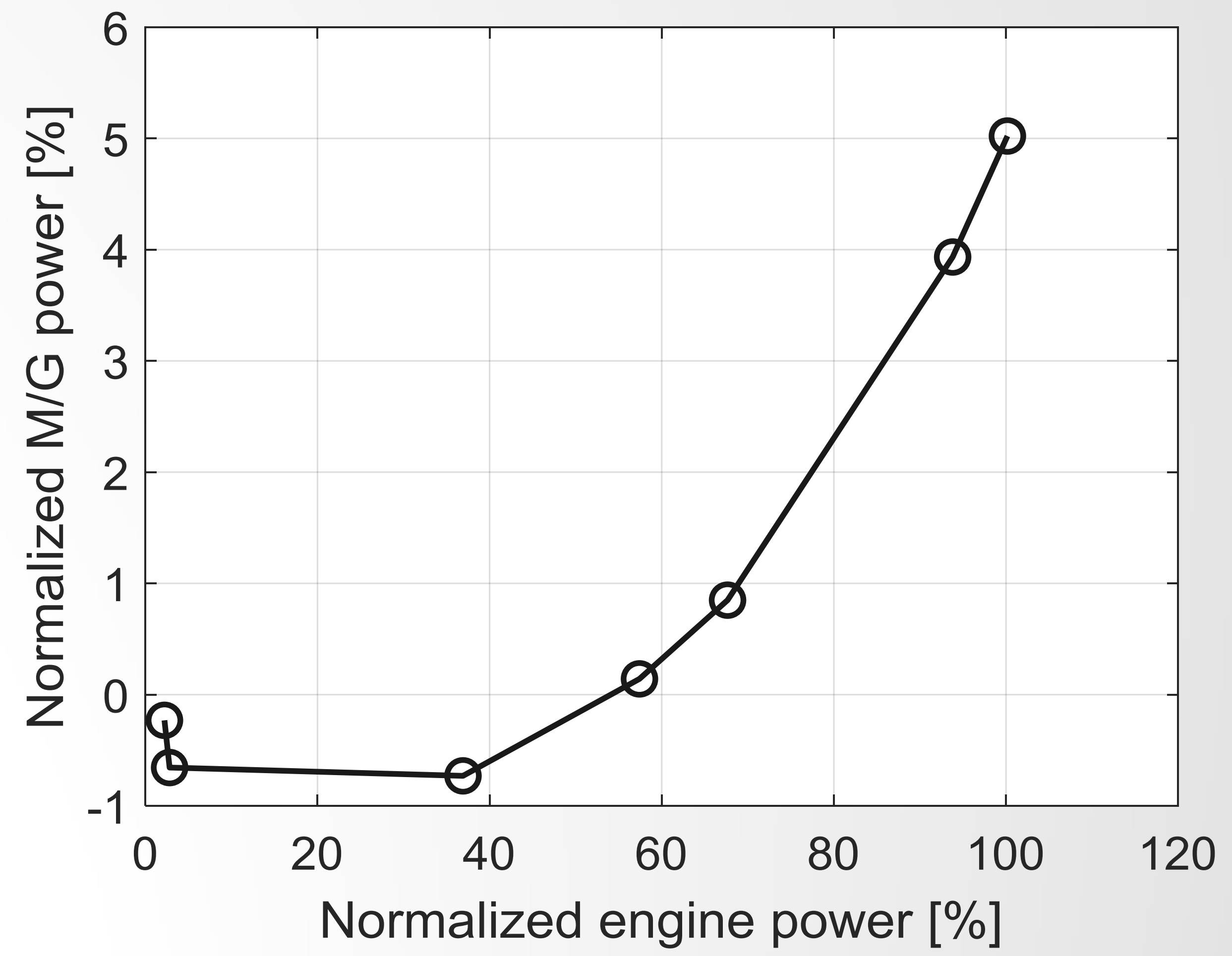
POWER & MOBILITY

- For low engine loads (less than 50% PLA):
  - M/G: negative sign ➔ motoring regime
  - Increased EAT speed to meet MAP targets
  - Improved fuel efficiency (next slide)

