Emissions and Fuel Consumption Trade-offs of a Turbocharged Diesel Engine Equipped with Electrically Heated Catalyst

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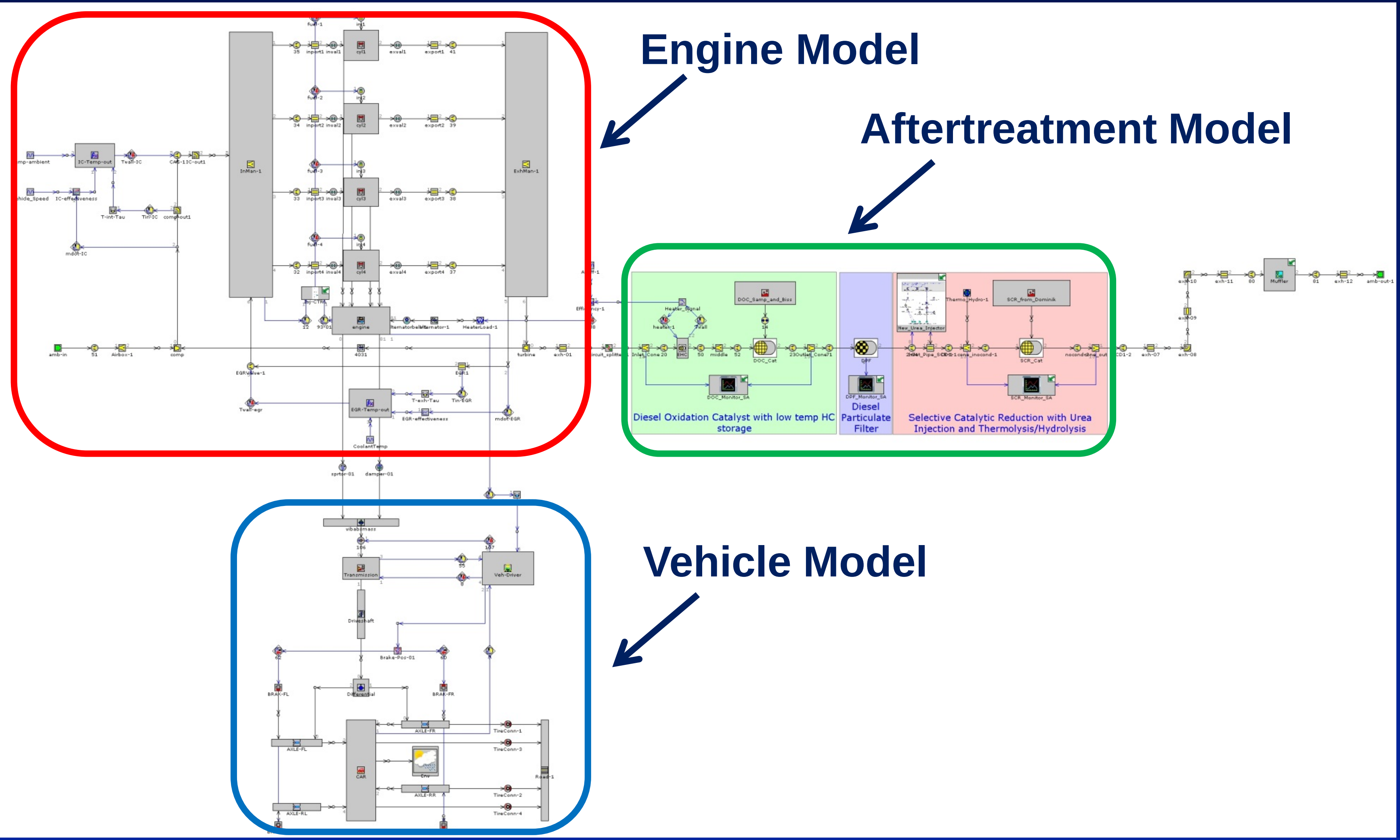
Overview

- An integrated model (engine + vehicle + AT system) was executed to study the optimum strategies of electrical heating for achieving best fuel consumption/emissions trade-offs
- A 2.0L common rail TC diesel engine mated with a European midsize passenger car was modeled
- The vehicle model includes a driver module allowing simulation of standard driving cycles (NEDC, FTP etc.)
- Multi-catalyst system was modeled including detailed kinetics
- Electrically Heated Catalyst (EHC) was used to preheat the exhaust gases, to shorten the light-off time and help maintain high conversion efficiency
- The published version of this paper will appear in the proceedings of the upcoming SIA conference (June, 2012, Rouen)

Integrated GT-SUITE Model



Engine and Vehicle Model

Engine and Vehicle Model
Fast-Running Engine Model

- **GT-POWER has several levels of engine models for different applications, from fully detailed to map-based**

- **A simplified engine Fast-Running Model (FRM) was derived from a detailed engine model by reducing the number of computational volumes in the flow system (465 to 44 in this model), but retains all the detailed in-cylinder sub-models (combustion, heat transfer, etc.)**

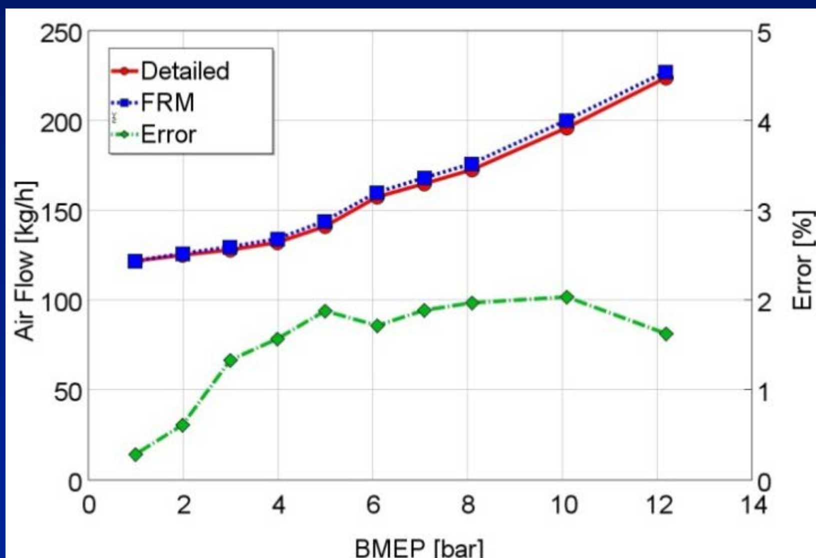
- **The FRM is 22 times faster than the original detailed model, yet maintains good accuracy**

- **The vehicle is controlled by a driver model. The pedal position and brake actuator position are controlled by following a user-specified speed schedule for the drive cycle**

