19ICENA-0040

Hybrid Powertrain Technology Assessment through an Integrated Simulation Approach

Author, co-author (Do NOT enter this information. It will be pulled from participant tab in MyTechZone)

Affiliation (Do NOT enter this information. It will be pulled from participant tab in MyTechZone)

Abstract

Global automotive fuel economy and emissions pressures mean that 48 V hybridisation will become a significant presence in the passenger car market. The complexity of powertrain solutions is increasing in order to further improve fuel economy for hybrid vehicles and maintain robust emissions performance. However, this results in complex interactions between technologies which are difficult to identify through traditional development approaches, resulting in sub-optimal solutions for either vehicle attributes or cost. The results presented in this paper are from a simulation programme focussed on the optimisation of various advanced powertrain technologies on 48 V hybrid vehicle platforms. The technologies assessed include an electrically heated catalyst, an insulated turbocharger, an electric water pump and a thermal management module. The novel simulation approach undertaken uses an integrated toolchain capturing thermal, electrical and mechanical energy usage across all powertrain sub-systems. Through integrating 0-D and 1-D sub-models into a single modelling environment, the operating strategy of the technologies can be optimised while capturing the synergies that exist between them. This approach enables improved and more informed cost/benefit ratios for the technologies to be produced and better attributes by identifying the optimum strategy for the vehicle. The results show the potential for CO_2 reductions in the range of 2-5% at no additional cost, through co-optimisation of the technologies in a single simulation environment. The simulation work forms part of the THOMSON project, a collaborative research project aiming to develop cost effective 48 V solutions, in order to reduce the environmental impact of the transportation sector.

Introduction

The challenges facing the automotive industry with regard to fuel economy and air quality targets are driving an increase in the development of hybrid electric vehicles, with many manufacturers focussing on 48 V hybrid systems for near-term future applications. Electrification of additional powertrain components has the potential to achieve improvements in fuel economy and ensure robust emissions performance. For this reason, the Horizon 2020 funded THOMSON project was created with the objective to develop cost effective 48 V solutions through a clever combination of advanced engine technologies, electrification and wider use of alternative/renewable fuels.

Incorporating more electrified components into the powertrain increases its complexity, as it introduces interactions with the hybrid system and across other sub-systems. This represents a challenge for the optimisation of the vehicle to identify the optimum synergies between the components and maximise the benefits of the technologies on the vehicle attributes. For this reason, the role of Ricardo in the project was to create an integrated toolchain capturing electrical, mechanical and thermal energy flows throughout the powertrain and enabling simultaneous optimisation of the hybrid system strategy and the engine plus aftertreatment calibration. This toolchain was used to assess the various technologies being developed in the project, predict the benefits in terms of fuel economy and emissions, and use the results to inform the development of the demonstrator vehicles being performed by the project partners.

This paper begins by describing the integrated toolchain that has been developed, the software tools used and the optimisation routine. Following that there is a description of the hybrid demonstrator vehicles that have been used for the simulation studies, before the results and key findings from the technology studies are presented.

Method

In order to capture all of the energy flows between the technologies considered in this study, the toolchain consists of six different, inter-dependent sub-models. The architecture of the co-simulation models, and the interdependencies is indicated in Figure 1.

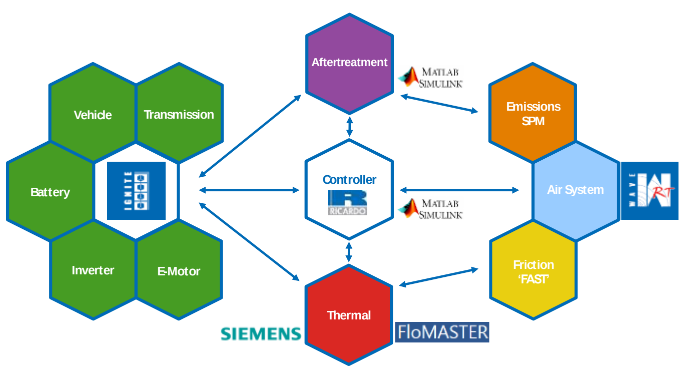

Figure 1. Integrated co-simulation model architecture

The vehicle, transmission and hybrid components (e-machine, battery and inverter) are simulated in Ricardo IGNITE, a physics-based vehicle system modelling tool, capturing the mechanical and electrical energy flows between the sub-systems. The air system is simulated using Ricardo WAVE-RT – a fast running version of the standard WAVE 1-D engine performance simulation code using a Quasi-Propagatory Model to solve the fluid domain [1]. This enables dynamic air-path modelling to be incorporated to the simulation, allowing the transient impact of the boosting systems to be captured. The instantaneous engine torque and speed is then be passed to various other sub-models, and the turbine outlet temperature and mass flow used in the exhaust aftertreatment model to predict tailpipe emissions.

The engine out emissions for most of the studies presented in this paper are characterised by maps derived from test data. This approach is suitable as the engine calibration for the demonstrator vehicles is fixed due to the project timescales. However, in some of the studies presented, the toolchain has incorporated emissions SPMs, derived from engine DoE test results. This approach enables the engine calibration to be modified and optimised with other vehicle control strategy variables to find further benefits from combinations of technologies.

