freedomCAR & vehicle technologies program

Vehicle Fuel Economy Improvement through Thermoelectric Waste Heat Recovery

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BSST Thermoelectrics Program

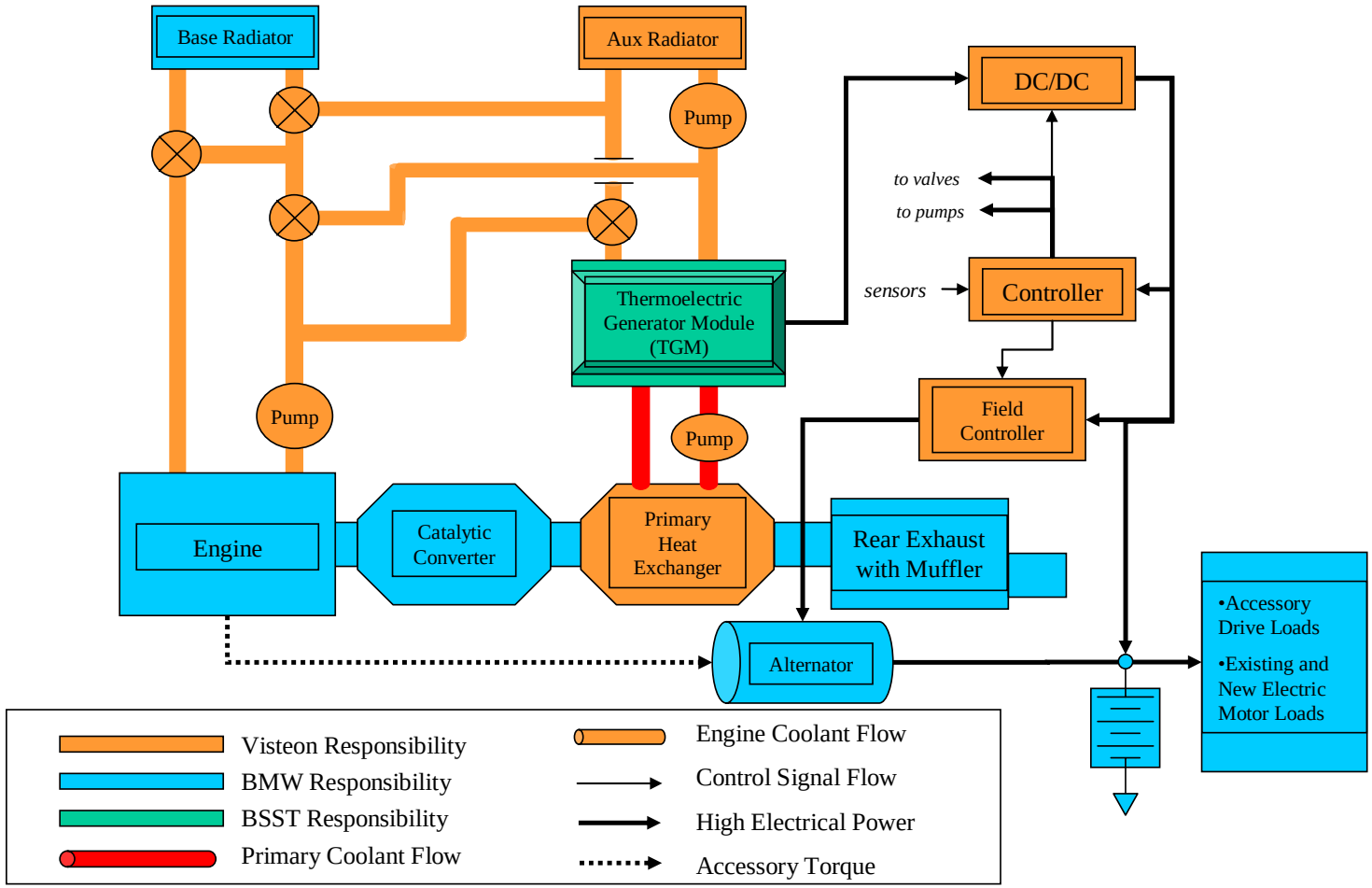
Program funded by the DOE- Freedom Car Office

One of four teams working to achieve 10% fuel economy improvement through conversion of waste heat to electric energy using thermoelectric power generation

BSST has started the second of four phases and will have a bench system operational in Q4 2006

