Alternatives for Improving Heavy Truck Fuel Economy

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Introduction

- Project funded by NESCCAF and ICCT
- Scope: heavy duty, line haul trucks
  - Classic combination tractor with 53 foot box van trailer
  - Mostly highway duty cycle
  - Evaluate range of potential technologies and packages
- Results may be used to help guide development of potential regulations
- All improvements are listed in % fuel saved
  - Fuel consumption, not economy
    - The metric is important
    - Recommendation: fuel consumption per unit work
  - This is the same as the % reduction in GHG
  - Improvements in MPG will give a bigger % number
Duty Cycle

Graph showing speed and grade over time and distance.
Technological Package #1

- Baseline engine/vehicle package
  - **Kenworth T600 truck**
    - Meant to represent average of 2007 on-the-road fleet
    - Mild aero package: bumper fairing, partially aerodynamic mirrors, partial fuel tank fairing, integrated roof fairing, exhaust system out of the air flow, and cab side extenders
    - Total measured vehicle Cd: 0.63 (coast down test results)
    - Eaton / Fuller 10 speed manual transmission
    - Coefficient of rolling resistance CRR=0.0068, typical of current standard tires
Technology Package 1

**Volvo D13 engine**
- Not actually sold in this truck, but similar in performance and is available in the market in similar trucks
- SwRI HDD Benchmarking program data was used to calibrate the GT-Power cycle simulation model
- High pressure loop cooled EGR, electronic very high pressure fuel injection, VG turbo
- DPF-equipped for 2007; extrapolated to SCR + DPF for 2010
- SwRI assumption: 2010 fuel consumption with SCR and 0.2 g/HP-hr Nox is the same as 2007
- Actual 2010 fuel consumption is still under development – may be equal to or slightly better than 2007
- The SwRI 2010 assumption may be off by a few %, but for comparing the packages we are looking at differences rather than absolute levels
Technology Package 1

Package 1: Fuel Economy vs GVW

- Fuel Economy (mpg)
- Percent Fuel Saved

GVW (lbs)

Fuel Economy (mpg)

Percent Fuel Saved
Package 1 Conclusions

- Baseline vehicle fuel economy is 5.4 MPG on the line haul drive cycle
  - 5.96 MPG at 65,000 pounds GVW

- Weight reduction provides an improvement of about 0.6% per 1000 pounds GVW reduction
  - Tractor and trailer weight reduction will help, but have only a minor overall benefit for cubed-out vehicles
  - Grossed-out vehicles will gain 2.2% per 1000 pounds due to higher freight capacity
  - Reduction in freight load improves vehicle MPG, but will actually reduce fuel economy on a ton-mile/gallon basis
Technology Package #2

- Baseline + EPA Smartway package + Wide Base Tires (Super Singles)
  - Aero devices assumed in addition to Package #1:
    - Tractor: full fuel tank fairings, fully aerodynamic mirrors
    - Trailer: side fairing, and one of (boat tail, splitter plate, or gap fairing)
    - Overall aero benefit: 5% fuel economy improvement from trailer package, 2% improvement from tractor package
  - Rolling resistance improvements:
    - Low rolling resistance Wide Base tires, CRR = 0.0055
  - Actually modeled as a sweep of Cd
    - Cd = 0.5 was selected to represent this package
      - Note: this Cd may not be achieved in service
  - Weight penalty: 250 lb.
Technology Package #2: Cd Sweep

Package 2: Cd Sweep: Crr=0.0055, GVW = 80klbs

The graph shows the relationship between the coefficient of drag and fuel economy for Package 2. The Coefficient of Drag (Cd) is plotted on the x-axis, ranging from 0.35 to 0.65, and the Fuel Economy (mpg) is plotted on the y-axis, ranging from 9 to 0. The graph also indicates the Percent Fuel Saved, compared to Package 1.
Package 2 Conclusions

- Crr reduction from 0.0068 to 0.0055 provides a 6% improvement
- Cd reduction from 0.6298 to 0.5 provides an 8% improvement
- The full Package 2 provides a 14% improvement at 80,000 lbs. GVW
Technology Package #3