For legacy reasons, the coolant and oil circuits are modelled in Siemens AMESim for one demonstrator vehicle, and FloMASTER for the other – both codes are able to co-simulate with the other sub-models. The thermal models receive the in-cylinder conditions from the air-path model and calculate the coolant-side and engine structure thermal conditions, passing the calculated wall temperatures back to the engine model. Friction is calculated using Ricardo's proprietary friction analysis tool, FAST, which feeds the predicted FMEP to the air-path model taking into account the impact of oil temperature as predicted by the thermal model.

The MATLAB -based supervisory controller interfaces with all sub-models and contains the control strategies that are used to provide the required motive power for the drive-cycle and any associated ancillary loads. Certain elements of this control strategy are defined by variables which are optimised using Ricardo's Global DoE Toolkit, Efficient Cal. The optimisation approach used is to identify key variables within the hybrid, engine and aftertreatment control strategies and create a test matrix using a LHC filling approach. Simulations are then performed for each point in the test matrix, using the integrated model, to generate a predicted drive-cycle fuel consumption or emissions result for a given combination of variables. The responses of the output parameters are then modelled, as a function of the input variables using a Stochastic Process approach [2], and an optimiser used to identify the best combination of input variables to achieve a set of objectives, obeying any constraints that are defined. Primarily, the optimisation objective used for the studies in this paper are to minimise the fuel consumption, with a constraint on tailpipe emissions, and ensuring battery SOC neutrality over the cycle. As a verification, the predicted optimum set of variables is then tested over the drive-cycle using the co-simulation model and the results compared to the optimiser prediction.

Demonstrator Vehicles

The toolchain has been used to perform several technology studies for the demonstrator vehicles that have been developed by the project partners. Some of the key vehicle parameters are shown in Table 1.

Table 1. Demonstrator Vehicle Parameters

Vehicle	Ford Grand C-Max	FIAT 500X
Mass	1800 kg	1350 kg
Hybrid Architecture	P2, 48 V	P0, 48 V
Transmission	6-speed AMT	6-speed Manual
E-machine Max. Power	15 kW	10 kW
Battery Capacity	1 kWh	0.4 kWh
Engine Capacity & Type	1.0 ℓ CNG	1.6 ℓ Diesel
Boost System	FGT + E-compressor	VGT + E-compressor
Aftertreatment	Electrically-heated TWC	Electrically-heated DOC + SCRF + U/F SCR
Cooling System	Electric Water Pump + TMM	Mechanical Water Pump + Thermostat

Both demonstrator vehicles utilise an e-compressor to maintain the transient response of the vehicles even when using a downsized engine, and both incorporate electrical heating in the aftertreatment systems to ensure robust emissions performance, using devices similar to that shown in Figure 2 which have been developed by Continental-Emitec. The usage of these technologies has a strong impact on the battery SOC, and therefore the control and calibration need to be optimised at the same time as the hybrid system usage in order to maximise the benefits to the vehicle.

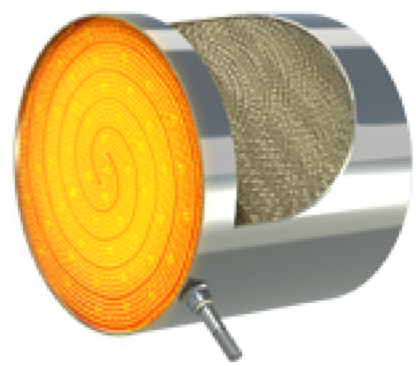

Figure 2. Electrically Heated Catalyst – Continental Emitec

The Ford vehicle also incorporates a Thermal Management Module (TMM), developed by Schaeffler, in the engine cooling circuit. The TMM is essentially a 4-way valve that controls the flow area through several routes of the cooling circuit, actuated by a single rotating actuator. Its operating strategy can be optimised to achieve a faster warm-up, however with it being installed on a circuit containing an electric water pump, the calibration of both components needs to be optimised together in order to find the optimum synergies between them.

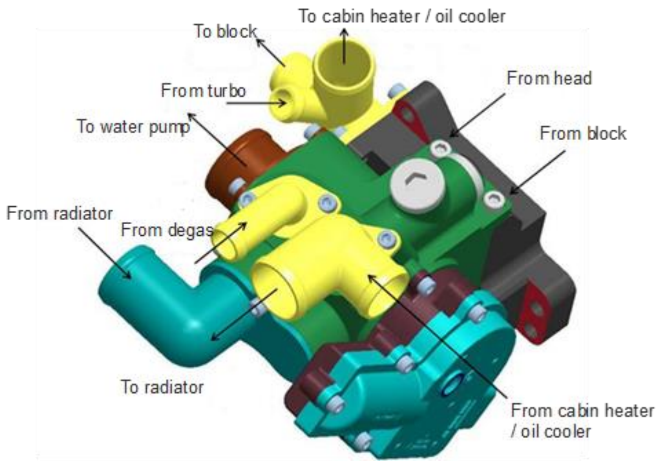

Figure 3. Thermal Management Module - Schaeffler

Technology Studies

The studies presented in this section are divided first into the technology in focus, and then subsequently into the vehicle application where appropriate. Primarily the fuel consumption benefits are presented on a WLTC basis, as this is the cycle against which the demonstrator vehicle targets are set, however in some cases other cycles have been simulated, either to ensure emissions robustness or to emphasis the benefit of the technology under different operating conditions.