BSST is developing a system that will be installed in a BMW series 5 platform

System Architecture



Visteon

Vehicle / Engine Selection

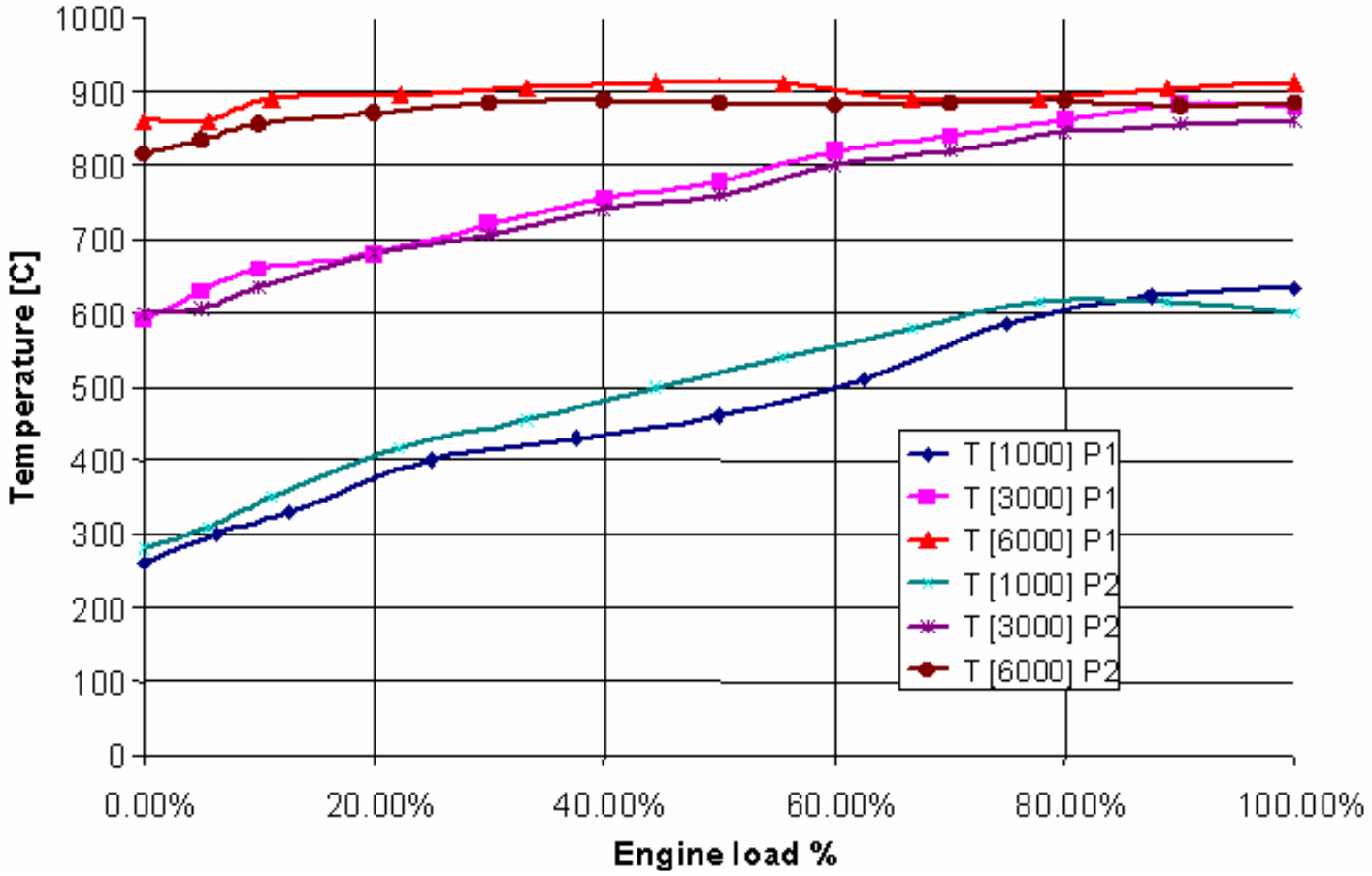
Selected vehicle platform (BMW 530i, MY2006)

The selected vehicle is a state-of-the-art BMW sedan with a 3 liter displacement engine (BMW 530i, MY 2006, automatic transmission)

Selected engine platform (Inline 6 cylinder, 3.0L displacement)

The engine is the newest generation of highly efficient, in-line, 6-cylinder engines with characteristics representative of engines in the 2010 to 2015 timeframe