- **Baseline + advanced Smartway package (2017)**
  - **Aero devices under consideration:**
    - Tractor / trailer gap flexible fairing
    - Improved tractor profile for lower Cd
    - Additional trailer features
    - Assumed Cd = 0.40
  - **Rolling resistance improvements:**
    - Crr = 0.0045 selected with EPA and industry input
  - Actually modeled as a sweep of Cd and CRR
  - Weight penalty: 500 lb.
Technology Package #3: Cd Sweep

Package 3: Cd Sweep with Crr=0.0045, GVW = 80klbs

Fuel Economy (mpg) vs Coefficient of Drag (-)

- Blue line: Fuel Economy (mpg)
- Green line: Percent Fuel Saved vs Package 1

Package 3 C_d = 0.4
Package 3 Conclusions

- Crr reduction from 0.0068 to 0.0045 provides a 10.6% fuel consumption reduction
- Cd reduction from 0.6298 to 0.4 provides an additional 14.1% fuel consumption reduction
- The full Package 3 provides a 24.7% fuel consumption and GHG reduction at 80,000 lbs. GVW
- If it becomes possible to achieve a 0.3 Cd, an additional 6% fuel consumption improvement is available
  - Many technical and practical challenges remain to achieve even 0.4 Cd
Package 4: Parallel Hybrid

- **Parallel hybrid**
  - 50 kW motor/generator
  - Engine side of clutch and vehicle side of clutch
  - Both engine and motor/generator always available to drive the truck
  - Evaluated a range of battery sizes

- **Setup Assumptions**
  - Reduced engine accessory load to 3 kW (compared to baseline 5kW in Package 1), assuming electrification of several accessories
  - Set Battery at 4 kWh with 2 kWh usable (allowing 50% discharge)
  - **Integrated motor into transmission downstream of clutch**
    - Clutch is disengaged during braking events (assumes AMT)
    - Engine friction is eliminated during braking, which allows increased regenerative braking
Package 4: Fuel Savings

Fuel Savings at 80,000 lbs

- **Line Haul Drive Cycle**
  - Package 3: 7.18 mpg (baseline)
  - Package 3+4: 7.61 mpg (5.65% Fuel Saved)

- **Hybrid provides savings on line haul cycle due to:**
  - Regenerative braking on hills and in suburban portion of cycle
  - Reduction in engine accessory load via electrified accessories
  - Elimination of idle time during the test cycle (night idle reduction is not considered here)
Package 5 & 6: Turbocompound

- Turbocompound simulation approach:
  - Compare fixed geometry and VG turbochargers
    - Allow fully open EGR valve for VG configurations
  - Use fixed geometry power turbine
  - Maintain baseline or higher A/F at high loads where A/F is minimum and lower would be problematic
  - Allow lower A/F at low loads where the baseline configuration has significant excess air
  - Maintain baseline EGR flow to provide NOx control
Package 5 & 6: Turbocompound

- **Package 5: mechanical turbocompound**
  - Power turbine geared directly to the crankshaft through fluid coupling
    - Power turbine and crank speeds are related
  - Overrunning clutch to prevent BSFC loss at light load
  - Includes VVA and fixed geometry primary and power turbines

- **Package 6: electric turbocompound**
  - Power turbine drives an electrical generator
    - Power turbine and crank speeds are independent
  - Electric power used to drive a motor connected to the transmission
  - Includes VVA and fixed geometry primary and power turbines
  - Includes electrification of accessories
    - Water pump, A/C compressor, air compressor, power steering
Package 5 & 6: Turbocompound

Fuel Economy Improvement vs Pkg 3

Vehicle GVW (lbs)

% Fuel Saved

Mech TC Fuel Saved

Elec TC Fuel Saved
Conclusions:

- Turbocompound can provide a significant benefit
  - 2.4 to 2.8% for mechanical turbocompound
  - 4.0 to 4.3% for electrical turbocompound

- Turbocompound works best with high GVW vehicles
  - High load favors turbocompound efficiency