Electrically Heated Catalyst

Both demonstrator vehicles have 48 V electrically heated catalysts (EHCs) installed in the exhaust systems to improve the emissions conversion efficiencies under cold conditions. The first study presented is related to the FIAT demonstrator vehicle with the Diesel engine, followed by the studies performed on the Ford vehicle with the CNG engine.

FIAT 500X

Due to the time restrictions of the project, the FIAT demonstrator vehicle will be developed with a carry-over engine calibration. Therefore, the first studies presented in this section consider this as a constraint. While the focus of the project is WLTC fuel consumption improvements, this must be achieved while demonstrating Euro 6d-Temp emissions compliance. The NEDC represents a usage pattern that falls under current RDE legislation and is challenging for a Diesel application due to the low vehicle and engine speeds, resulting in relatively cold exhaust temperatures. For this reason, the studies focussed on this application considered an optimisation approach that maximised the benefit of the technology over the WLTC, while maintaining a calibration that gives constant tailpipe NOx emissions over the NEDC. This approach is also possible for a wide range of real world drive cycles and previous work on the "dieper" consortium show a method for determining worst case cycles for a given application and hardware [3].

The baseline vehicle, without the 48 V hybrid system, utilises an aftertreatment heating strategy that involves late fuel injection into the cylinder to increase exhaust and catalyst temperatures in order to reduce the tailpipe NOx emissions. At the NOx engineering target for the programme, this strategy results in a fuel consumption penalty of 3.7% on the WLTC and 11% on the NEDC.

Implementing the 48 V hybrid system but without the electrically heated catalyst (EHC) results in a 2.6% fuel consumption benefit over the WLTC, when the calibration is optimised to give the same NEDC tailpipe NOx level as the baseline. When the EHC is then added to this system, and the calibration re-optimised, a further 5.8% fuel consumption benefit can be achieved through reducing the amount of fuel used for the late injection aftertreatment heating strategy. The optimisation uses target temperature setpoints for both the EHC and the late injection strategy, as well as several hybrid strategy parameters. The resulting optimum calibration utilises both heating modes at an aftertreatment temperature of below 90°C, but only uses the EHC above this threshold.

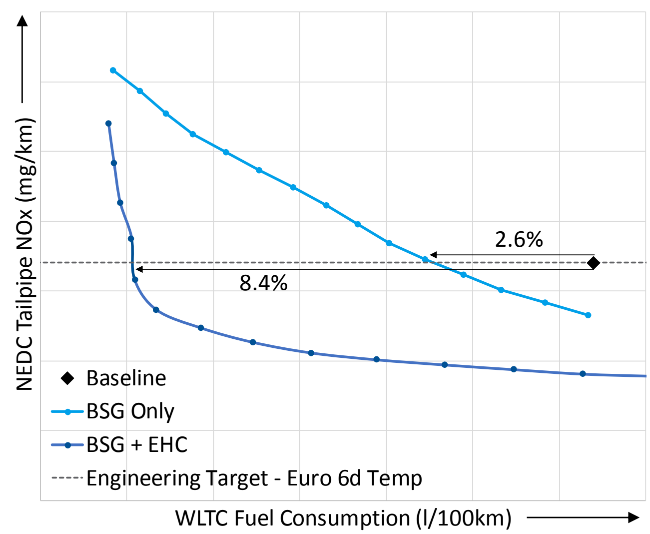

Figure 4. Assessment of the impact of BSG and EHC WLTC Fuel Consumption and NEDC Tailpipe NOx

Figure 4 also shows that if the tailpipe NOx target were to reduce, the benefit of the EHC would increase as the two trade-off curves begin to diverge. While the legislation beyond Euro 6 is not yet finalised, the tailpipe NOx limits may be reduced even further. Utilising the results from the optimisation, it is possible to calculate a cost/benefit ratio for the EHC based on an optimised calibration to give maximum WLTC fuel consumption benefit, whilst maintaining NEDC tailpipe NOx to the target. Figure 5 shows that under the emissions targets for the project, the cost/benefit ratio of the EHC is ~12 €/(gCO_2/km), but as the emissions constraints reduce the benefit of the technology increases significantly, resulting in a value of ~8 €/(gCO_2/km) for an estimated future emissions target.

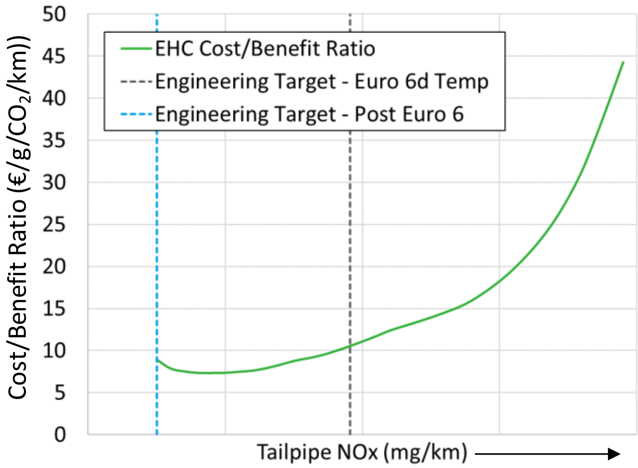

Figure 5. FIAT Demonstrator Vehicle EHC Cost/Benefit Ratio

The final study on the FIAT application relating to the electrically heated catalyst was to optimise the hybrid and aftertreatment strategy as before, but also include engine calibration maps, specifically the boost pressure and EGR maps. The results from this optimisation, in Figure 6, show the potential for a further 2-5% improvement in fuel economy for the demonstrator vehicle. This additional benefit is possible through re-optimising the engine calibration maps, in some areas making the engine BSFC worse, but leading to increased exhaust temperatures. This in turn reduces the requirements on the EHC which enables more of the energy recovered under regenerative braking to be used for motoring, leading to an overall fuel consumption improvement, as shown in Figure 7.