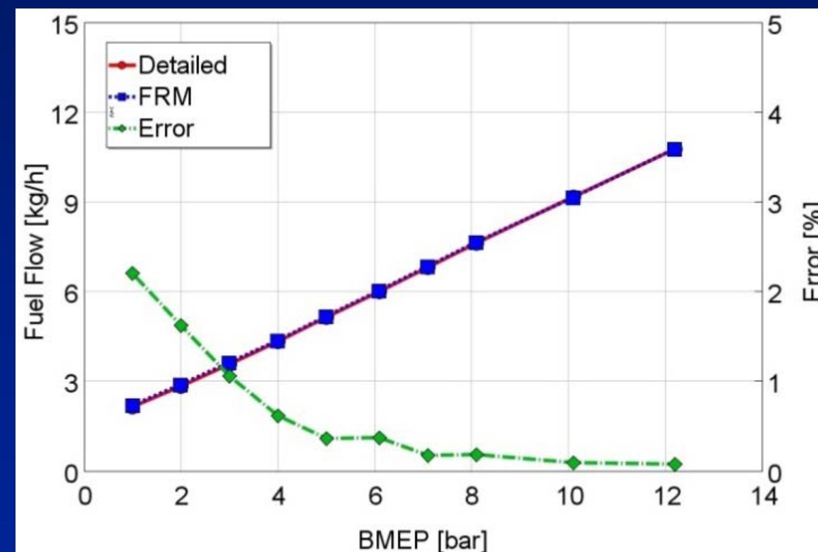
Engine Model : *FRM Results*

The accuracy of prediction from FRM was found to be within 2% when compared to the results of the detailed model

Steady-State Results



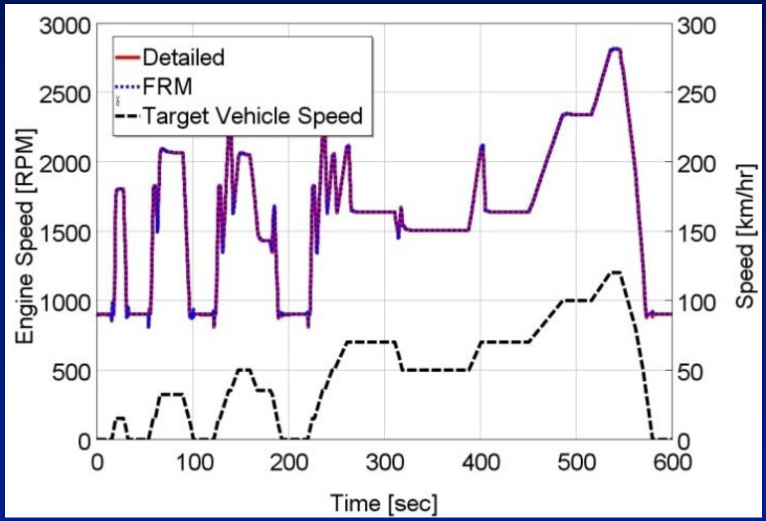
Air Flow over a load sweep at 2500 rpm, detailed model and FRM.



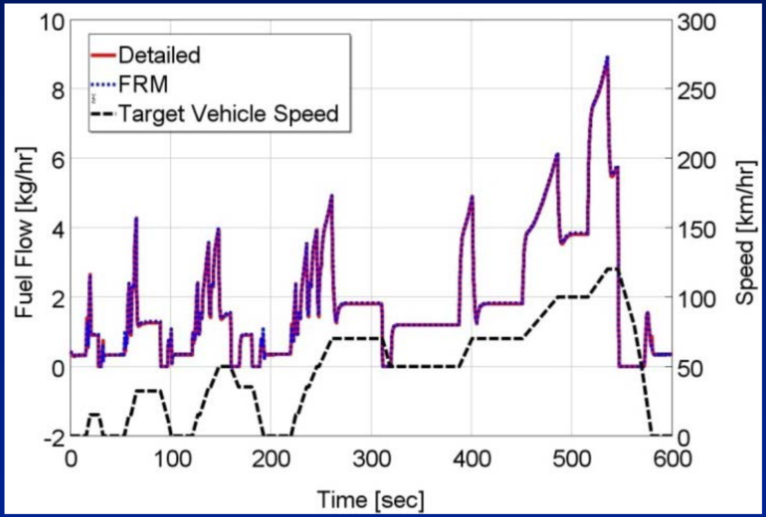
Fuel Flow over a load sweep at 2500 rpm, detailed model and FRM.

Engine Model: ***FRM Results (cont.)***

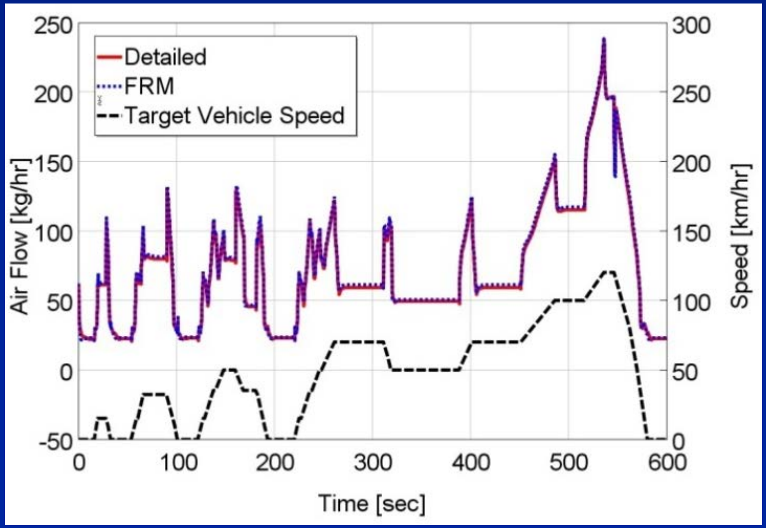
Transient Results



Engine speed over the last 600 s of the NEDC, detailed model and FRM.



Fuel Flow over the last 600 s of the NEDC, detailed model and FRM.

