Heavy Duty Powertrain Integration: Trends and Opportunities

Carl Hergart
PACCAR Inc.
The Power of Integration
Powertrain Integration: An Industry Trend

Dr. Wayne Eckerle, Cummins

Model 579 SuperTruck

Engine Efficiency: Impact of Integration

1. Cruise operating point 2010 Baseline
   • Volvo XE13 and Mack Super Econodyne — Down-speeded engine, enabled by integrated
     AMT and high torque, yields 22-23% FE
   • 1-2: chassis and trailer improvements reduce load
   • 2-3: downsizing improves efficiency
   • 3-4: downsizing increases percent load
   • RESULT:
     • Major improvement in vehicle fuel consumption with same engine efficiency

Subsystem Technology Palette

Combustion & Fuel Systems
Air Handling & Energy Recovery
Transmission Integration
System Optimization

Cummins 15L High Efficiency ISX Engine
Advanced Formula Aftertreatment
Cab and Trailer Aero Components
GPS Cruise Control
Advanced Super Single Tires

Waste Heat Recovery System
High Efficiency Cooling Package
Pneumatically Retractable Trailer Skirts
180° Trailer Tandem Service Door
Brief PACCAR History

1905: Seattle Car Mfg. Co Founded
1928: DAF Founded
1939: PACCAR Technical Center Established
1972: Pacific Car & Foundry becomes PACCAR
2009: New PACCAR Engine Factory in Columbus, MS
2010: MX Engine in North America
2014: New Engine And Powertrain Test Cells
Advanced Powertrain: Fuel Economy

Truck Energy Losses

- Engine (55-60%)
- Drivetrain (2-6%)
- Auxiliaries (1-4%)
- Aero (16-25%)
- Rolling (12-17%)
Demand for Energy for Commercial Transportation Expected to Grow as a Result of Expanding Economies

Heavy-Duty Trucks Move Over 70% of Freight Value and Tonnage

Diesel Expected to Remain Primary Fuel Used in Commercial Transport

The Outlook for Energy: A View to 2040, ExxonMobil Dec. 2014
Trucking Operating Costs

Every Cost Matters
Fuel Is The Largest Variable

- Driver Wages: 27%
- Driver Benefits: 9%
- Fuel & Oil Costs: 32%
- Lease/Purchase Payments: 16%
- Repair & Maintenance: 7%
- Insurance Premiums: 3%
- Permits & Licenses: 2%
- Tires: 2%
- Tolls: 2%

Annual Per Truck Fuel Costs vs. MPG
6 MPY = $84k
7 MPY = $72k
Savings = $12k

Compiled From American Transportation Research Institute ATRI 2011 Update for 2008-2010
Regulations

NOx and PM

- 1994
- 1998
- 2002
- 2007
- 2010

GHG

<table>
<thead>
<tr>
<th>Model Years</th>
<th>Vocational (FTP) (g CO2 / bhp-hr)</th>
<th>Tractor (RMC_SET)</th>
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</thead>
<tbody>
<tr>
<td>2014 – 2016</td>
<td>567</td>
<td>475</td>
</tr>
<tr>
<td>2017 - 2020</td>
<td>555</td>
<td>460</td>
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U.S. GREENHOUSE GAS POLLUTION INCLUDES:

- **Carbon Dioxide (CO2)** 82%
  - Enters the atmosphere through burning fossil fuels (coal, natural gas, and oil), solid waste, trees and wood products, and also as a result of certain chemical reactions (e.g., manufacture of cement).

- **Fluorinated Gases** 3%
  - Hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride are synthetic, powerful greenhouse gases that are emitted from a variety of industrial processes.

- **Nitrous Oxide (N2O)** 6%
  - Emitted during agricultural and industrial activities, as well as during combustion of fossil fuels and solid waste.

- **Methane (CH4)** 9%
  - Emitted during the production and transport of coal, natural gas, and oil as well as from landfills.

Source: EPA
Growth in OBD Complexity

Engine Platforms
- MX-13
- MX-11

Markets
- North America
- Europe
- Rest of the World

Service Tools
- Generic Scan Tool
- DAVIE

Monitor 1
Monitor 6
Monitor 20

2013
2020
Engine Efficiency Building Blocks

The Energy Available

Reciprocator

Fuel Energy

Exhaust Energy

Cylinder Heat Rej.