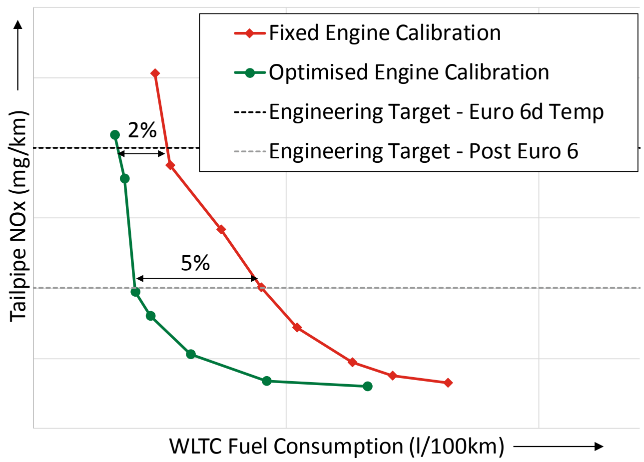

Figure 6. Impact of engine calibration optimisation on the FIAT Demonstrator Vehicle

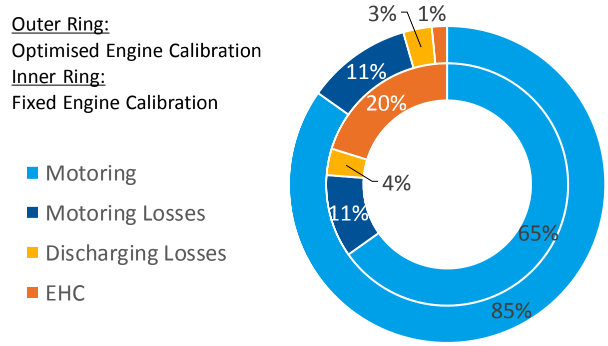

Figure 7. Regenerative braking energy usage, excluding auxiliary load usage

The results from this study emphasise the benefits of optimising the vehicle as an integrated system, rather than a set of individual sub-systems. In order to achieve these benefits, a systems-led approach needs to be taken utilising integrated model-based development to identify optimum synergies between sub-systems and deliver improved vehicle attributes for minimal additional cost.

Ford Grand C-Max

The Ford demonstrator vehicle uses a gasoline engine that is converted to run on CNG, enabling a significant reduction in CO_2 to be achieved due to the lower carbon content of the fuel. The improved knock tolerance of this fuel also enables the compression ratio of the engine to be increased to achieve further fuel economy improvements. In order to reduce engine out emissions, the exhaust system is equipped with a TWC which is formulated to consider CH_4 as the main component of the hydrocarbon exhaust emissions. The conversion efficiency curve for a CH_4 formulation is significantly different to a standard gasoline HC conversion curve, biased towards a higher exhaust gas temperature by a margin of 100-150°C. This higher conversion temperature, coupled with the increased compression ratio, means that an EHC is required to reduce the emissions to meet the legislation considered for the demonstrator vehicles. The CH_4 emissions also have an impact on the CO2e of the vehicle, although at the emissions levels considered for the project this represents a <3% increase on the vehicle CO_2.

The Ford hybrid system is in a P2 configuration, which enables the vehicle to operate in EV mode. Clearly under these conditions, the exhaust system will be cooling down as the engine is not in use. Therefore, the optimisation of the vehicle needs to consider the requirements of the EHC and how the overall vehicle fuel consumption and emissions may interact with increased usage in EV mode. Additionally, the usage of EV mode can also have a strong impact on the driveability of the vehicle due to the requirements to stop and start the engine at increased vehicle speeds. The driveability of the vehicle can be improved by lowering the allowable maximum vehicle speed in EV mode, but this also may have an impact on vehicle fuel consumption and emissions. For this reason, the study presented in this section considers these factors and predicts the impact on vehicle attributes both over the WLTC and an urban RDE cycle.

