

# Fuel-Economy Performance Analysis with Exhaust Heat Recovery System on Gasoline Engine

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## Abstract

As the electrification and connectivity technologies penetrate the market, the opportunities for intelligent thermal management of the vehicles become more salient. When an exhaust gas heat recovery (EGHR) system is used to recover waste heat from gasoline engine exhaust, the thermal parameters of the exhaust gas vary greatly, and these influence the performance of the heat exchanger (HE) system. To improve the recovery of exhaust waste heat and its conversion to faster coolant warm-up and cabin heating performance effectively, the heat transfer evaluation and optimal performance analysis are conducted on different EGHR system designs with different exhaust thermal parameters. This study aims at analyzing the fuel economy benefit with state-of-the-art HE designs in the automotive industry for exhaust gas-to-oil and exhaust gas-to-coolant heat transfer. Both physical testing and virtual simulation helped us develop a method to take advantage of the exhaust gas heat. The test result indicates that with the integration of the exhaust gas-to-coolant and exhaust gas-to-oil HEs, the gasoline engine makes a 0.5% and 0.8% fuel efficiency improvement, respectively. More specifically, the Worldwide harmonized Light vehicles Test Cycles (WLTC) fuel consumption on the 1.0L engine can be reduced by 0.5% with the integration of exhaust gas to the coolant HE, which has a smart bypass control strategy upstream of the oil cooler. Also the implementation of exhaust gas-to-oil HEs leads to a WLTC fuel consumption reduction of 0.8%. HE design with bypass valve and valve-controlled oil cooler from the experiments proved to be the most efficient HE design among the four investigated designs. The proposed simulation-based performance and engine dynamometer (dyno) evaluation shed light on the importance of selecting bypass valve and valve-controlled oil cooler HEs and design-related improvements in fuel economy for practical applications in building intelligent thermal management for vehicles.

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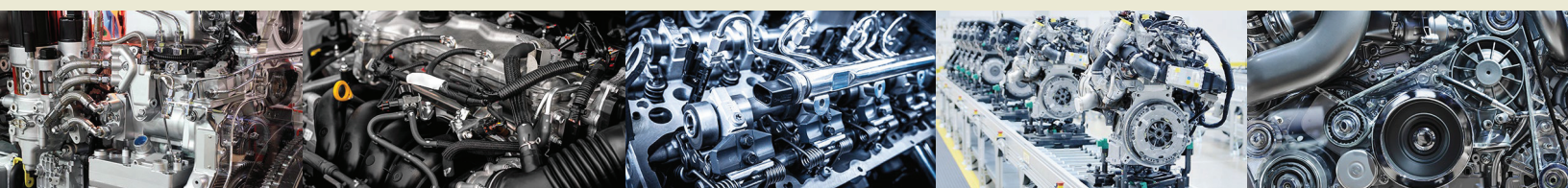
## Keywords

Waste heat, Thermal efficiency, Heat transfer, Fuel economy

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impact of the failed controlled valve due to stuck behavior and the hardware durability of HEs as the heat recovery system ages are not considered as part of our fuel economy estimate. Based on the above test results, it can be concluded that the best integration of the most efficient exhaust gas-to-coolant HE from HE2 leads to a WLTC fuel economy benefit of 0.5% applying a smart bypass control strategy. The exhaust gas-to-oil HE from HE1 OIL improves the WLTC fuel consumption by 0.8% if oil temperatures up to 130°C is tolerated and the oil-cooler is deactivated. All values have been determined for a Fox GTDI engine in combination with a B6 manual transmission.