- For high engine loads (more than 50% PLA):
  - M/G: positive sign ➔ generating regime
  - Generated electrical power using some exhaust waste energy
  - Generated surplus electrical energy approximately 5% at 100% PLA ➔ This surplus energy was directed to ambient in baseline case through wastegate actuation



Engine power vs. PLA



M/G Power with engine power

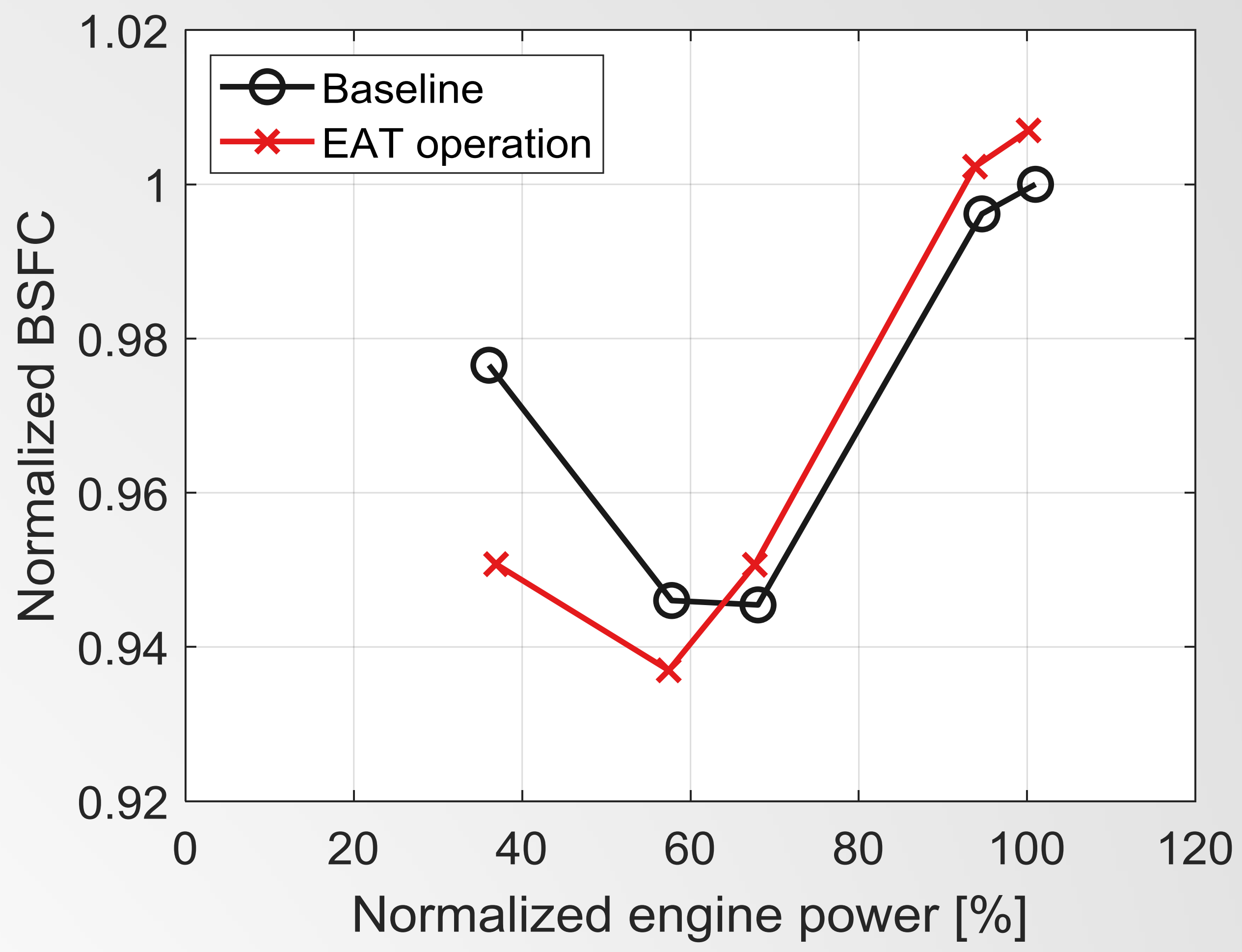
* Note M/G and engine powers normalized by the maximum rated engine power