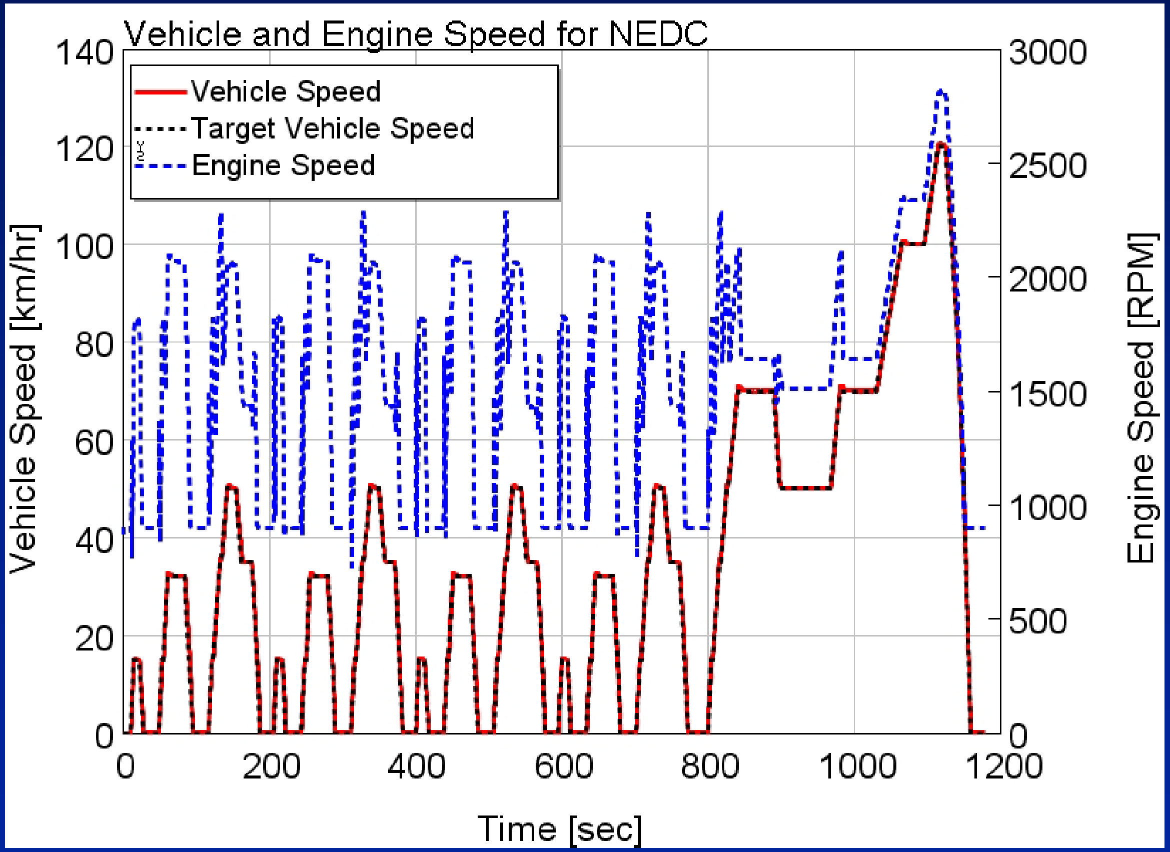


Air Flow over the last 600 s of the NEDC, detailed model and FRM.

Vehicle + Engine Model Results

Vehicle and Engine Speed

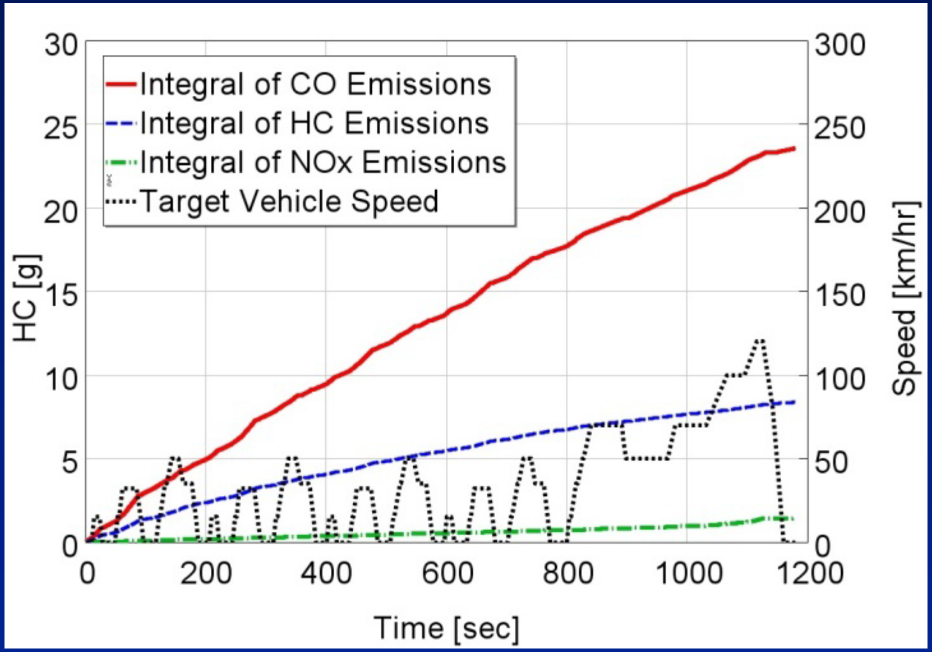
The integrated model comprising of the FRM engine model and vehicle model is simulated over the NEDC



The vehicle is controlled by a driver model (pedal position and brake controller) to follow a user-specified speed schedule for the drive cycle

Vehicle + Engine Model Results (cont.)
Consumption and Engine-out Emissions

The results in terms of fuel consumption and engine-out emissions were computed to obtain the baseline results