## 6. Summary/Conclusions

As part of this project, the performance of several exhaust gas HEs has been investigated and optimized on a steady-state engine dyno. Detailed heat transfer maps have been determined and compared against each other for performance. To evaluate the benefits of these exhaust heat recovery technologies and to determine the ideal control strategy and integration into the cooling/lubrication system, a new numerical method has been developed and applied. This study presents the fundamental findings acquired from the experimental and numerical investigation of HEs. The key findings are summarized as follows:

1. It can be concluded that the WLTC fuel consumption of the Fox engine can be reduced by 0.5% by the integration of exhaust gas-to-coolant HE with a smart bypass control strategy upstream of the oil-cooler.
2. The implementation of exhaust gas-to-oil HE upstream of the main oil gallery leads to a WLTC fuel consumption reduction of 0.8%. The benefits will be even higher if the investigated exhaust heat recovery systems are combined with electrified or conventional powertrains without sophisticated thermal management technologies.
3. Among all the discussed exhaust gas-to-coolant HE designs, HE2 with bypass valve and valve-controlled oil cooler from the experiments proved to be an efficient HE design in terms of heating the coolant at a faster rate. The exhaust gas-to-oil HE from HE1 OIL improves the WLTC fuel consumption by 0.8% if oil temperatures up to 130°C are tolerated and the oil-cooler is deactivated.

This article reviews opportunities to improve the cost-benefit ratio; however, other aspects like quality, package, and cabin heating performance will be investigated in future research.

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## Definitions/Abbreviations

**BMEP** - brake mean effective pressure  
**BSFC** - brake-specific fuel consumption  
**CVSP** - corporate vehicle simulation program  
**FC** - fuel consumption  
**FMEP** - friction mean effective pressure  
**GHG** - greenhouse gas emissions  
**GT** - GT-Suite model simulation  
**GTDI** - gasoline turbocharged direct injection  
**HC** - hot-cold factor  
**HE** - heat exchanger  
**HE1** - heat exchanger from supplier 1  
**HE2** - heat exchanger from supplier 2  
**HE3** - heat exchanger from supplier 3  
**HDV** - heavy-duty vehicles  
**HX** - heat exchanger  
**ICE** - internal combustion engines  
**NEDC** - New European Driving Cycle  
**PH** - powertrain hybridization  
**OFCA** - oil filter cooler adapter  
**OHEX** - oil heat exchanger  
**ORC** - organic Rankine cycle  
**RRc** - rolling resistance coefficient  
**WHR** - waste heat recovery  
**WLTC** - Worldwide harmonized Light vehicles Test Cycles

## References

1. Joshi, A., "Review of Vehicle Engine Efficiency and Emissions," SAE Technical Paper [2019-01-0314](https://doi.org/10.4271/2019-01-0314), 2019, <https://doi.org/10.4271/2019-01-0314>.
2. Mihelic, R., "Fuel and Freight Efficiency - Past, Present and Future Perspectives," *SAE Int. J. Commer. Veh.* 9, no. 2 (2016): 120-216, <https://doi.org/10.4271/2016-01-8020>.
3. Pettersson, N. and Johansson, K., "Modeling and Control of Auxiliary Loads in Heavy Vehicles," *International Journal of Control* 79, no. 5 (2006): 479-495, <https://doi.org/10.1080/00207170600587333>.
4. Chiara, F. and Canova, M., "A Review of Energy Consumption, Management, and Recovery in Automotive Systems, with Considerations of Future Trends," *Proceedings of the IMechE Part D: Journal of Automobile Engineering* 227, no. 6 (2013): 914-936, <https://doi.org/10.1177/0954407012471294>.
5. Kelly, K.L. and Gonzales, J., "What Fleets Need to Know about Alternative Fuel Vehicle Conversions, Retrofits, and Repowers," 17 September 2017, <https://doi.org/10.2172/1402411>.