EAT Characterization: Results – cont’d

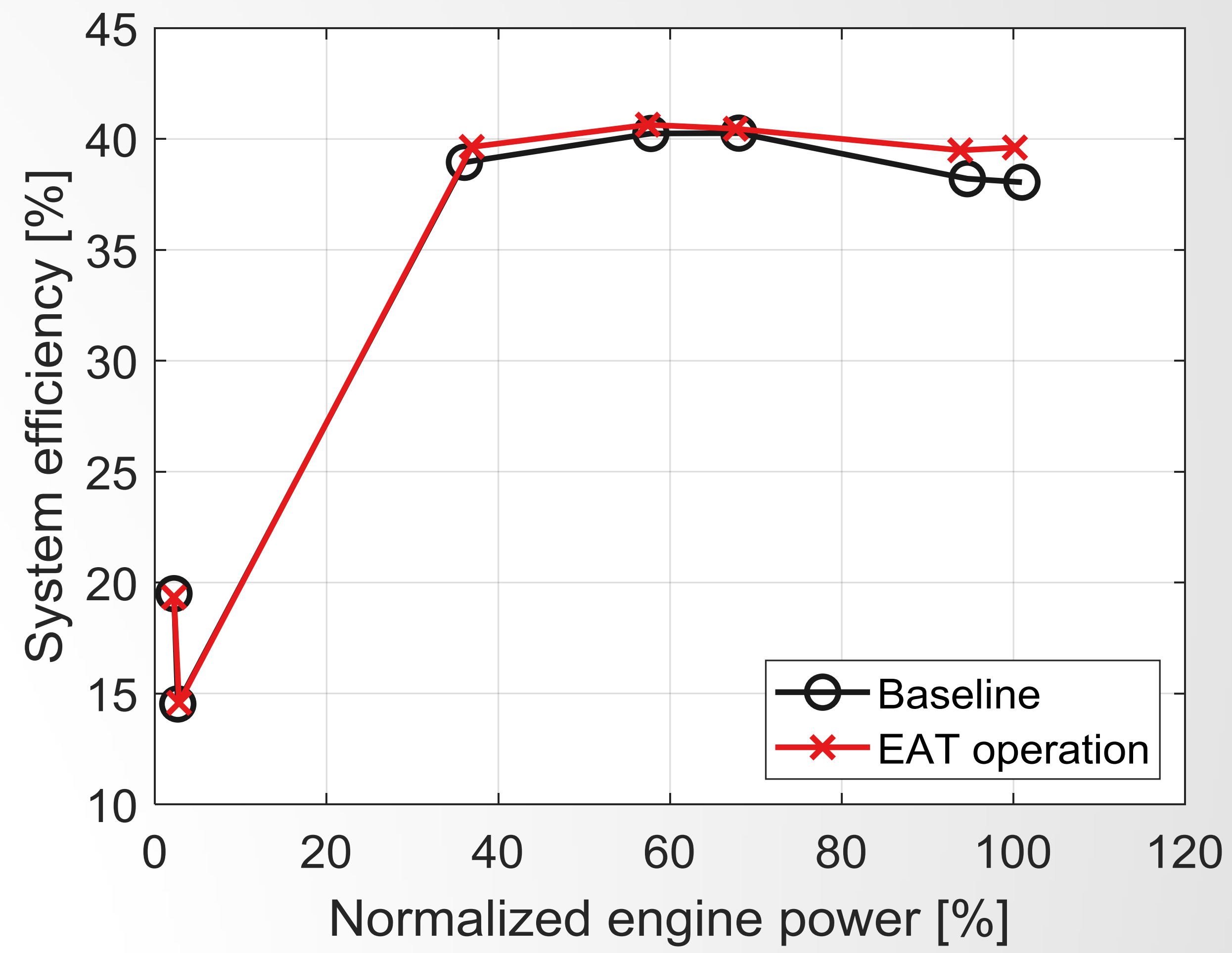
- Brake specific fuel consumption ($BSFC = \frac{\dot{m}_f}{P_c}$)
- Motoring regime ➔ fuel efficiency improved significantly
- Generating regime ➔ fuel efficiency slightly decreased
- BSFC is the least at cruise conditions

