e-Charging System Investigation on Fuel Economy and Performance for a Heavy Duty Diesel Engine

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AGENDA

• Introduction / Ford Otomotiv Sanayi A.S
• Motivation
• E-Turbo Full Load TC Matching Results without e-Machine
• E-Turbo TC Matching Results with e-Machine (Energy Recuperation)
• E-Turbo EGR Flow Capability Analysis
• E-Booster High Altitude Performance
• Conclusion
FORD OTOMOTIV SANAYI A.S

• Ford Otomotiv Sanayi A.S (OTOSAN) is the leading company of Turkish Automotive Industry, equally owned by Ford Motor Company and Koc Holding.

• The company operates at 5 facilities in Turkey.

Transit

Transit/Tourneo Courier

Ford Cargo Trucks

Sancaktepe Engineering Center

Ecotorq EUVI 12.7L
• The motivation of the research study was to investigate potential of mild hybrid charging systems for a heavy duty engine in terms of fuel economy, emissions and engine performance.

• An electric motor/generator is connected to conventional turbocharger by using turbocharger’s shaft as a rotor for e-turbo simulation.

• Two types of operation [E-Turbo]:
  - Generating (energy recuperation from exhaust enthalpy)
  - Charging Assist (electric power usage with exhaust enthalpy)

• Compressor with electric motor is installed downstream of charger air cooler for e-booster simulations.

Engine : Ecotorq Eu6
Volume : 12.7L
Max Power : 480 PS
Max Torque : 2500 Nm

48V e-Charging Systems
HEAVY DUTY RECUPERATION OPPORTUNITIES

Power Flow to Driveline By Transmission\Clutch to Fly Wheel

ORC WHR  Turbocompound  Parallel Turbine  E-Turbo  48V Smart Alternator

Energy Flow to Battery/Consumer By Electric Generator

Auxiliary Electrification

E-HPS  ECP  Etc.

Boost Assist

Engine Power Assist?

24V Network Remains to support low and medium power consumers
**SIMULATION STUDY WORKFLOW**

**Strategy Step**
- Match a new TC which can work with e-Machine optimally

**Simulation Step**
- TC Matching
- Energy Recuperation from e-Turbo
- Fuel Economy, Emissions, Performance

**Up-size turbo**
- improved SFC
- Eliminate LET & transient response penalty

**Compare performance of TC’s [baseline and new matched without e-machine]**

**Develop e-Turbo Targets for Energy Recuperation and Boost Assist**
GT-SUITE MODEL

- GT-SUITE Model of e-Turbo has motor/generator model and control system links additional to standard turbocharged heavy duty 6 cylinder diesel engine model.
NEW TURBOCHARGER MATCHING

- Match a new turbocharger which can work with e-Machine optimally.

- Engine pressure difference reduced due to PMEP reduction which resulted as 1.1% improved BSFC at steady state full load engine operating conditions.
- New match has ~5% higher turbocharger efficiency
ENERGY RECUPERATION STRATEGY

- Controller Target: Keep (P3-P2) same with base calibration
- Controller Output: Brake-Power Demand from e-Motor
- All other calibration settings were kept constant.

Turbocharger speed intends to increase due to VNT position change. However, turbocharger speed must be same due to constant boost pressure target. This extra energy can be modulated by e-turbo's generator.
- Mass flow decrement due to increased EGR rate for e-Turbo allows higher compressor efficiency

- E-Turbo turbine VNT setting for same boost pressure calibration for full load increases the turbine efficiency

- E-Turbo has better efficiency due to improved compressor efficiency and turbine efficiency.