6. Gao, H.O. and Stasko, T.H., "Cost-Minimizing Retrofit/Replacement Strategies for Diesel Emissions Reduction," *Transportation Research Part D: Transport and Environment* 42 (2009): 111-119, <https://doi.org/10.1016/j.trd.2008.11.006>.
7. Quoilin, S., Broek, M.V.D., Declaye, S., Dewallef, P. et al., "Techno-Economic Survey of Organic Rankine Cycle (ORC) Systems," *Renewable and Sustainable Energy Reviews* 22 (2013): 168-186, <https://doi.org/10.1016/j.rser.2013.01.028>.
8. Allouache, A., Leggett, S., Hall, M., Tu, M. et al., "Simulation of Organic Rankine Cycle Power Generation with Exhaust Heat Recovery from a 15 liter Diesel Engine," *SAE Int. J. Mater. Manf.* 8, no. 2 (2015): 227-238, <https://doi.org/10.4271/2015-01-0339>.
9. Imran, M., Haglind, F., Lemort, V., and Meroni, A., "Optimization of Organic Rankine Cycle Power Systems for Waste Heat Recovery on Heavy-Duty Vehicles Considering the Performance, Cost, Mass and Volume of the System," *Energy* 180 (2019): 229-241, <https://doi.org/10.1016/j.energy.2019.05.091>.
10. Koeberlein, D., "Cummins Supertruck Program Relevance—Program Objectives," 2013, accessed May 2019, [https://www.energy.gov/sites/prod/files/2014/03/f13/ace057\\_koeberlein\\_2013\\_o.pdf](https://www.energy.gov/sites/prod/files/2014/03/f13/ace057_koeberlein_2013_o.pdf).
11. Howellm, T. and Gible, J., "Development of an ORC System to Improve HD Truck Fuel Efficiency," Presented at in *DEER Conference*, Detroit, Michigan, USA, 2011, [https://www1.eere.energy.gov/vehiclesandfuels/pdfs/deer\\_2011/wednesday/presentations/deer11\\_howell.pdf](https://www1.eere.energy.gov/vehiclesandfuels/pdfs/deer_2011/wednesday/presentations/deer11_howell.pdf), accessed May 2019.
12. Renault Trucks, "Reducing Consumption by Recovering Heat from Exhaust Gases," November 5, 2012, accessed May 2019, <https://corporate.renault-trucks.com/en/press-releases>.
13. Seher, D., Lengenfelder, T., Jurgen, G., Nadja, E. et al., "Waste Heat Recovery for Commercial Vehicles with a Rankine Process," Presented at in *21st Aachen Colloquium Automobile and Engine Technology*, Aachen, Germany, 2012.
14. Teng, H., "Waste Heat Recovery Concept to Reduce Fuel Consumption and Heat Rejection from a Diesel Engine," *SAE Int. J. Commer. Veh.* 3, no. 1 (2010): 60-68, <https://doi.org/10.4271/2010-01-1928>.
15. Amicabile, S., Lee, J.I., and Kum, D., "A Comprehensive Design Methodology of Organic Rankine Cycles for the Waste Heat Recovery of Automotive Heavy-Duty Diesel Engines," *Applied Thermal Engineering* 87 (2015): 574-585, <https://doi.org/10.1016/j.applthermaleng.2015.04.034>.
16. Tribioli, L., Fumarola, A., and Martini, F., "Methodology Procedure for Hybrid Electric Vehicles Design," SAE Technical Paper 2011-24-0071, 2011, <https://doi.org/10.4271/2011-24-0071>.
17. De Santis, M., Agnelli, S., Silvestri, L., Di Ilio, G. et al., "Characterization of the Powertrain Components for a Hybrid Quadricycle," *AIP Conference Proceedings* 1738 (2016): 270007, <https://doi.org/10.1063/1.4952046>.