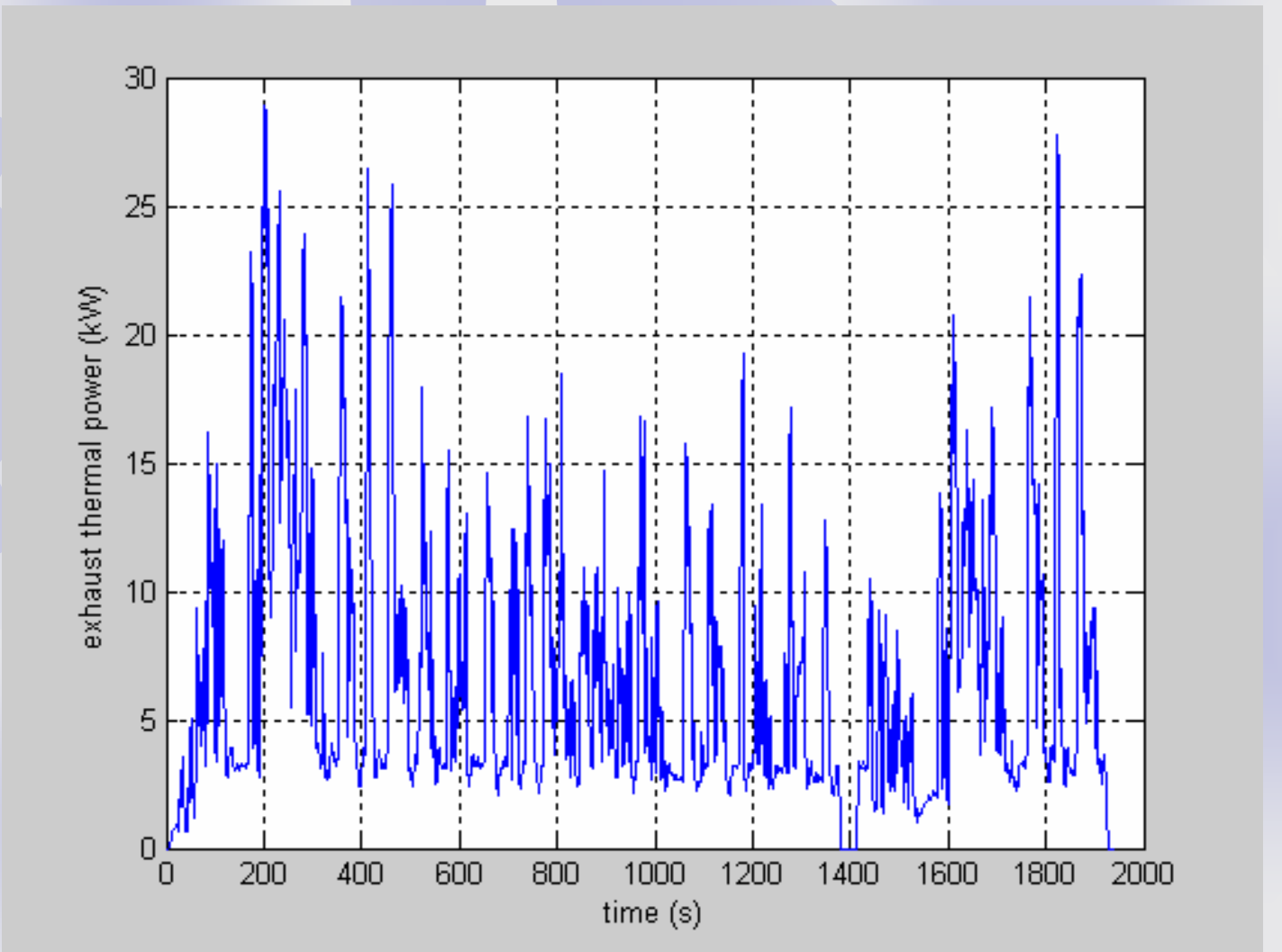
Exhaust Gas Temperature



Ref: Eder, Bertram, Liebl: Visions of Thermoelectrics in Vehicle Applications, DoEThermoelectricityWorkshop, San Diego, 2004

Exhaust gas temperatures for different engine speeds (1000, 3000, 6000 rpm) measured in front of (P1) and behind (P2) the catalytic converter

Available Thermal Power in Exhaust for FTP-75 Drive Cycle



Performance Targets

Minimize the increase in exhaust gas pressure

No degradation of engine power or torque

Minimize weight and volume increase

Average Thermoelectric Generator Module (TGM) electric output 700-1000W

- Electric output should be “clean” DC without noise

Positive influence on engine heat-up time (fuel economy gain/emissions reduction) due to heat transfer from the exhaust gas to the coolant

Capturing Exhaust Gas Waste Energy

Primary heat exchanger (PHx) designed to recover waste heat from the exhaust gas (downstream from the catalytic converter) and provide high quality thermal energy to the TGM

PHx optimized to manage wide variations in exhaust gas mass flow and temperatures

Backpressure created by the PHx is traded-off Vs heat exchange effectiveness (subsequent analysis will take into account muffler backpressure)

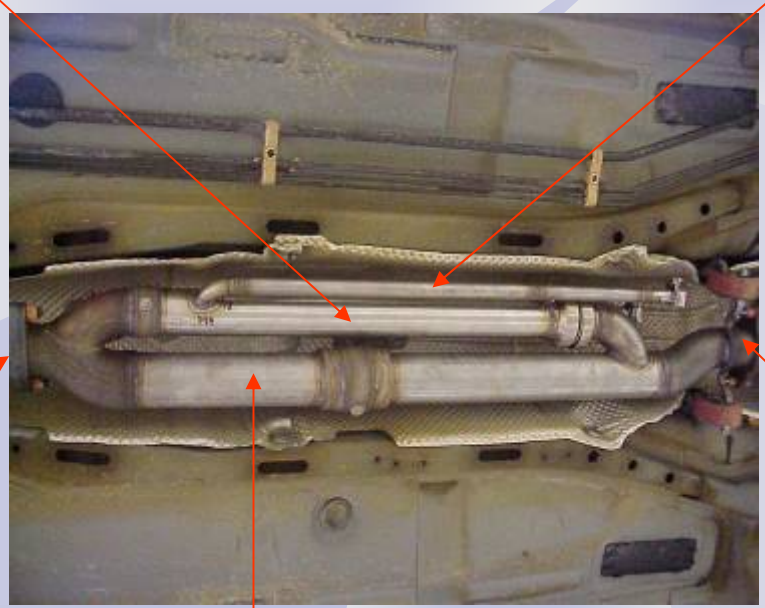
Preliminary design and modeling based on existing heat exchanger

- Performance models validated
- Candidate designs identified for prototyping

Primary Heat Exchanger

Shell & tube heat exchanger for exhaust gas heat transfer

He/Xe working fluid transports thermal energy to TGM



Cat converter

Muffler

Exhaust gas bypass flow

TGM Configuration with Primary Control Loop

Improves efficiency

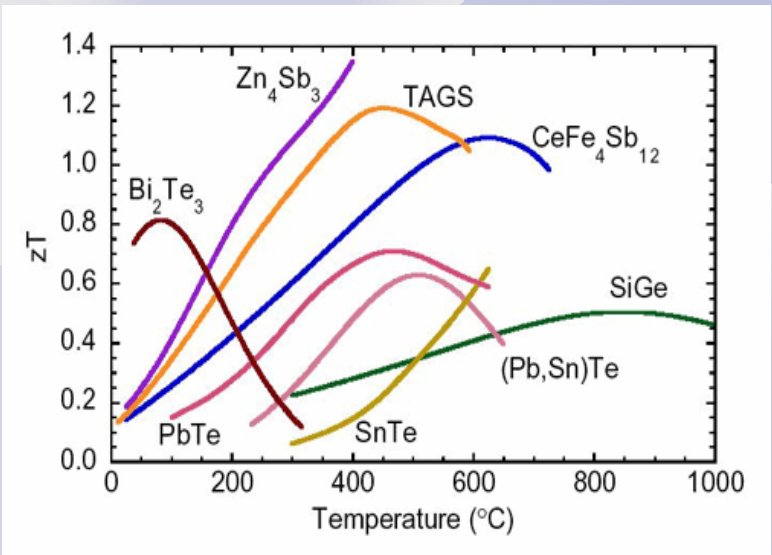
- Improves thermal impedance match with exhaust gas
- Enables heat flux control
- Allows thermodynamic cycle optimization