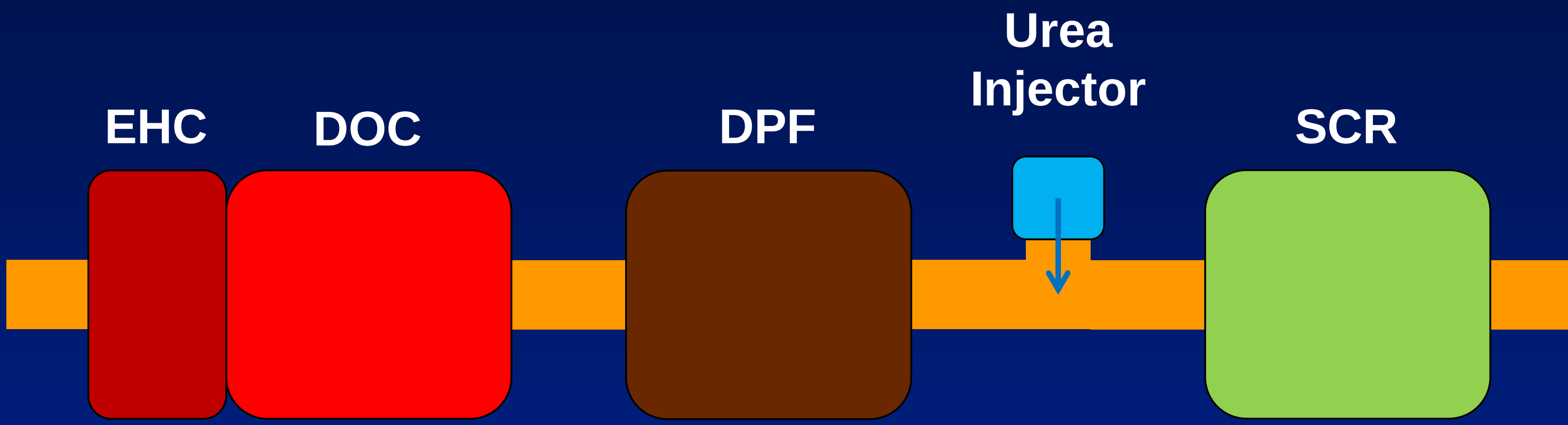


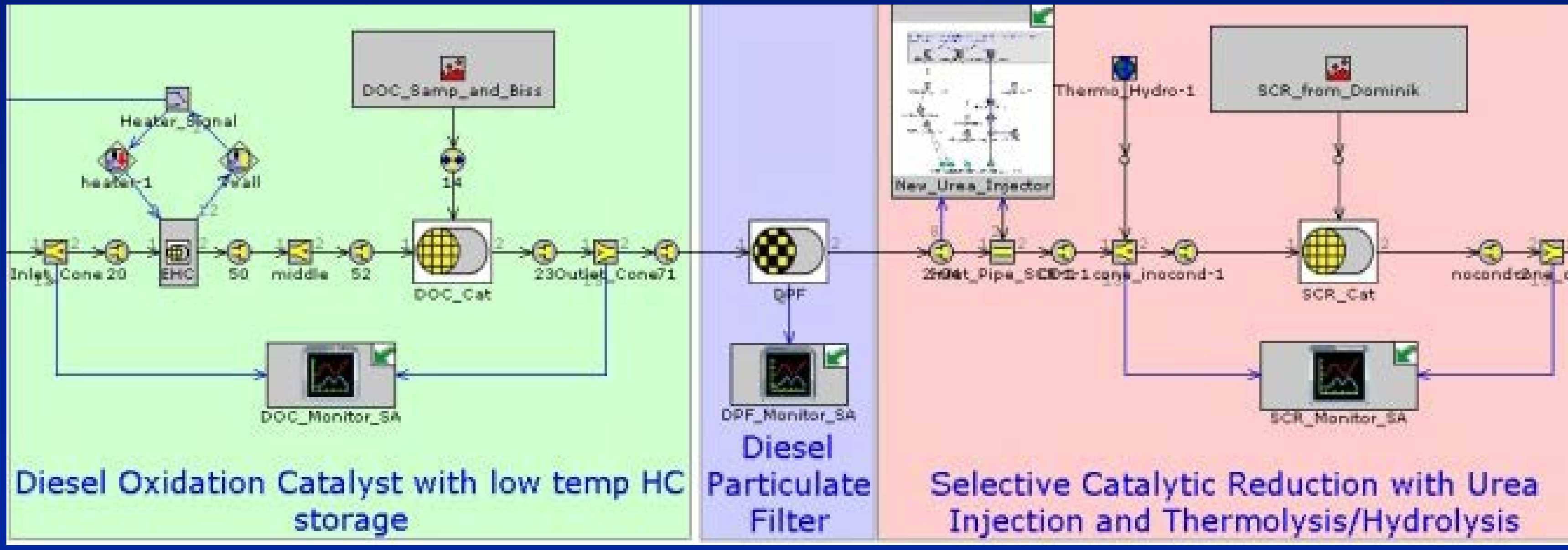
Integrated Cold-start Engine-out Emissions (CO, THC, NOx), simulated values over the NEDC

Fuel Consumption [L/100 km]	5.9
Engine out CO Emission [g]	23.6
Engine out THC Emission [g]	8.4
Engine out NOx Emission [g]	1.4
Engine out Soot Emission [g]	0.14

Aftertreatment Model

Aftertreatment System Model





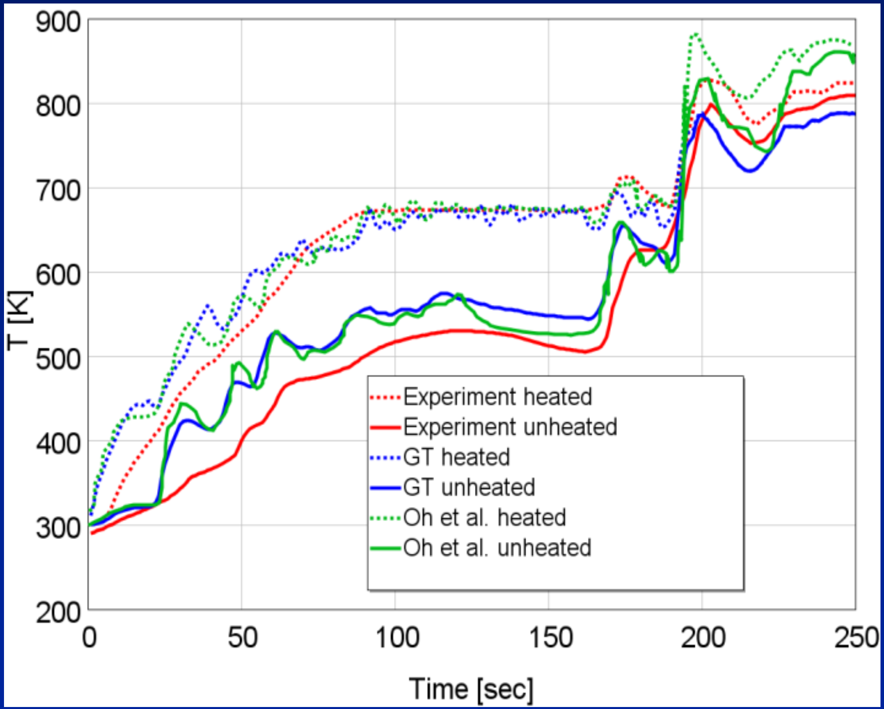
Aftertreatment Model Components

The exhaust aftertreatment system was comprised of:

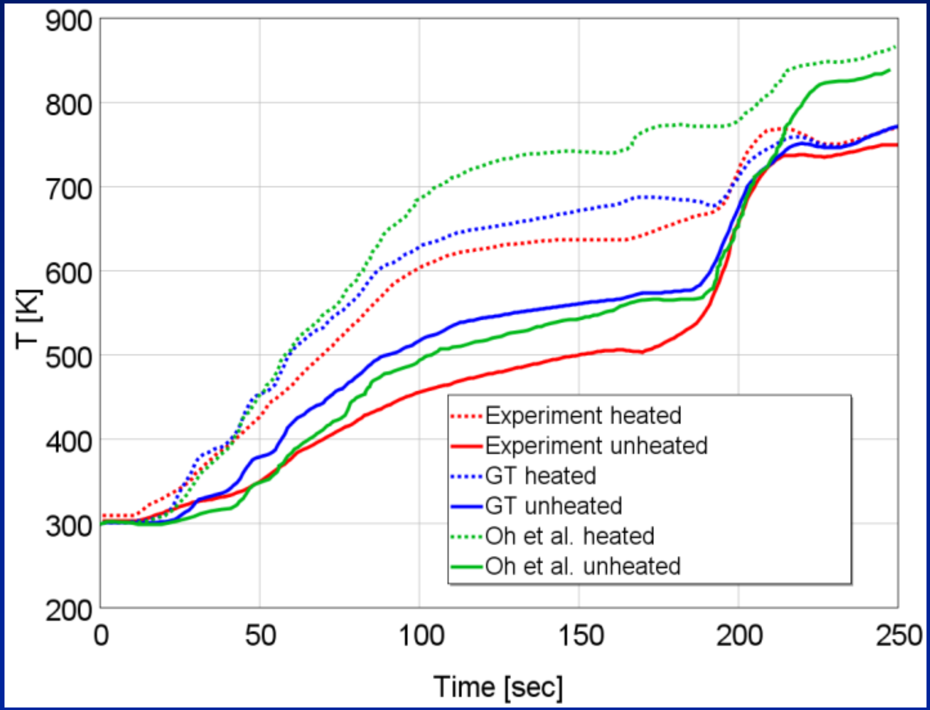
- **Electrically Heated Catalyst brick: powered by electro-mechanical system (alternator) connected to the crankshaft; Size is chosen based on recommendations from reference Bissett and Oh, 1999**
- **Diesel Oxidation Catalyst (DOC): Cordierite square channel, coated with PGM**
- **Diesel Particulate Filter (DPF): symmetric channel deep bed filtration with passive regeneration via NO2 oxidation**
- **Selective Catalytic Reduction (SCR) with a urea dosing system: Zeolite SCR with square channel**