- Electric turbocompound performed better
  - Power turbine speed independent from crank speed
  - Electric accessories save more than 1% of fuel
  - However, electric system is more expensive to implement

- A VG turbo is not required
  - Improved flexibility is cancelled by lower efficiency

- VVA helps turbocompound efficiency
  - Effect is a bit more than 1% improvement in BSFC
Fuel savings during drive cycle with application of VVA by itself:

<table>
<thead>
<tr>
<th>Package</th>
<th>Baseline Fuel Economy (mpg)</th>
<th>Fuel Economy with VVA (mpg)</th>
<th>% Fuel Saved by adding VVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1 - Baseline</td>
<td>5.38</td>
<td>5.43</td>
<td>0.99 %</td>
</tr>
<tr>
<td>P3 – Smartway 2017</td>
<td>7.18</td>
<td>7.26</td>
<td>1.0 %</td>
</tr>
<tr>
<td>P4 – Parallel Hybrid</td>
<td>7.61</td>
<td>7.72</td>
<td>1.4 %</td>
</tr>
</tbody>
</table>

VVA by itself has a modest positive effect on fuel economy.
The concept:

- Utilize waste heat from the engine to produce additional power
- SwRI selected a water based steam cycle
  - Offers good cycle efficiency
  - Requires cold weather protection
- SwRI evaluated four system configurations
  - Engine coolant based system
  - EGR based system
  - EGR supplemented by exhaust heat up to EGR cooler outlet temp.
  - EGR and full exhaust heat
- The coolant based system provides a lot of energy, but at very low temperature
  - BOTTOMING cycle efficiency is very low
- EGR and full exhaust heat performs the best
  - About twice the power of EGR only, and much better than EGR supplemented by exhaust heat
  - Requires a secondary EGR cooler
Bottoming Cycle

- Bottoming cycle schematic

- Engine
- EGR pre-cooler/BC superheat
- EGR suppl. cooler
- Stack heat exch/BC pre-heater
- Aftertreatment
- Pump
- Expander
- Condensor
- Air to Air A/C
- Inlet Air

- White (ATA A/C): cooled by ambient air
- Gray: Assoc’d with BC
- Green: (EGR suppl. cooler): cooled by engine coolant
- Blue: engine-related
Bottoming Cycle Temps/Pressures
Rated Power, Full-sized System

Bottoming cycle flow: 3.8 kg/min
Exhaust stack flow: 27.0 kg/min
EGR flow: 8.5 kg/min
BC expander output: 57.2 kW

- EGR pre-cooler/BC superheat
  - T: 644°C
  - Q: 60 kW
- Stack heat exch/BC pre-heater
  - T: 242°C
  - P: 3490 kPa
  - T >150°C
  - Q: 167 kW
- EGR suppl. cooler
  - T: 629°C
  - P: 3480 kPa
- Aftertreatment
  - T: 480°C
- Pump
  - T: 40.1°C
  - P: 3500 kPa
- Expander
  - T: 629°C
  - P: 3480 kPa
- Condenser
  - T: 40°C
  - P: 7.4 kPa

Air to Air A/C
Inlet Air

- Turbine
  - Comp
  - T: 256°C
- Comp
  - T: 40°C
  - P: 7.4 kPa
- Condenser
  - Q: 170 kW
- EGR suppl. cooler
  - T: 629°C
  - P: 3480 kPa
- EGR suppl.
  - Q: 7.4 kW

All pressures absolute
Bottoming Cycle Conclusions

The performance potential of a bottoming cycle is substantial – around 7 to 10% fuel savings

- Bottoming cycle thermal efficiencies of 20 to 25% appear feasible
- By far the best results were achieved by combining exhaust and EGR heat inputs

The engineering challenges, cost, and packaging issues are also substantial

- A small, efficient expander is required
- The system must adapt to a wide range of source temperatures and energy flows – controls are key
- Several heat exchangers, some of which may experience condensation and other issues
- Increased overall vehicle system heat rejection
- Any water based system requires freeze protection
# Package 9: Longer / Heavier Vehicles