Figure 7 shows the results from a Pareto optimisation with the objective of both minimising CO_2 and tailpipe THC emissions. A clear trade-off exists which is primarily due to an increased usage of the EHC as the tailpipe emissions reduce – this can be seen in the EHC temperature target line that indicates the brick temperature at which the EHC is switched off. With no EHC, the tailpipe emissions over the WLTC would be 137 mg/km, significantly above the limit for the demonstrator vehicle of 100 mg/km. In order to reduce the emissions to the limit, a CO_2 penalty of 4.2% is expected. Although it should be noted that if the CH_4 emissions are considered as CO2e the penalty is reduced to 3.4%

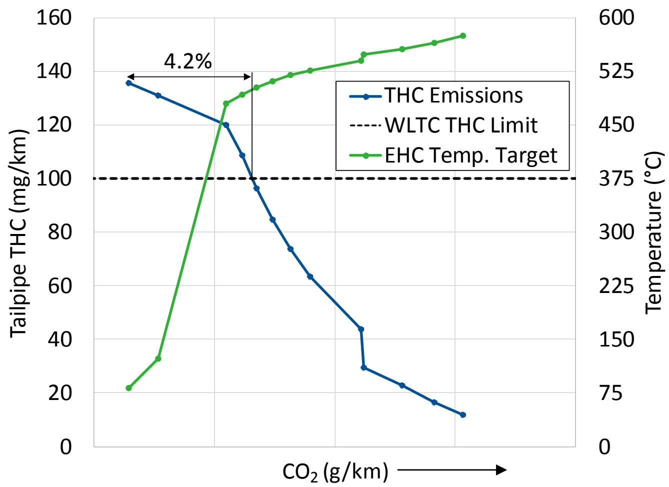

Figure 8. Ford Demonstrator Vehicle THC Emissions vs CO_2

Whilst many of the parameters remain approximately constant, one significant response is how the optimised maximum speed in EV mode changes with the tailpipe THC emissions. Figure 8 shows this by comparing the THC emissions resulting from the calibration on the Pareto curve and the duration spent in motive EV mode relative to the total cycle time, resulting from the optimised setting for maximum EV speed. For emission compliant calibrations that produce > 60 mg/km, the vehicle operates between 3% to 8% of the cycle in motive EV mode, with a decrease in this ratio as tailpipe THC emissions reduce. The maximum achieved EV speed is typically within the 30 – 40 km/h range for these calibrations.

However, in order to achieve emissions below 40 mg/km, the vehicle has to stop operating in EV mode entirely. Future THC emissions constraints for CNG applications are not yet determined, however if the requirement is reduced below this level the primary benefit of a P2 hybrid architecture could be entirely negated. This not only has an impact on the achieved fuel economy, but also user expectations of future hybrid vehicles which may require limited EV operation.

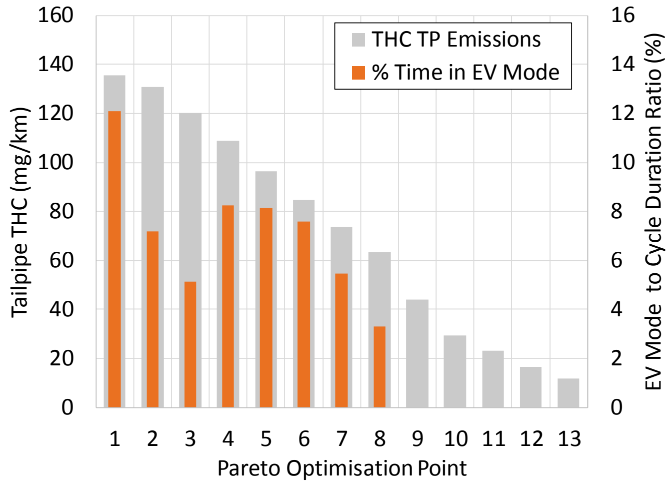

Figure 9. Optimised calibration of EV mode operation as percentage of cycle duration, as a function of tailpipe THC emissions

Figure 8 shows the results using an optimised maximum EV speed constraint, based on minimising fuel consumption alone. However, this parameter has a strong impact on driveability and engine restart requirements; therefore, it is possible that it is constrained by other requirements and cannot be set to the optimum. Figure 9 shows the fuel consumption penalty from the EHC that is required to meet the emissions target, as a function of different maximum EV speed limits. For the WLTC results, if the maximum speed in EV mode has to be reduced from the optimum 55 km/h down to 30 km/h to satisfy driveability constraints there is a modest fuel economy penalty of up to 1%.

The figure also shows the results from an urban RDE cycle which has a relatively low average vehicle speed. When the WLTC calibration is used on this RDE cycle, the THC emissions in mg/km are very similar to the WLTC results. This shows that the EHC enables robust emissions performance under different operating conditions. The fuel consumption penalty over the RDE cycle is generally higher than the WLTC, due to more time spent at low exhaust temperature conditions which requires greater usage of the EHC. Interestingly, there is a stronger impact of the driveability constraint on the fuel consumption under these real-world conditions. If the vehicle is constrained to only operate in EV mode up to a speed of 30 km/h, rather than 55 km/h, the fuel consumption penalty is almost doubled from 4.1% to 8.3%. These results emphasise the importance of considering these high-level driveability requirements and their impact on real-world operation in the early development stages in order to make decisions with greater robustness.