Validation of EHC Model

- The EHC was validated with reference Oh, Bissett, and Battiston, 1993, over the first 250 sec of the FTP cycle
- The EHC heat input power was actuated with max power 1150 W by an on-off control system with threshold temperature of 400° C (673 K)
- TWC mechanism from Ramanathan and Sharma, 2011, was used

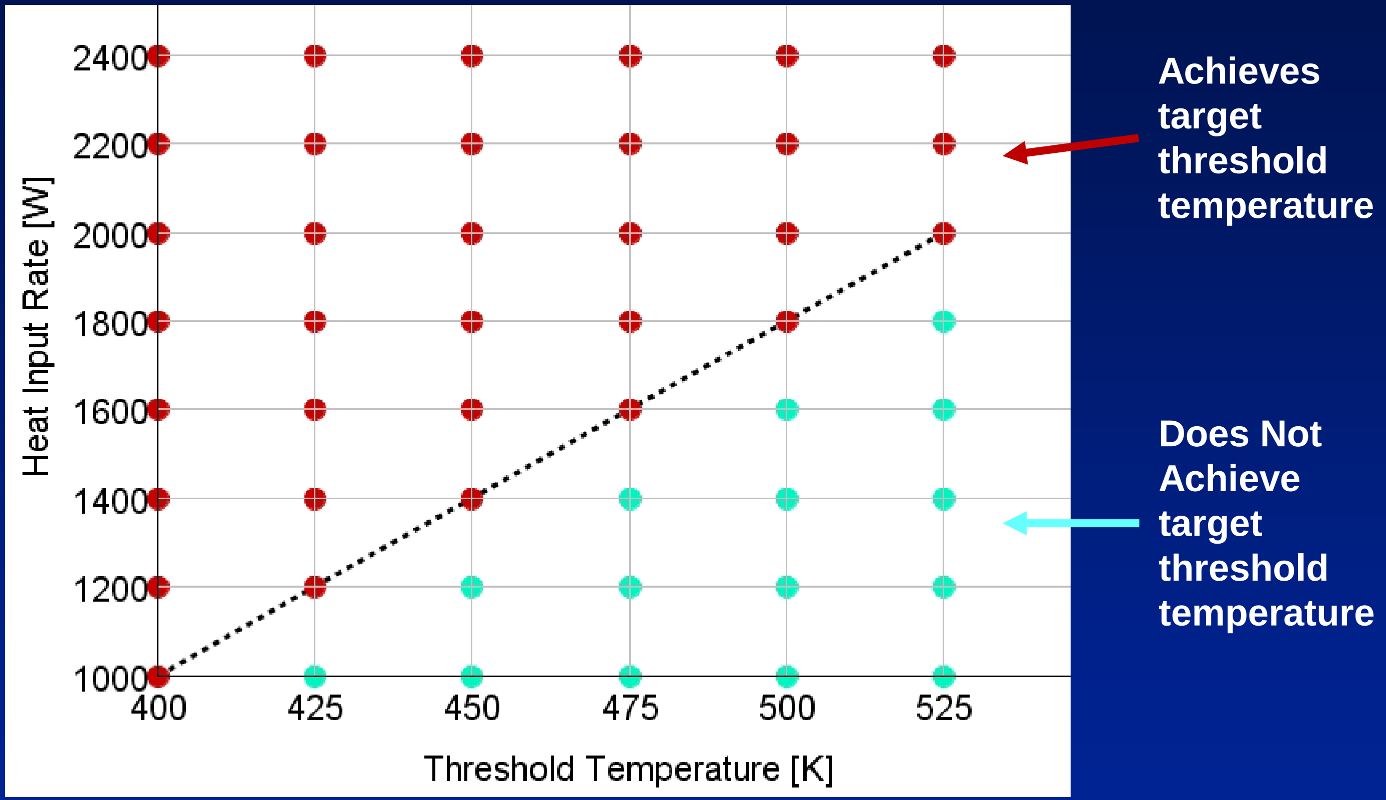


Mid-bed temperature of front metal element



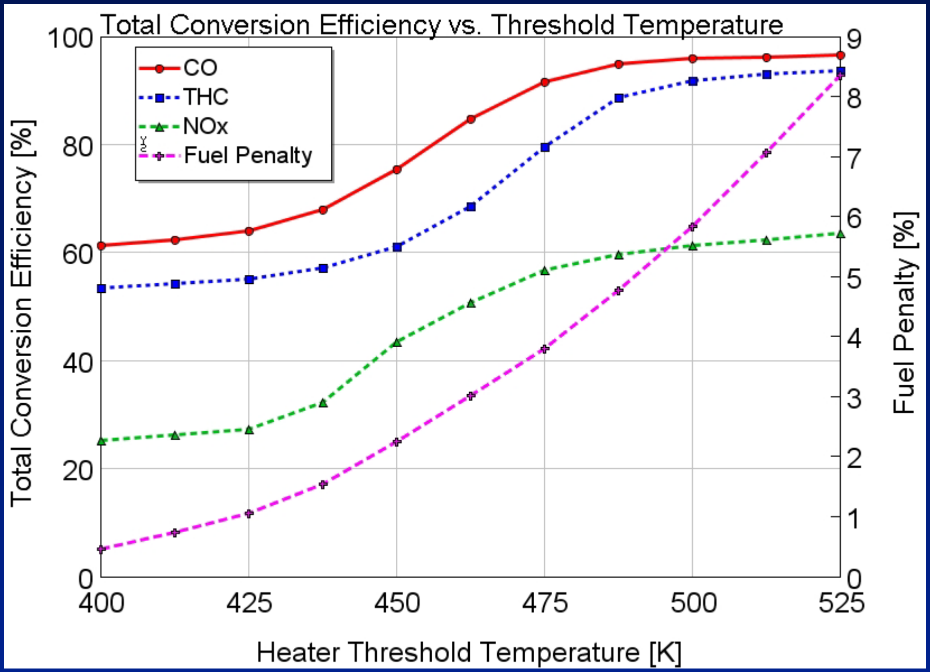
Mid-bed temperature of the rear ceramic brick

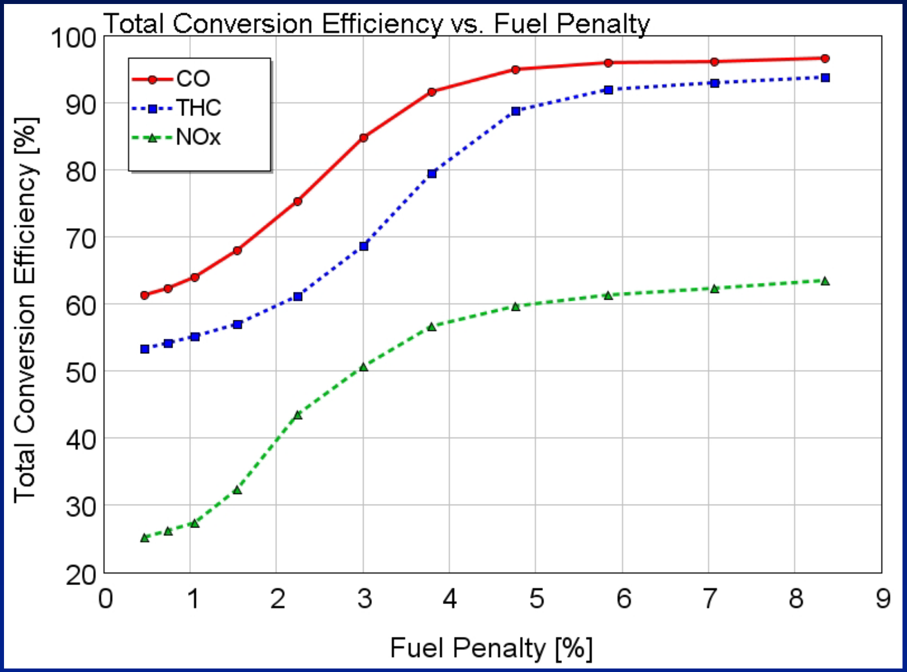
Determination of EHC Heat Input and Threshold Temperature