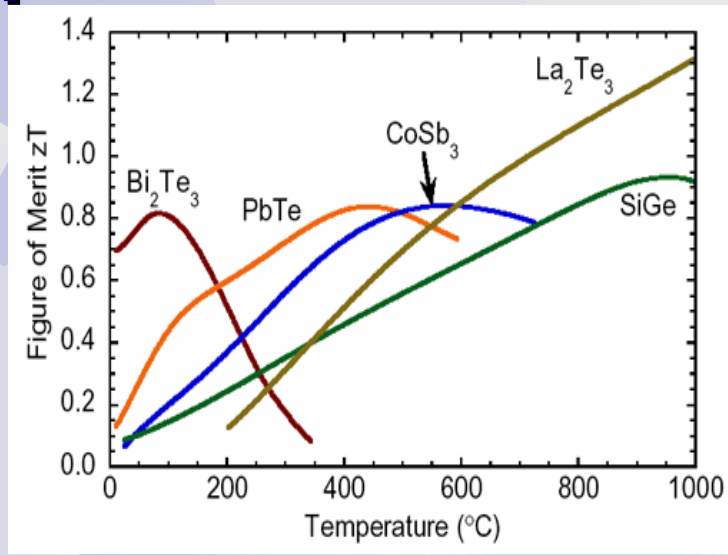
Contains TE materials within a separate hermetically sealed package

- Allows easier recycling of TE materials
- Compact design improves ruggedness
- Reduces TGM size, weight, and cost

Enables electrical load matching

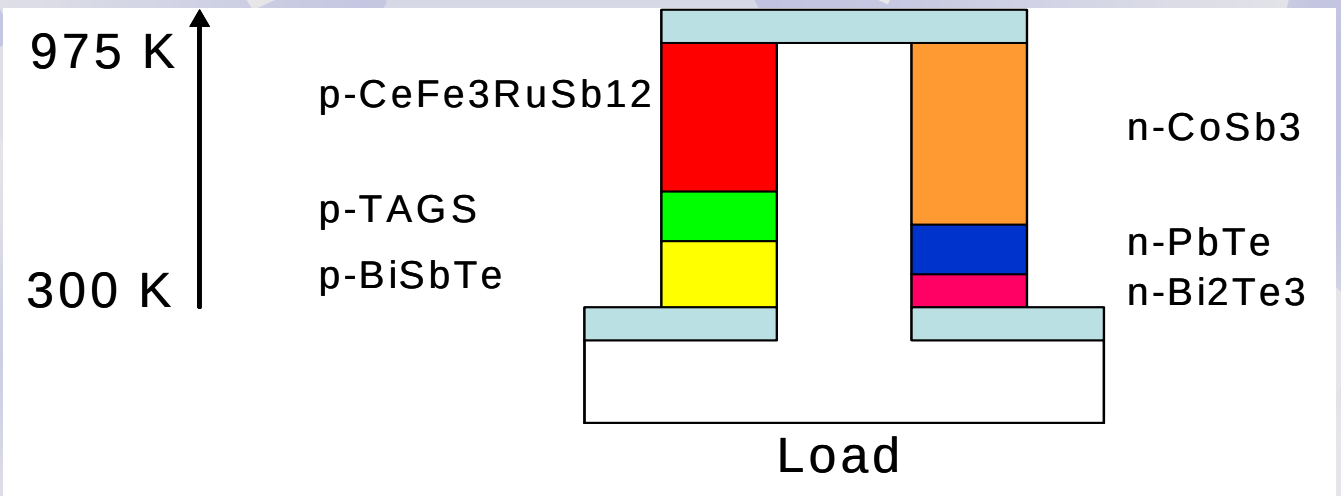
Current TE Materials & Segmented TE Couple