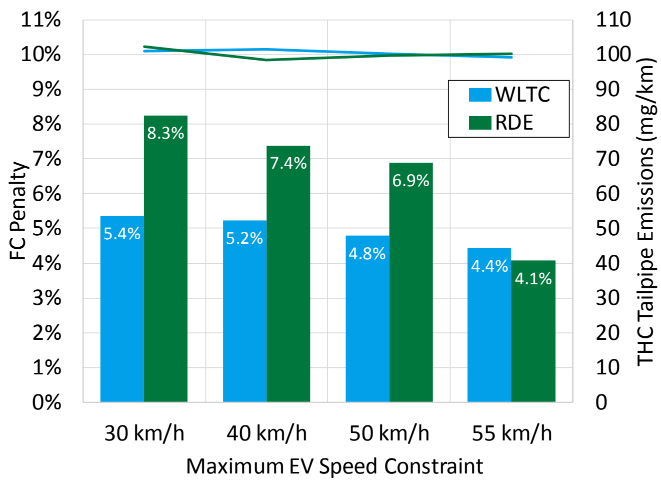

Figure 10. Impact of Maximum EV speed constraint on fuel consumption penalty to achieve WLTC emissions

Thermal Management Module and Electric Water Pump

The Ford demonstrator vehicle uses a Thermal Management Module (TMM) and an Electric Water Pump (e-WP) on the coolant circuit of the engine, with the intention of enabling a fuel economy improvement from both of these technologies. For this simulation study, the thermal circuit layout and operation were optimised to reduce combustion heat losses, friction losses and ancillary load. The lever used to improve the thermal system is a combination of an electric water pump and a thermal management module, replacing respectively the mechanically-driven water pump (m-WP) and wax thermostat. The circuit layout was modified to connect to the ports of the TMM, as illustrated in Figure 11. The TMM features two actuators, one controlling the block valve position, another controlling the rotation of the main valve, connecting the flow paths to the by-pass/cabin heater, radiator, degas bottle and oil cooler. The e-WP is used to control the total coolant flow rate independently from engine speed to minimise heat rejection by controlling the temperature delta between block outlet and heat inlet, resulting in lower pump work. It operates in zero-flow mode during warm-up for faster metal temperature increase and ancillary load cancellation. It can also be used in run-on mode when the engine is off to prevent local boiling in sensitive components, such as the turbocharger. The TMM controls the flow split between multiple branches of the circuit, for optimal heat rejection during warm-up and hot phases. In the hot phase, the head outlet coolant temperature is controlled to high level of up to 105°C.

In phase 1, the e-WP is off, there is no flow throughout the circuit for faster metal warm up and cancelling ancillary load. All valves are shut apart from the oil cooler port. The TMM enters phase 2 when the block metal temperature reaches a target value, requiring block cooling. Therefore, the pump is switched on and the block valve is partially opened, requiring the by-pass port to be opened to allow coolant to flow back to the pump. The coolant also flows through the oil cooler, rejecting heat to oil, until the oil temperature becomes higher than the coolant's. When this condition is reached, the TMM enters phase 3, where the oil cooler valve closes, in addition to the head outlet coolant temperature rising towards its target of 105°C, requiring the main valve to be rotated towards 140°. From this position onwards, the thermal system enters the warm temperature control mode, phase 4, where by-pass and radiator port opening areas are controlled to maintain the head outlet coolant temperature to the target, the block valve position is controlled based on block temperature and the e-WP speed is controlled to target a 10°C temperature delta across the engine. If critical conditions are met, the block and main valves are fully opened (apart from the by-pass port), with the e-WP running at rated speed to maximise cooling and protect the engine.

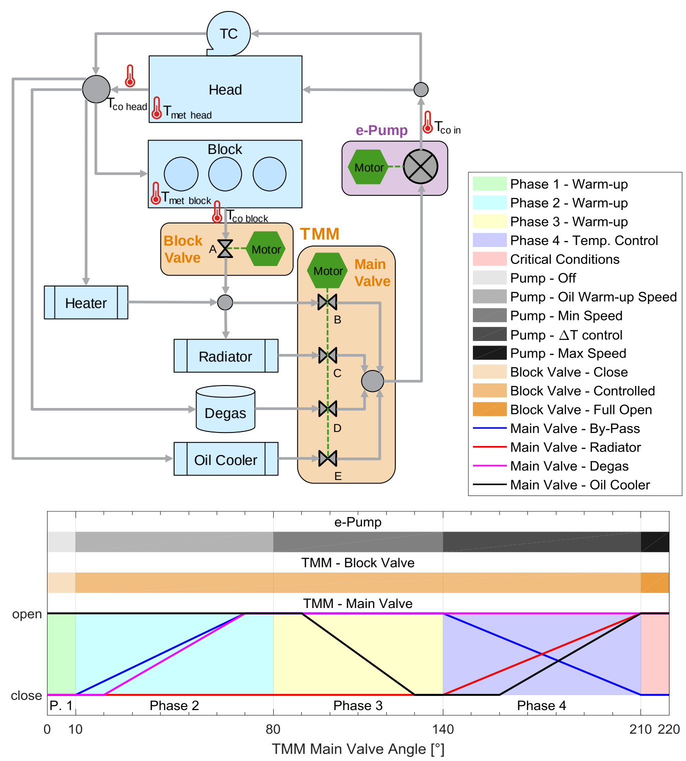

Figure 11. Engine thermal circuit layout with operation modes for e-WP and TMM block and main valves

The thermal system of the engine was modelled with both coolant and oil circuits, integrated to the overall vehicle model. The transient engine model provides gas temperatures and heat transfer coefficients from the combustion chamber and integrated exhaust manifold, as well as frictional heat losses, to the thermal system. The coolant, oil and metal temperatures responses were fed back to the engine model. The e-WP and TMM are electrified, their energy flows were captured by connecting the devices to the hybrid vehicle battery (in the modelling).