<table>
<thead>
<tr>
<th>Combo</th>
<th>Empty Weight (lb.)</th>
<th>Max. GVW (lb.)</th>
<th>Freight Volume (ft³)</th>
<th>Cd</th>
<th>Crr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard 53’ Trailer</td>
<td>32,000</td>
<td>80,000</td>
<td>4040</td>
<td>0.4</td>
<td>0.0045</td>
</tr>
<tr>
<td>6 Axle 53’ Trailer</td>
<td>35,000</td>
<td>97,000</td>
<td>4040</td>
<td>0.4</td>
<td>0.0045</td>
</tr>
<tr>
<td>Standard 28’ Doubles</td>
<td>35,500</td>
<td>80,000</td>
<td>4200</td>
<td>0.43</td>
<td>0.0043</td>
</tr>
<tr>
<td>33’ Doubles</td>
<td>37,000</td>
<td>80,000</td>
<td>4950</td>
<td>0.43</td>
<td>0.0043</td>
</tr>
<tr>
<td>Rocky Mtn. Doubles</td>
<td>43,500</td>
<td>120,000</td>
<td>5750</td>
<td>0.44</td>
<td>0.0043</td>
</tr>
<tr>
<td>Turnpike Doubles 48’</td>
<td>50,000</td>
<td>140,000</td>
<td>7300</td>
<td>0.44</td>
<td>0.0043</td>
</tr>
</tbody>
</table>
Package 9: How to Read Plots

- The figures show ton-miles per gallon, a common measure of freight efficiency
  - Ton-miles per gallon is simply vehicle MPG multiplied by the number of tons of freight carried
  - This is related to, but not identical to, fuel consumption and GHG emissions
- If the trailer is full, but the vehicle is not at max GVW (low density freight), there is an efficiency penalty in ton-MPG
- Once the vehicle reaches max GVW, the efficiency can no longer improve
  - This explains why the ton-mile per gallon curves go flat above a certain freight density
- Package 9 vehicles include Package 3 aerodynamic and rolling resistance improvements
Package 9: Fuel Savings

Package 9 Trailer Configurations at 500 HP

- Std 53 ft 5 Axle
- 28 ft Double
- 33 ft Double
- 28 ft Triple
- Rocky Mtn Double
- Turnpike Double
- 53 ft 6 Axle

Tons-Miles / Gallon Fuel vs. Freight Density (lb/ft^3)
Package 9: Fuel Savings

Package 9: Penalty for Higher Power Engines

- Turnpike Double at 700 Hp
- Turnpike Double at 500 Hp
- 53 ft, 6 Axle at 600 Hp
- 53 ft, 6 Axle at 500 Hp

Tons Miles per Gallon Fuel

Freight Density (lb/ft^3)
Package 9: Grade Performance at Max. GVW

Vehicle Configuration

Minimum Speed on 3% Grade, MPH

- Std. 53' trailer
- TD 500 HP
- TD 700 HP
- RMD
- 28' triples
- 33' doubles
- 28' doubles
- 53' 6 axle 600 HP
Package 9 Conclusions

- The 6 axle 53’ trailer helps with high density freight
  - 11.7% fuel savings for freight densities above 15.35 lb/ft³
  - Slight penalty for freight densities below 12 lb/ft³ because of increased empty vehicle weight
  - A 20% increase in power is required to maintain grade performance

- Turnpike doubles (two 48’ trailers) offer the biggest gains
  - 28% fuel consumption reduction at a freight density of 6.9 lb/ft³
  - Always at least a 24.7% improvement
  - Huge fuel economy and GHG benefit, however, safety concerns surrounding the operation of longer / heavier vehicles will need to be addressed
  - Large performance loss on grades – some loss even with 40% more power
Package 9 Conclusions

- Larger / heavier trailers offer substantial fuel economy and GHG reduction opportunities
  - Some versions work best for low density freight
  - Some work best for high density freight
  - Some offer advantages across the board
  - All suffer performance loss on grades – more power may be required

- The challenge for regulators will be to combine longer / heavier trucks with safety features, and sell a package deal to the public

- Note: all fuel consumption reductions are presented in percent fuel burned, not percent increase in ton-miles per gallon
  - Ton-MPG improvements in % give bigger numbers
Package 10: Reduced Speed Limit

The Line Haul drive cycle was modified by imposing reduced speed limits of 65, 60, and 55 mph.