P-type TE material

N-type TE material

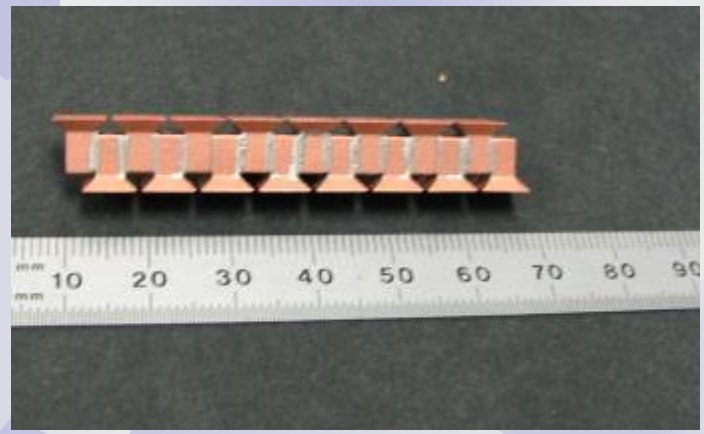


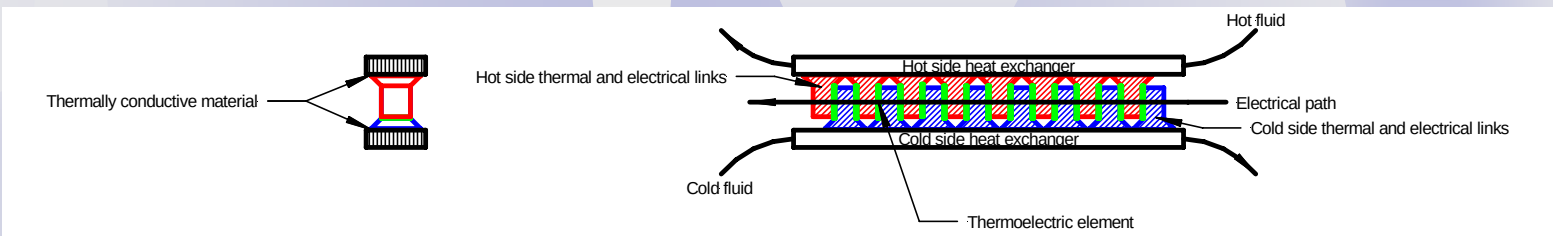
Ref: Modified from - http://www.its.caltech.edu/~jsnyder/thermoelectrics/

TE Power Generator Concept

1st generation TGM will incorporate:

- Segmented thermoelectric elements
- Advanced TE materials
- Effective ZT of 0.85





ADVISOR Development

Baseline BMW vehicle information implemented into ADVISOR

Each individual subsystem validated and integrated into ADVISOR

- PHX
  - Heat transfer effectiveness is calculated for each time step
  - Exhaust backpressure not included in model
- Power Converter
  - Dynamic operation implemented
- Alternator
  - Recalibrated ADVISOR to accept dynamic performance of Visteon alternator
- TGM
  - Extensive lookup table was created from in-depth BSST-developed TGM model for faster code operation with equivalent accuracy for each time step

Model Validations

ADVISOR, originally developed by NREL and commercialized by AVL, has been validated in a number of independent tests and studies

Fuel economy results were validated against BMW-provided data to within 2%

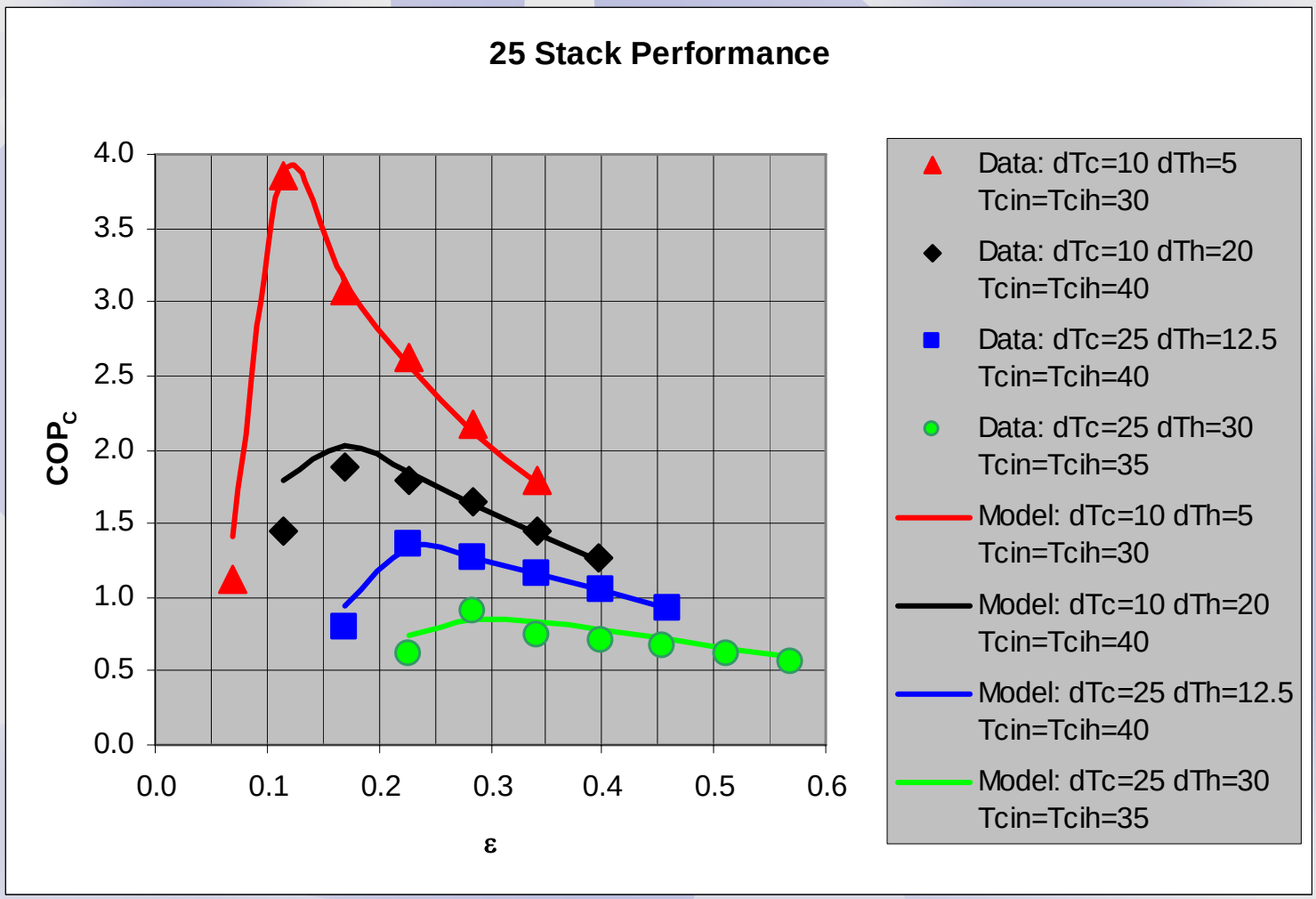
Exhaust temperatures validated against BMW-provided data to within 5% with the trends captured