- Increased efficiency allows more energy recuperation from exhaust enthalpy
• Full and part load (maximum residency) engine operating points were evaluated in terms of fuel economy (FE) benefit and power recuperation potential.
• E-Turbo enables 2.5% fuel consumption reduction between 1200-1700 rpm full load range with up to 12 kW energy recuperation potential.
• For part load points, higher EGR rates reduce energy recuperation potential.
• At cruise mode, e-turbo allows 2.3% fuel economy benefit. FIGE Cycle Based simulation is resulted 2.6% FE benefit

Assumption: 100% Electric Power Conversion Efficiency
Motor/Generator unit's assist power is depend on shaft(rotor) speed and the power which is given to the shaft by e-machine is limited by transient speed profile of e-turbo's shaft.

Torque to inertia ratio of e-machine limits e-turbo acceleration increment. Above this limit value in milliseconds, e-turbo's acceleration can't increase. 950 milliseconds is a limit for this e-turbo.

Transient response of engine is improved by about 3.75 seconds by e-Turbo's 950ms assist operation at 1100rpm.
1100 RPM - EGR CAPABILITY ANALYSIS

- E-Turbo can be used for increasing high pressure EGR flow, while recovering exhaust energy by generator. VNT position change drives this phenomenon.

Condition = FL @ 1100 RPM
Constant Boost Pressure
EGR Valve = Full Open
Recuperation Sweeps: [1:1:12] kW

Max EGR/Power Rec.
8 kW Recuperation ~12.6% EGR
BSFC (Normalize) = 1.02 (1 base turbo w/o EGR)

When recuperation power is used:
BSFC (Normalized) = 1.002 (e-Turbo Compounding)

<table>
<thead>
<tr>
<th></th>
<th>w/o e-Turbo</th>
<th>e-Turbo</th>
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<tbody>
<tr>
<td>EGR Rate</td>
<td>0%</td>
<td>12.6%</td>
</tr>
<tr>
<td>BSFC (normalized)</td>
<td>1</td>
<td>1.002</td>
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Assumption: 100% Electric Power Conversion Efficiency
E-BOOSTER HIGH ALTITUDE SIMULATION

E-BOOSTER assist is needed!

Graph showing Brake Torque [N-m] vs Engine Speed [RPM]
- T3: Turbine Inlet Temperature Limit
- T2: Compressor Outlet Temperature Limit

Flowchart:
- Altitude increases
  - Oxygen concentration, air pressure, air density, airflow reduce
- AFR reduces thus turbine inlet temperature increases
- Smoke limit exceeds?
  - Yes
    - Turbine inlet temperature limit exceeded?
      - Yes
        - Increase boost pressure (airflow) by closing turbine rack
      - No
        - Target torque achieved?
          - Yes
            - No derate
          - No
            - Boost pressure and airflow increase thus turbine inlet temperature reduces
    - No
      - Derate

Diagram:
- Turbocharger
- E-BOOSTER
- CAC
- ATS
- Koc
- Ford Otosan
E-BOOSTER+VGT FOR HIGH ALTITUDE

- E-booster assist increases the mass flow rate through TC compressor. This decreases the pressure ratio and increases the compressor outlet temperature due to reduction in compressor efficiency.
- E-Booster assist reduces the turbocharger performance instead of benefit at high altitude at higher rpms
- e-booster needs bigger compressor & LET penalty will be covered by e-booster
E-BOOSTER ENERGY CONSUMPTION OPTIMIZATION

- E-Booster requested power is optimized w/o target torque penalty.
- Lowering the power consumption reduces the electric system cost or increases the FE benefit.
- Optimization is allowed by new compressor match.
CONCLUSION

- 48V E-Turbo and E-Booster boosting systems were studied to investigate their effect on fuel economy, emissions and performance for EU6 heavy duty diesel engine.

- E-Turbo allows energy recuperation from exhaust enthalpy and also can assist for turbocharger’s transient response improvement. Also, increases EGR flow capability w/o bsfc penalty.

- E-Booster prevents high altitude torque derate problem with optimized compressor match. And Energy consumption of e-booster can be optimized via e-booster speed DOE.

- GT-SUITE has advanced modeling capability to evaluate novel electric assisted charging systems accurately.

- Expensive hardware prototype cost is eliminated by GT-SUITE simulations.