- System efficiency (η):
- Defined by total output divided total input (control volume)
- Motoring regime ($P_{M/G}$ is negative) ➔ $\eta = \frac{P_C}{\dot{m}_f \cdot LHV - P_{M/G}}$
- Generating regime ($P_{M/G}$ is positive) ➔ $\eta = \frac{P_C + P_{M/G}}{\dot{m}_f \cdot LHV}$

- System efficiency increased for all engine loads by virtue of EAT recovering otherwise lost energy from the exhaust



BSFC with engine power



System efficiency with engine power

* Note M/G and engine powers normalized by the maximum rated engine power

Engine Power Extension: Procedure

- Engine power extension using EAT
- Keeping the engine operating condition at 100% PLA
- Carefully adding more fuel through fine adjustment of FADEC commanded value
- Increasing the EAT speed (MAP) to maintain an equivalence ratio at 100% PLA
- Wastegate fully closed
- All the operating limits carefully monitored to avoid potential damage to the engine

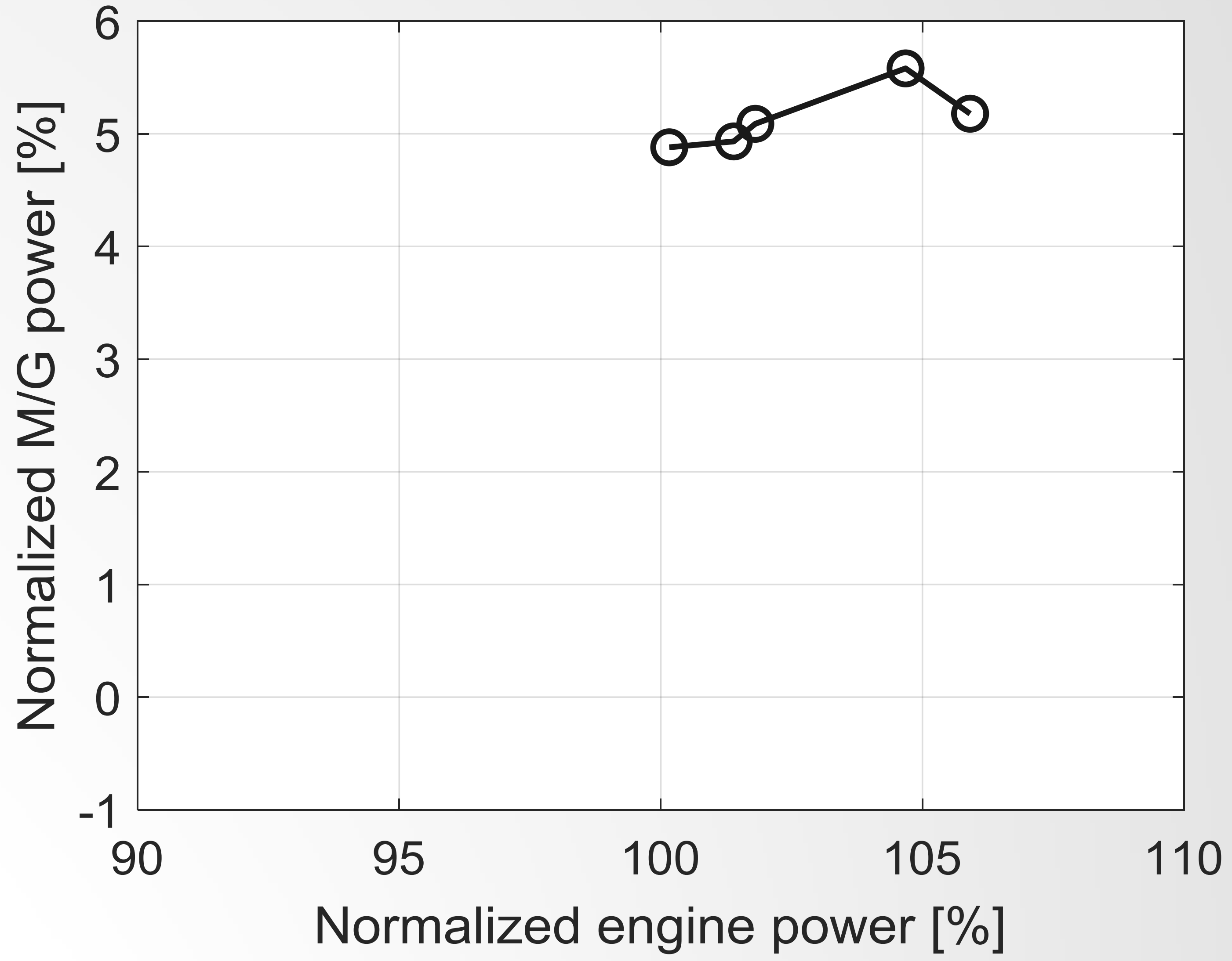
Engine Power Extension: Results

- Maximum extended engine power
  - **Approximately 106% of the maximum rated engine power**

- The experiment limited by the maximum acceptable cylinder peak pressure

- EAT still generated electrical power despite the increased EAT speed for required MAP

- M/G power generation during power extension
  - **5.6% of the rated engine output power at 104.7% of the maximum rated engine power**



M/G power during power extension

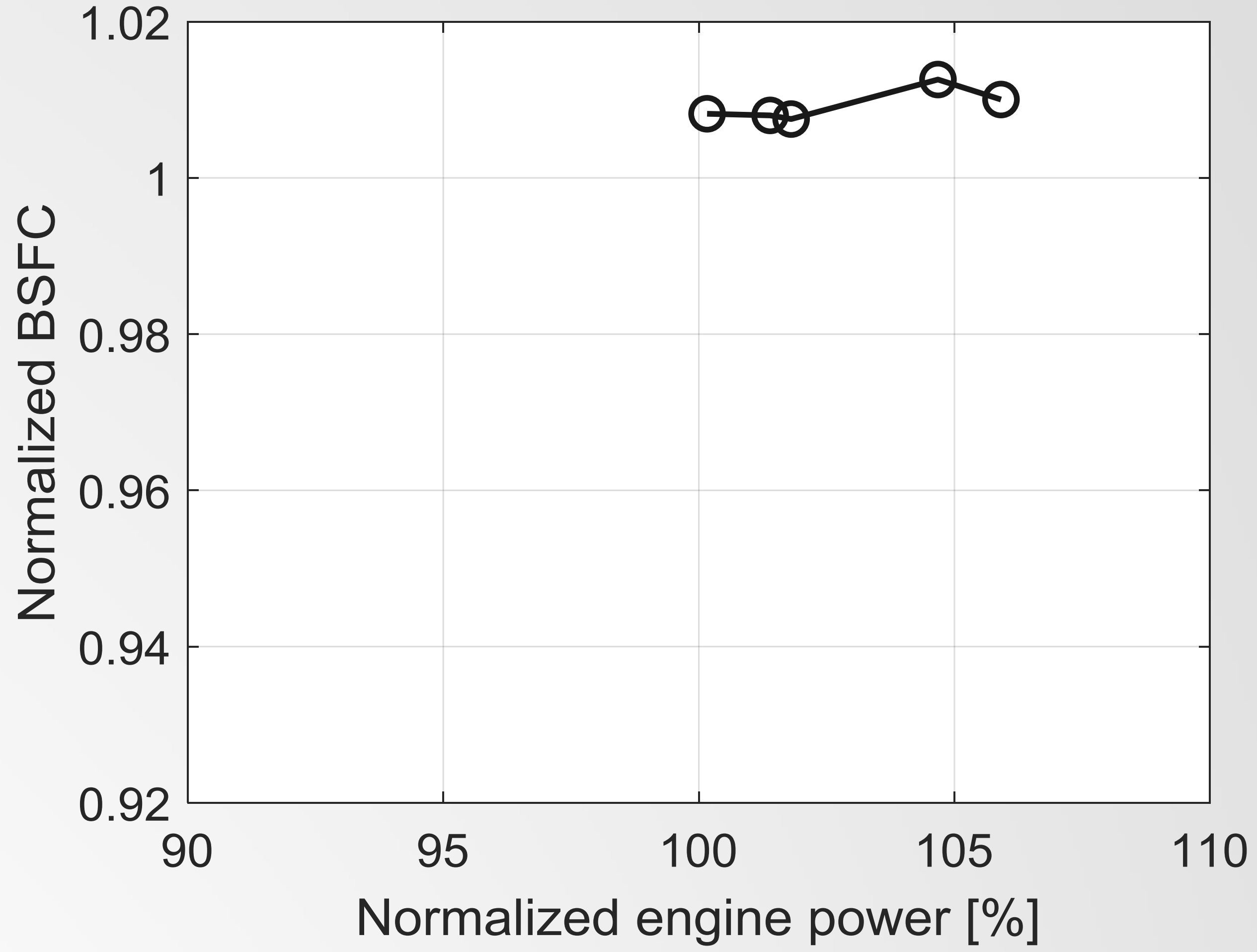
* Note M/G and engine powers normalized by the maximum rated engine power