- A design space of input points for EHC heat input rate and controller threshold temperature was simulated
- If wall temperature was held within 3% of the target threshold temperature it was considered a good point
- The dashed line represents the minimum heat input rate to achieve each threshold temperature (target wall temperature)

Total Conversion Efficiency vs. Fuel Penalty Trade-off Results



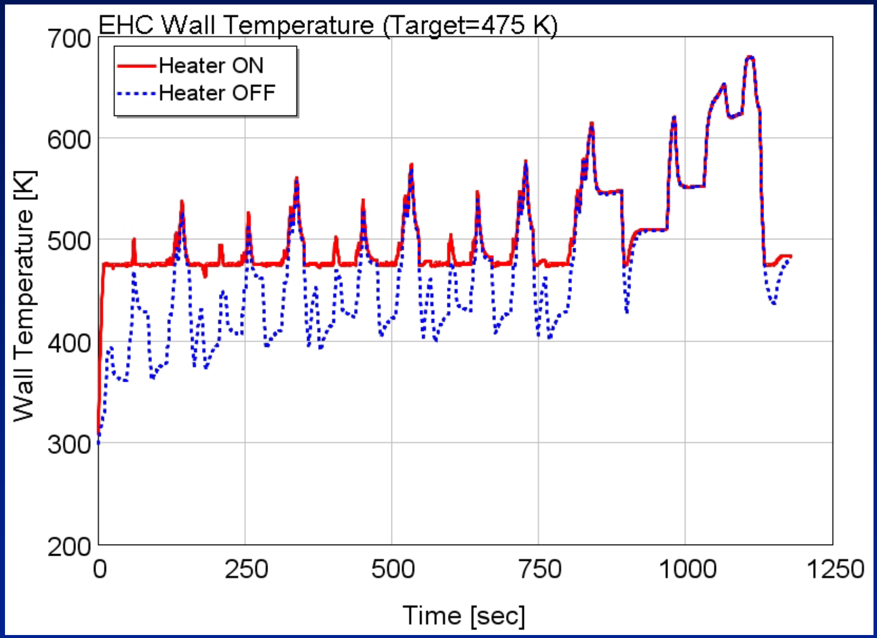


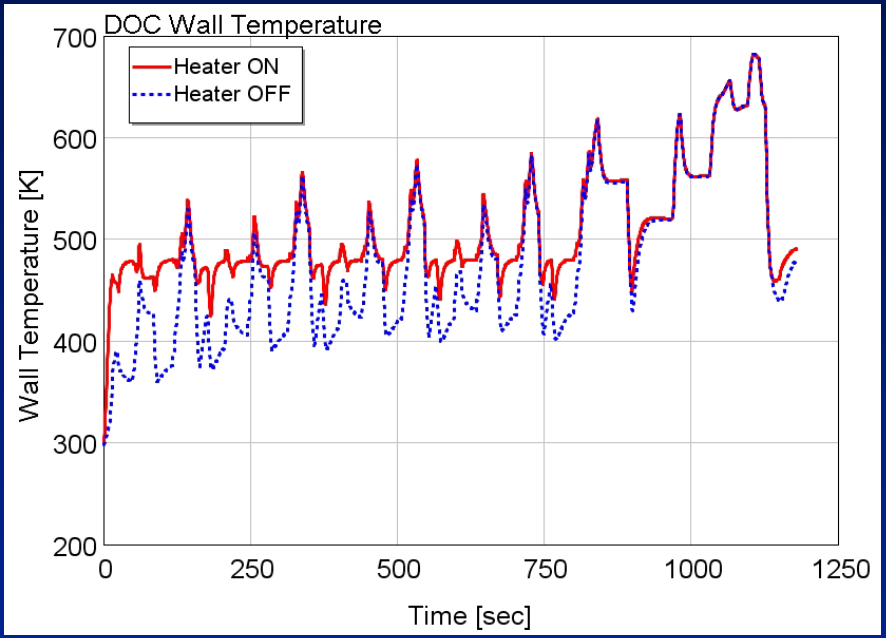
Total cumulative conversion efficiency and fuel penalty vs. heater threshold temperature.
The 4% fuel penalty corresponds to a threshold temperature 475 K and heat input rate 1600 W

Total cumulative conversion efficiency vs. fuel penalty. Beyond 4% of fuel penalty, the conversion efficiency does not show significant improvement.