Alternator model derived directly from Visteon experimental data

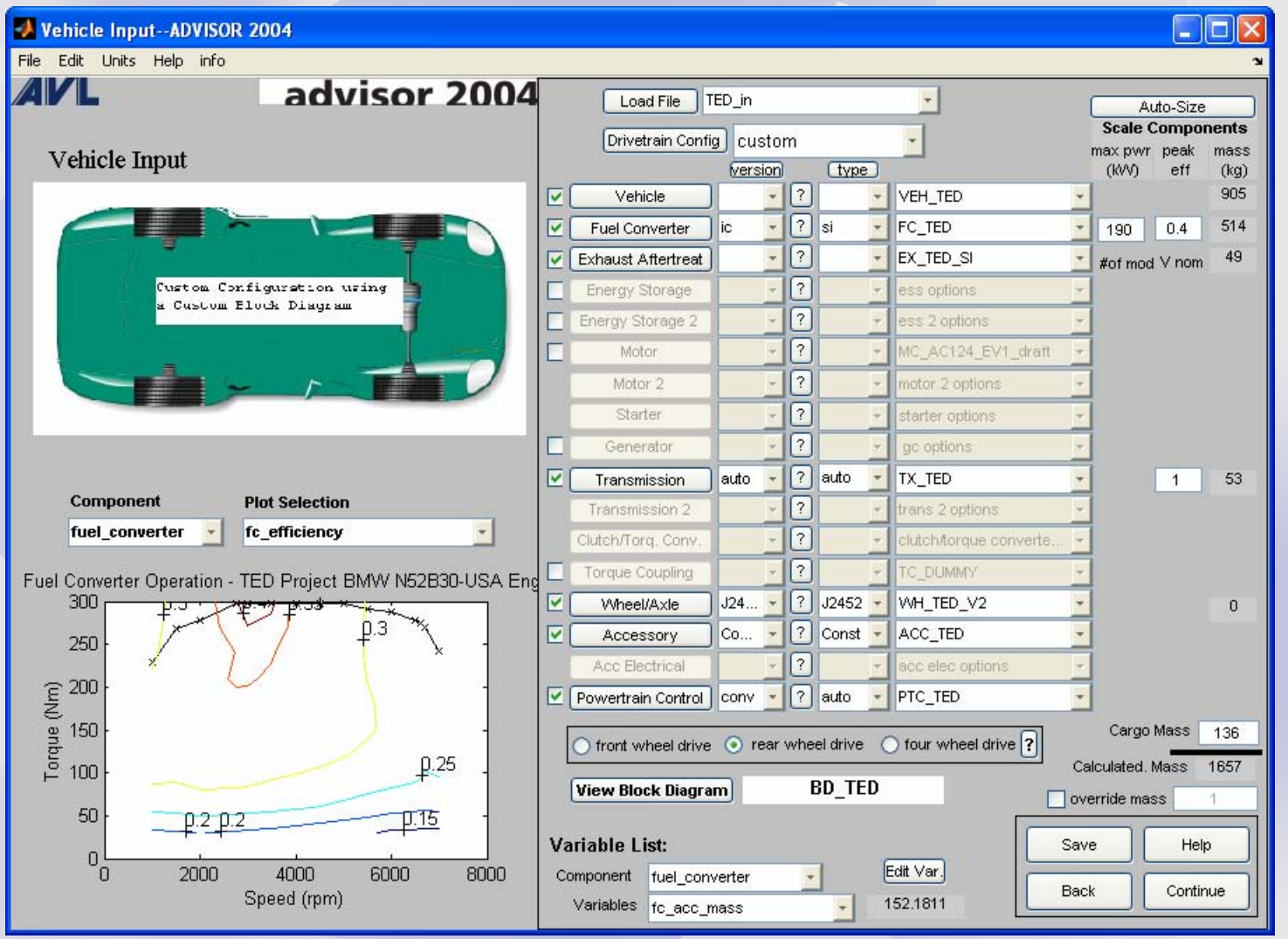
PHX model based on standard heat transfer correlations and Visteon modeling experience

TGM model uses similar concepts to those for TE heating and cooling models developed by BSST that have been validated to accuracies of 5%

Model Validation for TE Heating and Cooling Devices



ADVISOR Selection Screen



Drive Cycle Simulation Results

	Present (2005) System Capability			Projected for Dyno Test, 2008			Target for Dyno Test, 2008		
Drive cycle	FTP-75	HWFET	combined (1)	FTP-75	HWFET	combined (1)	FTP-75	HWFET	combined (1)
Average alternator load (W)	1000	1000	1000	2000 (2)	2000 (2)	2000 (2)	2000 (2)	2000 (2)	2000 (2)
Average ZT	0.85	0.85	0.85	1.00	1.00	1.00	1.25	1.25	1.25
% improvement - mpg	8.36	8.25	8.28	9.60	10.50	10.03	11.64	12.61	12.10
% change - HC (3)	-1.67	0.19	-1.03	-2.19	0.58	-1.26	-2.77	0.58	-1.65
% change - CO (3)	-1.86	-1.75	-1.82	-2.07	-2.65	-2.27	-2.53	-3.16	-2.75
% change - NOx (3)	-2.99	-1.50	-2.53	-3.77	-1.48	-3.09	-4.25	-2.22	-3.64