Engine Power Extension: Results – cont'd

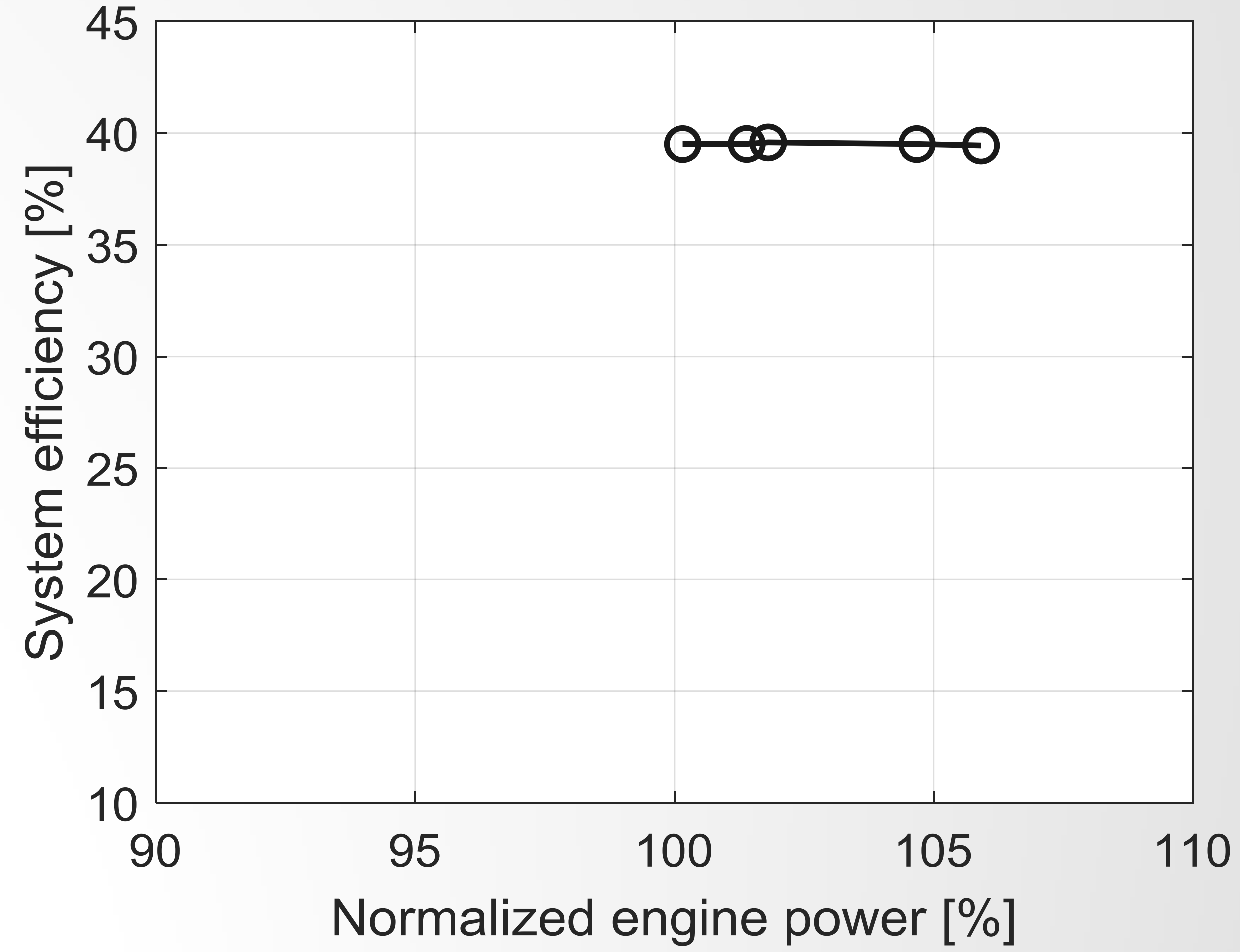
POWER & MOBILITY

- BSFC and system efficiency
- Remained constant during the engine power extension experiment

- Engine power extension using EAT does not negate the efficiency



BSFC with engine power



System efficiency with engine power

* Note M/G and engine powers normalized by the maximum rated engine power

Conclusions

- Investigated the power extension capability of an EAT implemented to a 2-liter diesel engine to address the ever-increasing power demand

- EAT Characterization
- Generated surplus energy approximately 5% at the maximum rated engine power
- Improved the system efficiency for all engine loads

- Engine Power Extension
- Extend the engine power by 6% of the maximum rated engine power
- M/G still generated surplus electrical power with the maximum of 5.6%
- BSFC and system efficiency remained constant during this experiment

References

[1] D. Cirigliano, A. M. Frisch, F. Liu, and W. A. Sirignano, “Diesel, Spark-Ignition, and Turboprop Engines for Long-Duration Unmanned Air Flights,” Journal of Propulsion and Power, vol. 34, no. 4, pages 878–892, 2018.

[2] W. Lee, E. Schubert, Y. Li, S. Li, D. Bobba, and B. Sarlioglu, “Overview of Electric Turbocharger and Supercharger for Downsized Internal Combustion Engines,” IEEE Transactions on Transportation Electrification, vol. 3, no. 1, pages 36-47, 2017.