Integrated Model Simulation Results

EHC and DOC Wall Temperatures

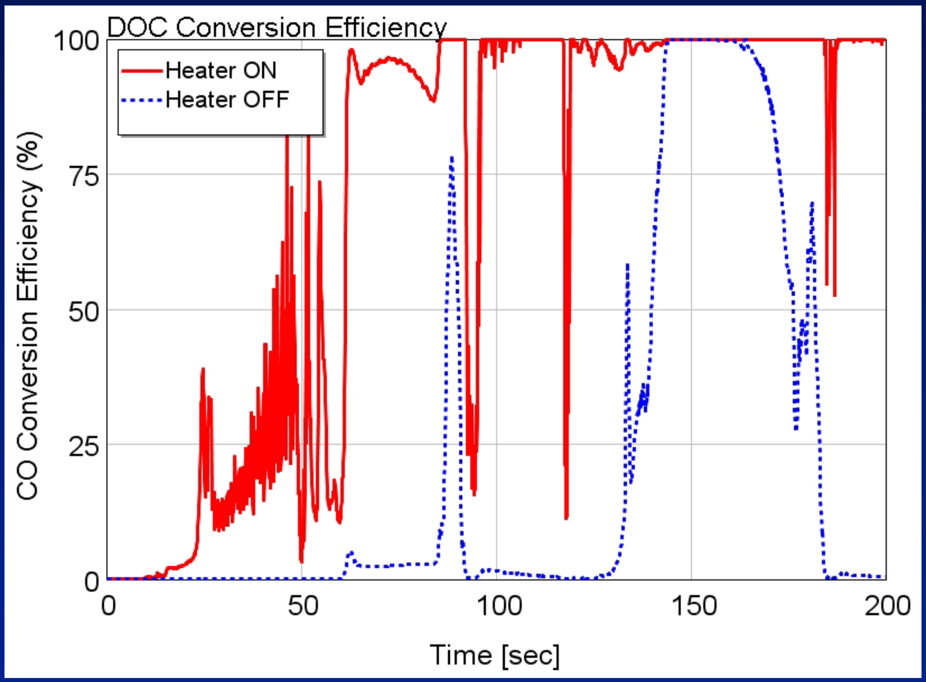


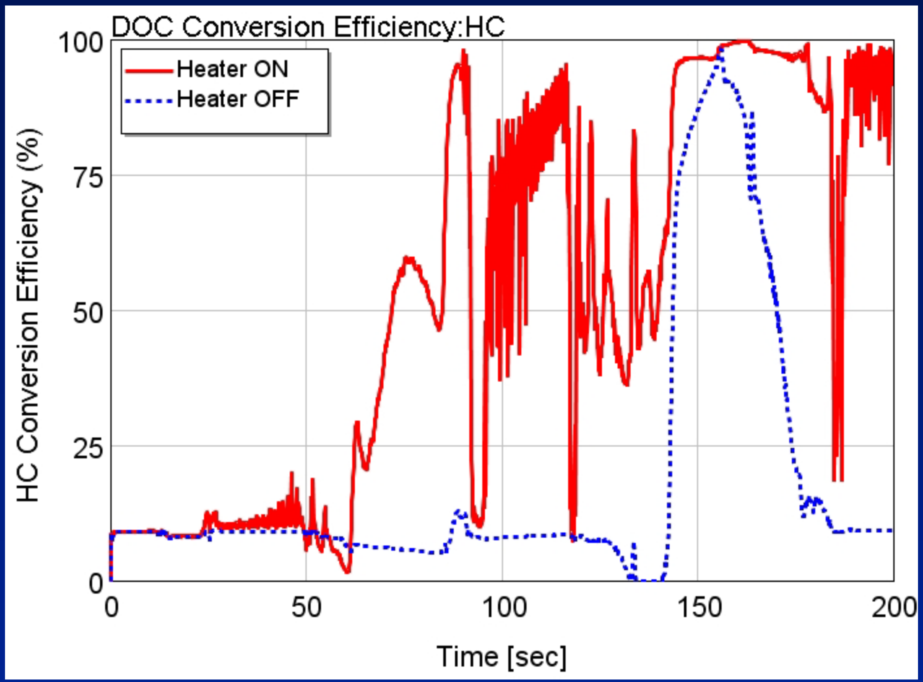


EHC wall temperature evolution With heat input wall temperature reaches target 475 K at 10 sec.

DOC wall temperature evolution With heat input wall temperature reaches sustained 50% light-off temperature of about 490 K at 60 sec.

Integrated Model Simulation Results
DOC Conversion Efficiency





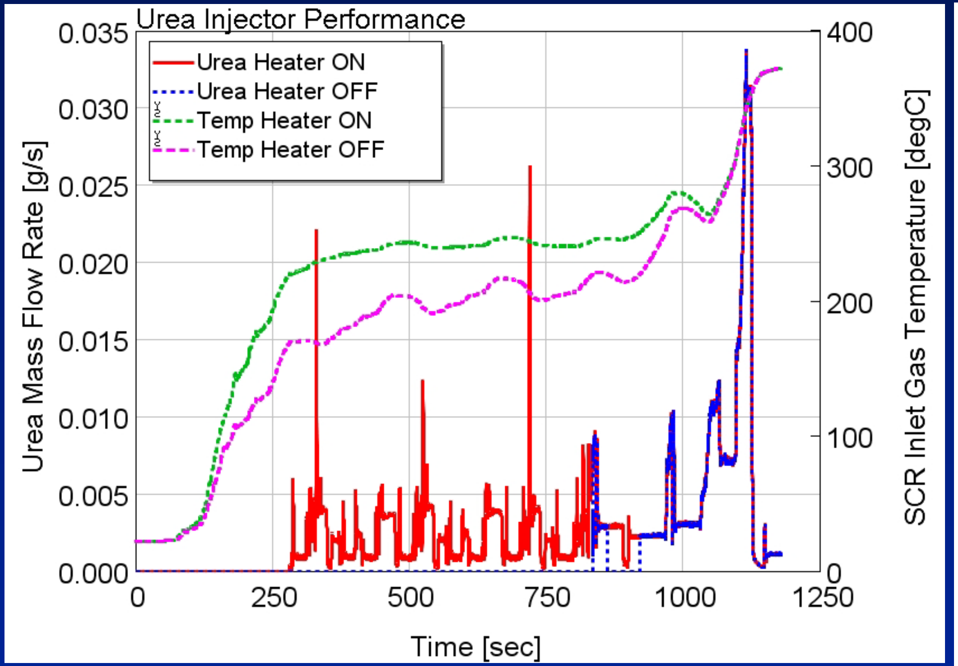
DOC CO conversion efficiency

DOC HC conversion efficiency

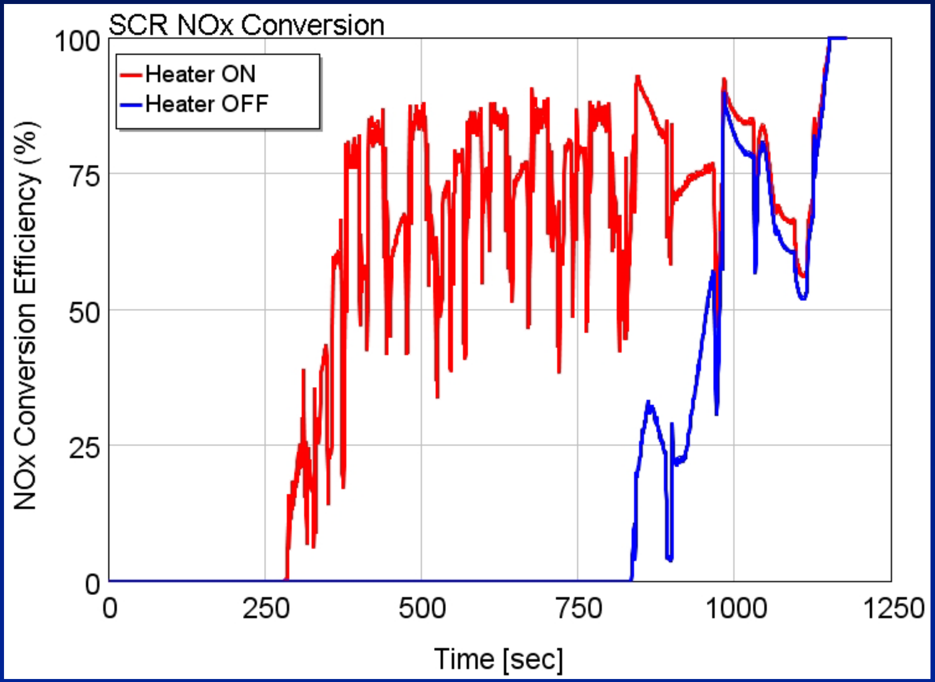
Heater ON: reaches 50% light-off at ~60 sec
Heater OFF: reaches 50% light-off at ~140 sec

Integrated Model Simulation Results
Urea Injector Performance and NOx Conversion

- Urea injector controller threshold temperature set at 215° C
- NH_3/NOx ratio controlled to maintain 1.0 when injector is active