(1) Combined drive cycle weighted 60% FTP-75 and 40% HWFET
(2) Increase in average alternator load is due to the estimated increase in electrification of vehicles by the year 2012
(3) Emissions results do NOT included significant reduction in emissions due to faster coolant warm-up

Factors Not Currently Captured in Simulation Results

Opportunities

- Effect of downsizing muffler
- Effect of downsizing the alternator
- Ability to run system without the use of power conversion
- Further optimization of primary control loop flow for maximized thermal management

Risks

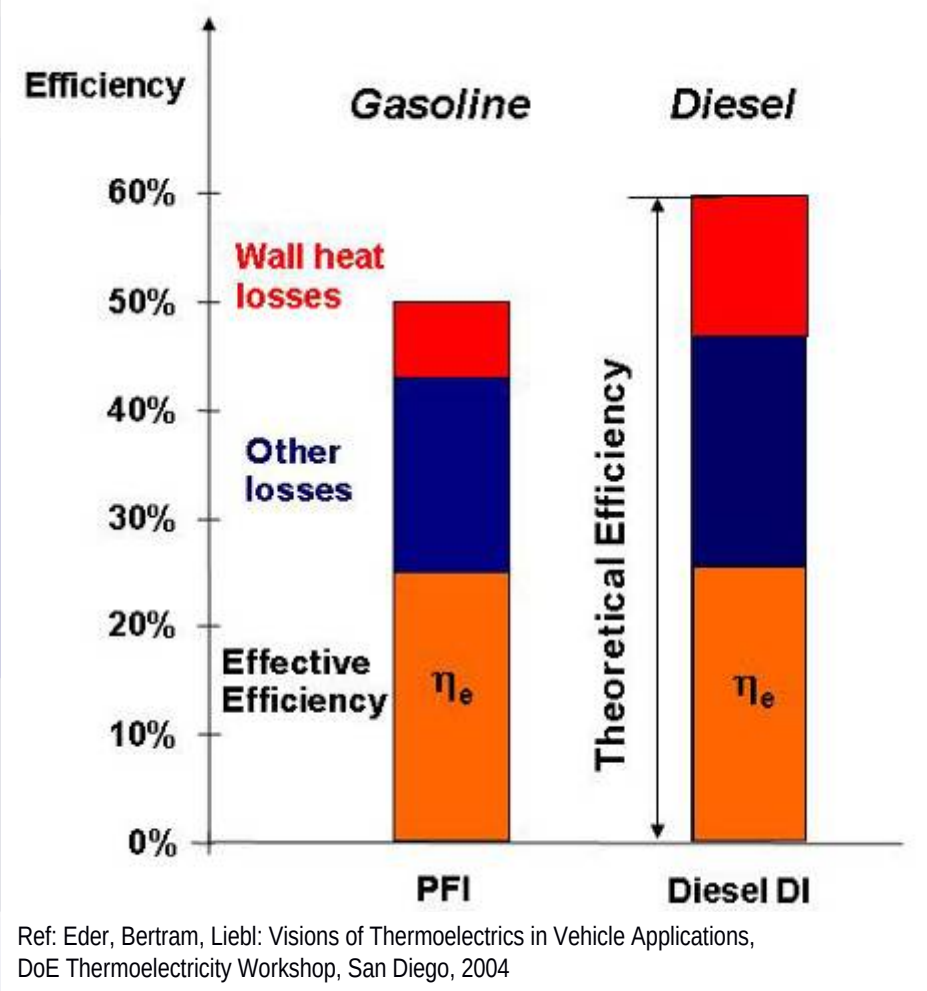
- Exhaust backpressure effects
- Additional pump power losses
- Effect of potential unmatched load resistance
- Certain weight and drag coefficient changes

Diesel vs. Gasoline Engine Systems

Engine:	Diesel	Gasoline
Vehicle:	BMW 530d	BMW 530i
Displ.:	2993 ccm	2996 ccm
Compr. ratio	17	10.7
Max. power	160 kW @ 4000 rpm	190 kW @ 6600 rpm
Max. torque	500 Nm @ 2000 rpm	300 Nm @ 2500 rpm
Fuel cons.	34,1 mpg (combined European Drive Cycle)	26,7 mpg (combined European Drive Cycle)