[3] Z. J. Frederick, T. J. Hallock, T. A. Ozoroski, J. W. Chapman, C. A. Kuhnle, and P. C. Frederic, “Design Exploration of a Mild Hybrid Electrified Aircraft Propulsion Concept,” AIAA Paper 2023-4226, June 2023.

[4] Y. Yamashita, K. Sumida, H. Ogita, and Y. Jinnai, “Development of the ‘Hybrid Turbo,’ an Electrically Assisted Turbocharger,” Mitsubishi Heavy Ind. Tech. Rev., vol. 43, no. 3, pages 1-5, 2006.

[5] M. Yang, C. Hu, Y. Bai, K. Deng, Y. Gu, Y. Qian, B. Liu, “Matching Method of Electric Turbo Compound for Two-stroke Low-speed Marine Diesel Engine”, Applied Thermal Engineering, vol. 158, 2019.

[6] N. Terdich, R. F. Martinez-Botas, A. Romagnoli, A. Pesiridis, “Mild Hybridization via Electrification of the Air System: Electrically Assisted and Variable Geometry Turbocharging Impact on an Off-Road Diesel Engine”, Journal of Engineering for Gas Turbines and Power, vol. 136, no. 3, 2014, pages 031703.

[7] N. Terdich and R. F. Martinez-Botas, “Experimental Efficiency Characterization of an Electrically Assisted Turbocharger”, SAE International, 2013-24-0122, 2013.

[8] S.-G. Kang, A. J. Pope, E. S. Schroen, K. M. Kruger, K. S. Kim, C.-B. M. Kweon, D. J. Micka, W. Finger, J. A. Gibson, R. D. Meininger, and M. R. Musser, “Development of Turbocharger Speed Sensor Using Fiber Optic Coupled Optical Method,” ASME Turbo Expo 2023: Turbomachinery Technical Conference and Exposition, Boston, MA, USA, 2023.