18. Tribioli, L., Cozzolino, R., and Barbieri, M., "Optimal Control of a Repowered Vehicle: Plug-In Fuel Cell against Plug-In Hybrid Electric Powertrain," *AIP Conference Proceedings* 2015 (2015): 1648, <https://doi.org/10.1063/1.4912800>.
19. Tribioli, L., "Energy-Based Design of Powertrain for a Re-Engineered Post-Transmission Hybrid Electric Vehicle," *Energies* 10, no. 7 (2017): 918, <https://doi.org/10.3390/en10070918>.
20. Lion, S., Michos, C.N., Vlaskos, I., Rouaud, C. et al., "A Review of Waste Heat Recovery and Organic Rankine Cycles (ORC) in on Off-Highway Vehicle Heavy Duty Diesel Engine Applications," *Renewable and Sustainable Energy Reviews* 79 (2017): 691-708, <https://doi.org/10.1016/j.rser.2017.05.082>.
21. Russell, R., Johnson, K., Durbin, T., Chen, P. et al., "Emissions, Fuel Economy, and Performance of a Class 8 Conventional and Hybrid Truck," SAE Technical Paper 2015-01-1083, 2015, <https://doi.org/10.4271/2015-01-1083>.
22. Gao, Z., Finney, C., Daw, C., LaClair, T. et al., "Comparative Study of Hybrid Powertrains on Fuel Saving, Emissions, and Component Energy Loss in HD Trucks," *SAE Int. J. Commer. Veh.* 7, no. 2 (2014): 414-431, <https://doi.org/10.4271/2014-01-2326>.
23. Okuy, N., "Estimation of Fuel Economy and Emissions for Heavy-Duty Diesel Plug-In Hybrid Vehicle with Electrical Heating Catalyst System," SAE Technical Paper 2017-01-2207, 2017, <https://doi.org/10.4271/2017-01-2207>.
24. Villani, M. and Tribioli, L., "Comparison of Different Layouts for the Integration of an Organic Rankine Cycle Unit in Electrified Powertrains of Heavy Duty Diesel Trucks," *Energy Conversion and Management* 187 (2019): 248-261, <https://doi.org/10.1016/j.enconman.2019.02.078>.
25. Gao, Z., Smith, D.E., Daw, C.S., Edwards, K.D. et al., "The Evaluation of Developing Vehicle Technologies on the Fuel Economy of Long-Haul Trucks," *Energy Conversion and Management* 106 (2015): 766-781, <https://doi.org/10.1016/j.enconman.2015.10.006>.
26. Wang, R., Zhao, X., Wang, C., and Li, Y., "Modeling and Model Order Reduction of Evaporator in Organic Rankine Cycle for Waste Heat Recovery," in *Proceedings of the International Conference on Advanced Mechatronic Systems*, Zhengzhou, China, August 11-13, 2011.
27. Sodja, A., Zupancic, B., and Sink, J., "Some Aspects of the Modeling of Tube-and-Shell Heat-Exchangers," in *Proceedings of the 7th International Modelica Conference*, Como, Italy, September 20-22, 2009.
28. Wei, D., Lu, X., Lu, Z., and Gu, J., "Dynamic Modeling and Simulation of an Organic Rankine Cycle (ORC) System for Waste Heat Recovery," *Appl Therm Eng* 28 (2008): 1216-1224.
29. Shah, R.K. and London, A.L., *Laminar Flow Forced Convection in Ducts* (Academic Press, Elsevier, headquartered in Amsterdam, Netherlands, 1978), <https://www.elsevier.com/books/laminar-flow-forced-convection-in-ducts/shah/978-0-12-020051-1>.
30. Gnielinski, V., "Zur Wärmeübertragung bei laminarer Rohrströmung und konstanter Wandtemperatur," *Chem Ing Tech* 61, no. 2 (1989): 160-161.
31. Gnielinski, V., "Ein neues Berechnungsverfahren für die Wärmeübertragung im Übergangsbereich zwischen