3L BMW diesel and gasoline engines

Engine Efficiency Comparison



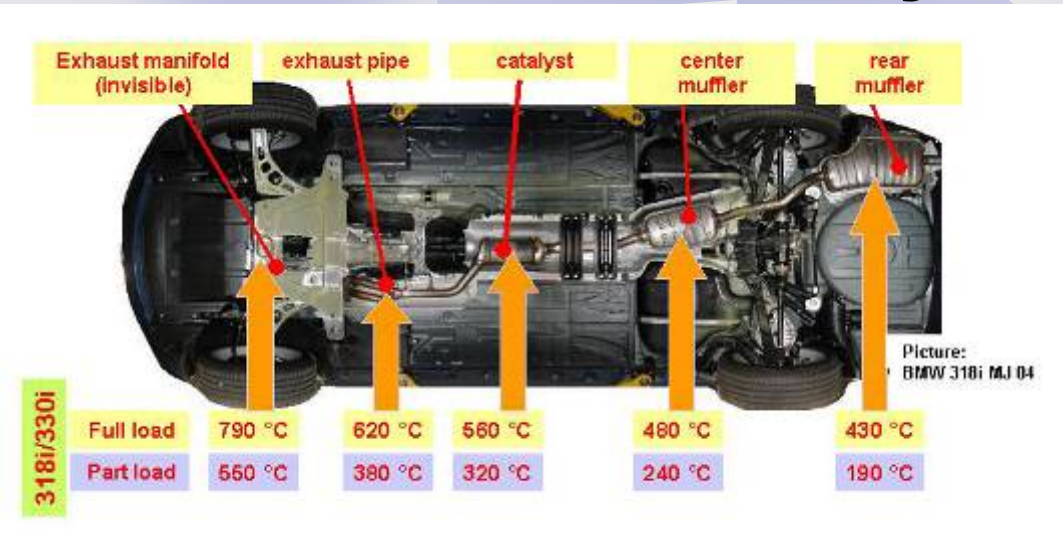
Ref: Eder, Bertram, Liebl: Visions of Thermoelectrics in Vehicle Applications, DoE Thermoelectricity Workshop, San Diego, 2004

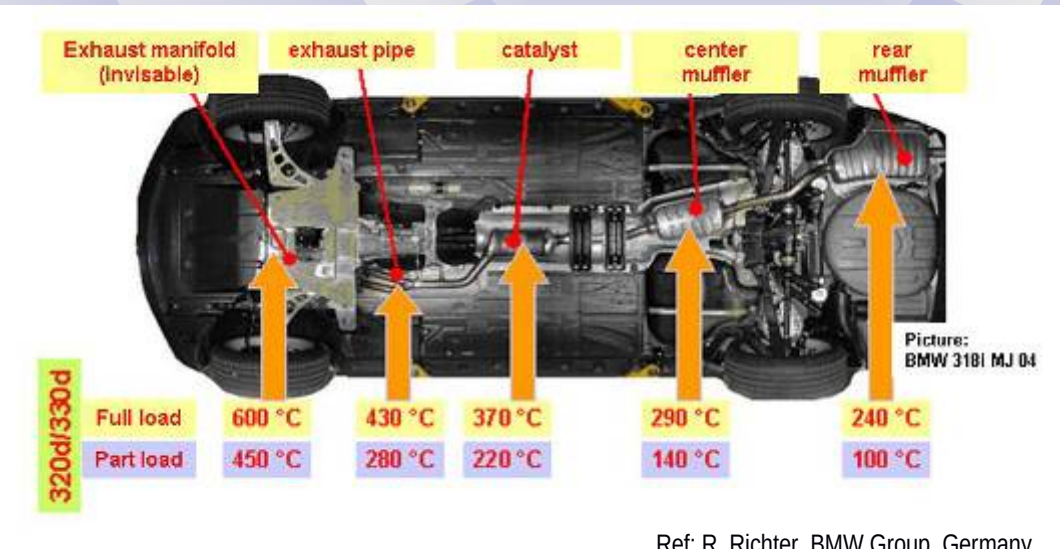
At part load operating modes (0.2 kJ/liter, 2000 rpm), effective engine efficiencies are almost identical

Diesel engines have higher heat losses to the walls of the cylinders at this FTP-75 representative load condition

17% higher fuel density in diesel fuel compared to gasoline accounts for much of the difference in fuel consumption between the two engine types

Temperature Gradients in Different Exhaust Systems





Ref: R. Richter, BMW Group, Germany

Diesel engine exhaust temperatures are approximately 100C lower than gasoline engine exhaust at part load and approximately 200C lower at full load.

Potential in Diesel Engine Systems

A lower fraction of heat is rejected to the exhaust in diesel compared to gasoline engine vehicles (22 – 35% compared to 34 – 45%)[1]

A higher fraction of heat is rejected to the coolant in diesel compared to gasoline engine vehicles (16 – 35% compared to 17 – 26%)[1]

With lower temperatures and potentially less heat in the exhaust system and more heat in the coolant system for diesel engine vehicles, TE waste heat recovery from these engines would be more focused on the following:

- Increased ZT for more low (100C – 250C) to medium (250C – 500C) temperature TE materials
- Extracting waste heat from more components than just the exhaust system (i.e. cooling system)

1. J. B. Heywood, *Internal Combustion Engine Fundamentals*, McGraw-Hill, Inc., 1988

Commercialization Vehicle-level

We estimate that TE power generation in gasoline engine vehicles can be ready for production introduction around CY2012 (MY2013).

- Implementation discipline of automotive OEMs requires a ~4-5-year lead-time prior to Start-of Production (SOP).
- Prototype vehicle performance results in the CY2010/11 timeframe will help determine the rate of expansion of application beyond initial introduction.

Conclusion

Around 10% improvement in vehicle fuel economy through thermoelectric waste heat recovery in gasoline engine vehicles in the next few years is achievable.

Although technical development may be slightly different than that for gasoline engine vehicles, significant fuel economy improvement through thermoelectric waste heat recovery in diesel engine vehicles is also achievable.

In Phase 2 (which has been funded with work concurrently beginning), the team will iterate the model, design, build and test a bench system to validate analytically derived predictions in preparation for Phase 3, system integration, and Phase 4, engine level integration and test.