The benefit of this advanced thermal system was compared against a conventional configuration with a m-WP and thermostat, with an opening temperature of 90°C. The performance of each component constituting the advanced system was also analysed independently to check for adverse interactions. The model was also configured with a TMM and m-WP to enable further comparison. All comparisons between configurations were performed over WLTC at a cold start condition of 23°C. Figure 12 shows that a CO_2 benefit ranging between 0.5% to 0.8% is expected over the baseline thermal system.

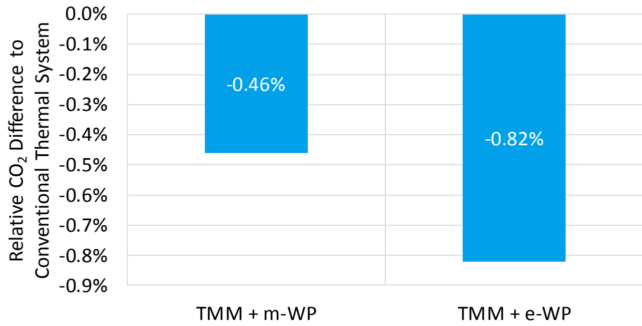

Figure 12. Fuel consumption benefit of two thermal system configurations compared to TST + m-WP baseline

The primary contributor to the CO_2 benefit observed with each thermal system is the reduction of in-cylinder heat transfer from the combustion gas to the walls of the combustion chamber and ports, as shown in Figure 13, introduced by the hotter wall temperatures. This is achieved by using the TMM for greater temperature control and in the case of the advanced circuit using the e-WP to reduce the flow rate, thereby resulting in higher metal temperatures.

The two secondary factors which contribute to lowering the fuel consumption are the reduction in friction losses, through a decrease in base engine friction by operating with hotter oil, and reduced water pump work by either lowered mass of coolant to circulate when the ports of the TMM are closed, or lowered pump speed for the e-WP. Overall, the 'TMM +e-WP' case provides the lowest friction loss energy.

The combined reduction in losses, from both friction and heat losses, is in-line with the trend observed in Figure 12 for the CO_2 benefit.

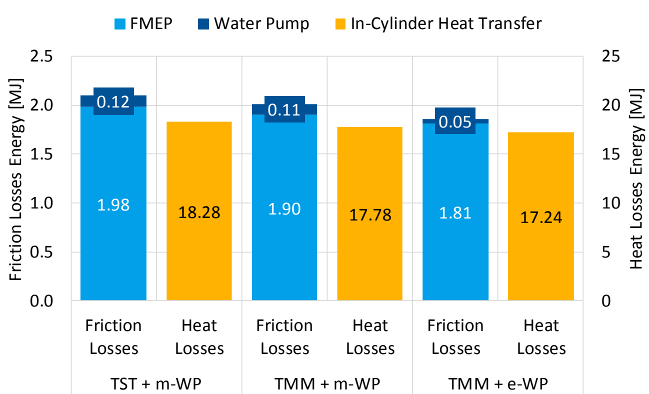

Figure 13. Friction losses and heat losses total energy of the three thermal system configurations

Thermally Insulated Turbocharger

A thermally insulated turbocharger was another technology developed through the THOMSON project by BorgWarner. The design of the turbocharger and the development of a bespoke heat transfer model are described separately [4]. The heat transfer model was integrated into the toolchain presented in this paper and optimisation studies were performed to predict the drive-cycle fuel consumption reductions through using this technology.

For the FIAT demonstrator vehicle, the initial simulation results over the WLTC showed an increase in turbine outlet temperature of 20 – 40°C throughout the majority of the cycle. However, if the engine calibration is optimised with the hybrid and aftertreatment calibration the requirements for electrical heating of the catalyst over the WLTC are small. Therefore, the benefit of the insulated turbocharger is negligible over the WLTC.

There is greater benefit from the insulated turbocharger under low operating load conditions, where the lower exhaust temperatures lead to significant electric heating requirements. In order to evaluate this, the NEDC was simulated which represents a challenging cycle for aftertreatment temperatures for the FIAT application. Figure 14 shows the tailpipe NOx and the fuel consumption for the baseline turbocharger and the insulated turbocharger vehicles – with both utilising the BSG and electrically heated catalyst (EHC). Applying an RDE Engineering Target for Euro 6d-Temp (the legislation level used for the demonstrator vehicles), shows a 2.1% fuel consumption reduction from the insulated turbocharger due to the energy usage in the EHC being reduced from 418 kJ down to 162 kJ. Beyond Euro 6, the fuel consumption benefit of the insulated turbocharger has the potential to reach 3.2%. Additionally, whilst the NEDC represents a challenging RDE cycle, more challenging cycles may exist. Under these extreme RDE conditions, it can be expected that the insulated turbocharger has the potential for even greater real-world fuel economy improvements than those presented over the NEDC.