- laminarer und turbulenter Rohrströmung," *Forsch Ing Wesen* 61, no. 9 (1995): 240-248.
32. Paikert, P. and Schmidt, K.G., Arbeitsbericht, Fachgeb. Verfahrenstechnik, Universität-GH Duisburg, Sept. 1990.
  33. Taylor, C.F. and Toong, T.Y., "Heat Transfer in Internal-Combustion Engines," ASME Paper 57-HT-17, 1957.
  34. Weber, C., Wirth, M., Frirdfeldt, R., Ruhland, H. et al., "1.0l EcoBoost 2nd Generation: A Success Story Continues," in *Aachen Colloquium*, Aachen, Germany, 2017.
  35. Dadam, S.R., Jentz, R., Lenzen, T., and Meissner, H., "Diagnostic Evaluation of Exhaust Gas Recirculation (EGR) System on Gasoline Electric Hybrid Vehicle," SAE Technical Paper [2020-01-0902](https://doi.org/10.4271/2020-01-0902), 2020, <https://doi.org/10.4271/2020-01-0902>.
  36. Zhu, D., Pritchard, E., Dadam, S.R. et al., "Optimization of Rule-Based Energy Management Strategies for Hybrid Vehicles Using Dynamic Programming," *Combustion Engines* (2021), <https://doi.org/10.19206/CE-131967>.
  37. Dadam, S., Ravi, V., Jentz, R., Kumar, V. et al., "Assessment of Exhaust Actuator Control at Low Ambient Temperature Conditions," SAE Technical Paper [2021-01-0681](https://doi.org/10.4271/2021-01-0681), 2021, <https://doi.org/10.4271/2021-01-0681>.
  38. Dadam, S.R., Ali, I., Zhu, D., and Kumar, V., "Effects of Differential Pressure Measurement Characteristics on High Pressure-EGR Estimation Error in SI-Engines," *International Journal of Engine Research* (2021), <https://doi.org/10.1177/14680874211055580>.
  39. Dadam, S., Van Nieuwstadt, M., Lehmen, A., Ravi, V. et al., "A Unique Application of Gasoline Particulate Filter Pressure Sensing Diagnostics," *SAE Int. J. Passeng. Cars - Mech. Syst.* 14, no. 2 (2021), <https://doi.org/10.4271/06-14-02-0007>.
  40. Kumar, V., Zhu, D., and Dadam, S.R., "Intelligent Auxiliary Battery Control-A Connected Approach," SAE Technical Paper [2021-01-1248](https://doi.org/10.4271/2021-01-1248), 2021, <https://doi.org/10.4271/2021-01-1248>.
  41. Dadam, S.R., Di Zhu, V.K., Ravi, V., and Palukuru, V.S.S., "Detection Method for Cybersecurity Attack on Connected Vehicles," SAE Technical Paper [2021-01-1249](https://doi.org/10.4271/2021-01-1249), 2021, <https://doi.org/10.4271/2021-01-1249>.
  42. Quoilin, S., Aumann, R., Grill, A., Schuster, A. et al., "Dynamic Modeling and Optimal Control Strategy of Waste Heat Recovery Organic Rankine Cycles," *Applied Energy* 88, no. 6 (2011): 2183-2190.
  43. Hoang, A.T., "Waste Heat Recovery from Diesel Engines Based on Organic Rankine Cycle," *Applied Energy* 231 (2018): 138-166.
  44. Quoilin, S., Declaye, S., Tchanche, B.F., and Lemort, V., "Thermo-Economic Optimization of Waste Heat Recovery Organic Rankine Cycles," *Applied Thermal Engineering* 31, no. 14-15 (2011): 2885-2893.
  45. van Kleef, L.M.T., Oyewunmi, O.A., and Markides, C.N., "Multi-Objective Thermo-Economic Optimization of Organic Rankine Cycle (ORC) Power Systems in Waste-Heat Recovery Applications Using Computer-Aided Molecular Design Techniques," *Applied Energy* 251 (2019): 112513.
  46. Horst, T.A., Rottengruber, H.-S., Seifert, M., and Ringler, J., "Dynamic HE Model for Performance Prediction and Control System Design of Automotive Waste Heat Recovery Systems," *Applied Energy* 105 (2013): 293-303, <https://doi.org/10.1016/j.apenergy.2012.12.060>.