SCR inlet gas temperature and Urea injector mass flow rate comparison



SCR NOx conversion efficiency comparison

Heater ON: injection starts at ~280 sec
Heater OFF: injection starts at ~835 sec

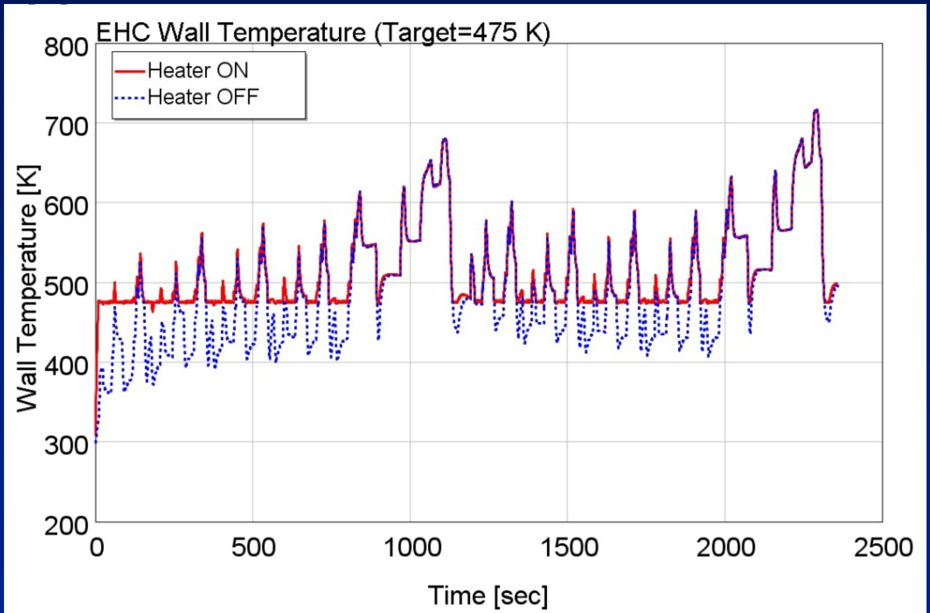
Emissions vs. Fuel Consumption Tradeoff: One NEDC, cold start

	Heater Status	CO	THC	NOx
Engine Out (g)	-	23.56	8.37	1.44
Tailpipe Out (g)	OFF	9.24	3.89	1.06
	ON	1.95	1.64	0.62
Reduction (%)	OFF	61	54	26
	ON	92	80	57
Improvement(%)	-	51	48	119

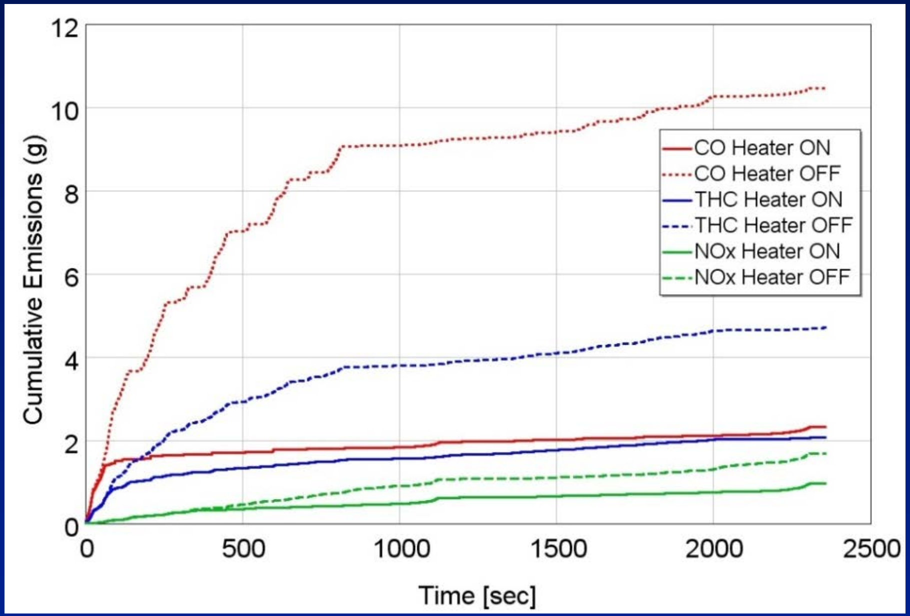
Fuel Consumption (L/100 km)		Fuel Consumption Penalty (%)
Heater OFF	Heater ON	
5.90	6.09	3.22

Back-to-Back NEDC Results

Cold start cycle followed by warm cycle, engine emissions switched accordingly



EHC wall temperature results



Cumulative emissions comparison

Emissions vs. Fuel Consumption Tradeoff: Back-to-Back NEDCs

	Heater Status	CO	THC	NOx
Engine Out (g)	-	34.68	11.51	3.21
Tailpipe Out (g)	OFF	10.46	4.70	1.67
	ON	2.23	2.07	0.96
Reduction (%)	OFF	70	59	48
	ON	94	82	70
Improvement(%)	-	34	39	46

Fuel Consumption (L/100 km)		Fuel Consumption Penalty (%)
Heater OFF	Heater ON	
5.67	5.79	2.19

Computation Time Analysis for the 1180 sec NEDC

- **FRM only: 32 min 34 sec**
- **Vehicle only: 2 min 36 sec**
- **AT system only: 2 min 06 sec**
- **FRM+Vehicle: 35 min 5 sec**
- **FRM+Vehicle+AT: 55 min 14 sec**
- **The integrated model is 2.8 times slower than RT when executed on an Intel i7 Quad-Core 3.4 GHz Desktop PC**
- **Further integrated model computation time reductions can be made with mean value engine and aftertreatment subsystems (see GTI references from MODEGAT 2010 and FISITA 2011)**

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Conclusions

- An integrated model (engine + vehicle + AT system) was used to study optimum strategies of electrical heating of a catalyst for analyzing fuel consumption/emissions trade-offs
- With EHC the emissions performance is improved by approximately 50% for CO and HC and 119% for NOx. Corresponding Fuel penalty is 3.22%.
- For back-to-back cycles the fuel penalty is reduced to 2.19%.
- GT-SUITE is highly capable of simulating complex system interactions and dependencies with conflicting time scales and disparate physical characteristics (engine, turbocharger, vehicle, alternator, EHC, aftertreatment system)
- Computational efficiency of such a complex integrated system model is on the order of real-time

References

- Pautasso, E., Servetto, E., Artukovic, D. Brown, J. and Wang, W., “Emissions and Fuel Consumption Trade-offs of a Turbocharged Diesel Engine Equipped with Electrically Heated Catalyst”, SIA conference, 2012

- Bissett, E.J. and Oh, S.H., "Electrically Heated Converters for Automotive Emissions Control: Determination of the Best Size Regime for the Heated Element", Chemical Engineering Science, Vol. 54, pp. 3957-3966, 1999

- Oh, S.H., Bissett, E.J., and Battiston, P.A., "Mathematical modelling of electrically heated monolith converters: model formulation, numerical methods and experimental verification", Ind. Eng. Chem. Res., Vol. 32, pp. 1560-1567, 1993

- Ramanathan, K., and Sharma, C. S., “Kinetic Parameters Estimation for Three Way Catalyst Modeling”, Ind. Eng. Chem. Res., 50 (17), pp. 9960-9979, 2011

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