- Distance traveled is unchanged, time is increased.
- Axle ratios were changed as required to maintain an adequate engine RPM in top gear for 60 and 55 MPH limits. We also simulated a situation with constant axle ratios.
- Only portions of drive cycle exceeding speed limit are modified. Most of our drive cycle is $\leq 66$ MPH.
- Package 3 was used as the baseline for the simulations.
Package 10: Fuel savings vs Speed Limit

- wrt Package 3 - no change in FD
- wrt Package 3 - with change in FD
Package 10: Conclusions

- The initial reduction from 70 MPH to 65 MPH has only a modest effect
  - This is because most of the drive cycle is at speeds below 70

- The fuel economy benefit of lower speed is about 0.8% per MPH

- There is some penalty for dropping final drive ratios to maintain adequate engine RPM at cruise
  - Required to maintain grade capability

- These results show a slightly smaller benefit than the 1% per MPH that is typically quoted
  - This may be because Package 10 includes the low Cd used in Package 3
Package 10: Issues

- Lower speed has other effects that are difficult to quantify
  - Longer trip time = higher labor cost
  - Longer trip time = fewer ton-miles of freight per truck per day
  - Longer trip time = more trucks required to deliver a given volume

- The relationship between lower governed speed and trip time is not well understood
  - Speed may be limited by traffic, road conditions, and grade
  - Some routes (long hauls on flat terrain with light traffic) may be dominated by governed speed effects, while for others, governed speed may be only a small factor

- How best to calculate the net benefit of lower speeds?
  - Fuel saved – (higher labor cost + more trucks required)
Package 11: Advanced EGR

- Lower EGR temperatures allow the use of more advanced injection timing or lower EGR flow rate at a constant NOx level
  - This can improve engine efficiency

- A secondary EGR cooler was added to reduce the temperature of EGR flowing back into the engine by about 60º C
  - This is about the limit of what can be done without excessive condensation
  - Condensation is still a big issue

- Simulation results show a little over 1% improvement in fuel consumption and GHG gas emissions
3 Versions:

- **12a:** Standard 53 foot trailer with bottoming cycle, hybrid, full aero package, full rolling resistance reduction, and 60 MPH road speed governor
  - Full technology package, standard size trailer

- **12b:** RMD with bottoming cycle, hybrid, full aero package, full rolling resistance reduction, and 60 MPH road speed governor
  - Full technology package, 48’ + 28’ trailers

- **12c:** RMD with electric turbocompound, VVA, hybrid, full aero package, full rolling resistance reduction, and 60 MPH road speed governor
  - Lower risk technology package, 48’ + 28’ trailers
## Package 12 – Full Monte

<table>
<thead>
<tr>
<th>Full Monte Version</th>
<th>Fuel / CO₂ Reduction</th>
<th>Grossed Out &gt; 13.3 lb/ft³ density</th>
<th>Cubed Out 8.2 lb/ft³ density</th>
</tr>
</thead>
<tbody>
<tr>
<td>12a</td>
<td>36.9%</td>
<td></td>
<td>38.6%</td>
</tr>
<tr>
<td>12b</td>
<td>50.0%</td>
<td></td>
<td>47.5%</td>
</tr>
<tr>
<td>12c</td>
<td>46.9%</td>
<td></td>
<td>44.2%</td>
</tr>
</tbody>
</table>
Full Monte Caveats

1. Some of the technologies have high risk
   a) Example: the bottoming cycle has many development, reliability, and packaging issues to overcome
   b) Example: fleets have reported that aerodynamic kit fuel economy gains in the field do not match wind tunnel and test track gains

2. Some vehicles can’t take full advantage of certain technologies
   a) Examples: aero treatment of flatbed, bulk hauler, and tanker trailers

3. Some technologies that are not evaluated in this study may become feasible in the 2017 time frame