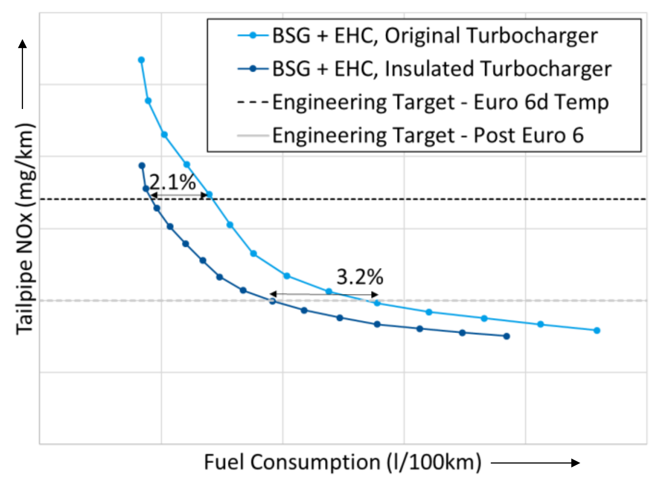

Figure 14. FIAT Demonstrator Vehicle NEDC Fuel Consumption and Tailpipe NOx for the original and insulated turbocharger

Summary

The integrated toolchain described in this paper has been used to perform multiple optimisations focussing on hybrid vehicle fuel consumption with a number of different technologies. In each case, the hybrid system and aftertreatment calibrations have been simultaneously optimised in order to find the best solutions, with the engine calibration also included for some results.

For the FIAT demonstrator vehicle, the fuel economy benefit of the EHC has been predicted to be 5.8% over the WLTC, using a calibration which also gives constant tailpipe NOx over the NEDC. This is mainly achieved through reducing the usage of engine-based exhaust temperature strategies by applying the heat directly to the aftertreatment system. The benefit of the EHC is predicted to increase with lower NOx emissions limits, leading to an improved cost/benefit ratio for this technology.

EHC requirements on the Ford CNG vehicle are predicted to cause a 4.2% penalty in fuel consumption when meeting the THC emissions limit for the demonstrator vehicle. Reducing the emissions further to meet future possible limits requires increased EHC usage, and could result in the vehicle being unable to operate in EV mode entirely, negating one of the key benefits of a P2 hybrid architecture. Driveability constraints, specifically relating to engine restart requirements, could have a negative impact on the WLTC fuel consumption and this penalty could be even larger for the real-world fuel consumption of the demonstrator vehicle.

The TMM with a mechanical water pump can be used to provide a fuel economy benefit of 0.5% through reducing a combination of pump work, friction and in-cylinder heat transfer. However, when it is combined with an electric water pump, the benefit is almost doubled as the e-WP allows a further reduction in pump work, friction and in-cylinder heat losses.

The thermally insulated turbocharger developed for the FIAT vehicle could reduce EHC requirements over a lower-load cycle, such as the NEDC. It is predicted to give a 2.1% fuel consumption benefit on this cycle, in the demonstrator vehicle.

The technologies assessed in this paper have significant interactions across the powertrain sub-systems with significant mechanical, thermal and electrical energy flows between them. Integrated toolchains, such as the one presented in this paper, are the only way to identify the synergies between components and find the optimal solutions for the powertrain as a whole. The insight provided by such toolchains can be used in the early development phases to inform cost/benefit ratios and lead to hybrid vehicles with improved attributes at minimal cost.

References

1. Cipollone, Roberto, and Antonio Sciarretta. The quasi-propagatory model: A new approach for describing transient phenomena in engine manifolds. No. 2001-01-0579. SAE Technical paper, 2001
2. Seabrook, J., T. Salamon, S. Edwards, and I. Noell. "A comparison of neural networks, stochastic process methods and radial basis function for the optimization of engine control parameters." In Second conference design of experiments in engine development. 2003
3. King, R., Souflas, I., Cantallops-Jimenez, R., Seabrook, J., Ward, A., Sellers, R., “Model-Based Exhaust Aftertreatment Technology Robustness Testing using Monte Carlo Generated RDE Cycles”. SIA Powertrain Rouen 2018
4. Burke, R., Liu Y., Vijayakumar R., Werner, J., Dalby, J., “Inner-Insulated Turbocharger Technology to Reduce Emissions and Fuel Consumption from Modern Engines.” SAE Naples 2019 Conference Proceedings 19ICENA-0075

Contact Information

For further details please contact Joshua Dalby through e-mail: joshua.dalby@ricardo.com

Acknowledgments

The THOMSON project acknowledges the contribution of the European Union, through which it has received funding from the Horizon 2020 Programme for research, technological development and demonstration under Agreement no. 724037.

The authors would like to acknowledge the work of Hui Niu and Petr Matajsz at Ricardo who performed some of the simulations described in this paper. The authors are also grateful to the directors of Ricardo for allowing the publication of this paper.

Definitions/Abbreviations

AMT	Automated Manual Transmission
CNG	Compressed Natural Gas
DOC	Diesel Oxidation Catalyst
DoE	Design of Experiments
EHC	Electrically Heated Catalyst
e-WP	Electric Water Pump
FGT	Fixed Geometry Turbine
LHC	Latin Hypercube
m-WP	Mechanically-driven Water Pump
SCR	Selective Catalytic Reduction
SCRF	Selective Catalytic Reduction Filter
SOC	State of Charge
SPM	Stochastic Process Model
THOMSON	Mild Hybrid Optimisation for Fast Market Penetration
TMM	Thermal Management Module

TST	Thermostat
TWC	Three-Way Catalyst
U/F	Underfloor
VGT	Variable Geometry Turbine