Indicated Power

Engine Out

Engine and Aftertreatment Integration

100% Fuel Energy

Radiation/Convection

Turbocharging

20-25% Exhaust

25-30% Coolant

15-25% Aerodynamic

10-20% Rolling

25-30% Exhaust

5-10% EGR

10-15% Heat Loss

Engine Pumps

45-50% Work

40-45% Flywheel

In Cylinder

Transmission Losses

Axle Losses

Truck Auxiliaries
Combustion Technology Building Blocks

- Injection Pressure
- Injection Rate Shape
- Injector Nozzle Configuration
- Piston Bowl Design
- Valve strategies
- Increased PCP
- Reduced Heat Rejection
- Fuel Formula
Air/EGR Management

- High-Pressure vs. Low-Pressure EGR
- EGR Driving Methods
- Fixed vs. Variable Geometry
- Single-Stage vs. Two-Stage
- Charge Air Cooling & Intercooling
- Exhaust Manifold Volume
- Divided vs. Undivided Exhaust Manifold
Waste Heat Recovery: Turbo Compounding

- Power to crank is ‘compounded’ by adding turbine shaft power to power from pistons
- Compound power can come from independent power turbine or from turbocharger turbine
- Improves engine thermal efficiency; trade-off of lower reciprocator power and efficiency vs. compound turbine power
- Requires power transfer (mechanical, electrical, hydraulic) between the shaft of the engine and an exhaust gas driven turbine
Waste Heat Recovery: Rankine Cycle

- Working fluid undergoes phase change (liquid to vapor) extracting energy from exhaust, using this energy to drive an expander
- Choice of working fluid key
  - Wet (e.g. water, ethanol) requires superheating, but not necessarily recuperator
  - Dry (e.g. R245fa) does not require superheating, but typically needs recuperator
- Available waste heat sources: EGR & Exhaust (high grade) and lube oil and coolant (low grade)
- Typical system efficiencies 10-20% for a 4-5% improvement in overall BSFC
- Requires power transfer (mechanical, electrical, hydraulic) between the shaft of the engine and the expander
Aftertreatment Integration

Fuel Consumption

Total Fluid Consumption

Engine-Out NOx [g/bhp-hr]
Automated Manual Transmission

Drivers:

• Improved Fleet Fuel Economy
• Shortage of Skilled Drivers
• Driver Fatigue

![Graph showing the comparison between Manual and AMT transmission systems in terms of fuel consumption and engine speed. The graph illustrates that AMT transmission results in lower fuel consumption and higher engine efficiency compared to Manual transmission.](image-url)
Axles

- Taller Rear Axle Ratios to Support Engine Downspeeding
- Improved Axle Efficiency Through Reduced Friction and Churning Losses
- Increased Torque
Intelligent Truck: Predictive Features

- **PCC (Predictive Cruise Control)**: Vehicle Set Speed is Adjusted For Optimal Fuel Consumption Based on the Terrain Ahead.

- **Neutral Coast**: Transmission Goes Into Neutral at Zero Torque Demand (Slight Downhill, Within a Speed Band), Engine Idles.

  - Set Speed Decreased on Uphill For Reduced Fuel Consumption.
  - Gradually Recover the Set Speed on Downhill Following Crest of Hill.
Intelligent Truck: Driver Performance Assist

- ABS
- Driver Coaching
- Adaptive Cruise Control
- Lane Departure Warning System
- Steer-By-Wire
Fuel Economy Analysis, Simulation, Measurement

Need to Understand and Quantify FE Impact:
- Hardware Selection
- New Features, Advanced Concepts

Early Analysis

Simulation
Rapid Evaluation of Concepts

Engine Dyno

Powertrain Dyno

Climatic Chassis Dyno
Increasing Degree of Hardware.
Repeatable & Consistent Testing.
Increasing Confidence in Results
Environmental Effects

Vehicle Test
Final Results
Correlation Data for Simulation & Testing

← Simulation

Hardware →
Summary & Outlook

• Continued Importance of HD Transport
• Powertrain Integration Key in Improving HD Truck Fuel Economy
• Trends:
  – Focus on Improved Engine Efficiency
  – Powertrain Downspeeding
  – Automated Manual Transmissions
  – Intelligent Truck
• Simulation and Gradual Use of HIL To Facilitate Development of New Technologies