An Investigation of Fuel Economy in Heavy Duty Diesel Engine Lubricants

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Presentation Overview

- Industry environmental and regulation
- The Volvo D12D FE Engine Test
  - An Evaluation of the Results From a Base Oil Type Comparison
  - Introduction of a New Method of Analyzing the D12D FE Results
  - Application of this method for
    - Viscosity grade comparison
    - Evaluation of the friction modifier impact
    - Study of the impact of soot
- Field Test Data
- Lubricant Additive Effect
- Conclusions
Emissions Regulations: Heavy Duty Diesel – Europe, USA and Japan

New Japan Target: \( 0.7 / 3 = 0.23 \text{ g/kWh} \) The lowest level in the world
Emissions Standards Driving Oil Quality Standards

- **NOₓ (g/kW-Hr)**
  - 2010: 0.27
  - 2007: 3.3
  - 2002: 5.4
  - 2000: 6.7
  - 1998: 6.7
  - 1994: 8.05
  - 1991: 14.4
  - 1990: 14.4
  - ~3,000 ppm Sulfur fuel

- **Particulate (g/kW-Hr)**
  - 2010: 0.013
  - 2007: 0.134
  - 2002: 0.33
  - 2000: 0.80
  - 1998: 2
  - 1994: 4
  - 1991: 5
  - 1990: 6
  - CE

- **Sulfur Levels**
  - Sulfur fuel: ~3,000 ppm

- **Oil Quality Standards**
  - CI-4
  - CH-4
  - CG-4
  - CF-4
  - CJ-4
  - PC-11?
  - CJ-4 PLUS

- **Year**
  - 1988
  - 1990
  - 1991
  - 1994
  - 1998
  - 2000
  - 2002
  - 2007
  - 2010
  - 20XX?
Fuel Prices

Weekly U.S. No 2 Diesel Retail Sales by All Sellers

US $ per Liter

CO2 and Fuel Economy Regulations Will Lead to Fuel Economy Improvements

Kilometers per Liter

EU: Diesel: 20.4 Km/L, 48 MPG
EU: Gasoline: 17.9 Km/L, 42 MPG
Japan
California
South Korea
Canada
Australia
China

United States

Liters per 100 Kilometers

Miles per Gallon

Active and Pending Fuel Economy Regulations

Japan
- First Truck Fuel Economy Standards in the World
  - Fully implemented in 2015
  - Based on engine dynamometer test
  - Fuel economy assessed at various operating conditions and parameters

United States
- On May 21, 2010, President Obama signed a memorandum that will lead to medium duty and heavy duty truck fuel economy standards being established by July 30, 2011
  - Study in progress to establish regulations and criteria – Not likely simple mpg, probably ton-miles/gallon or some other measure
  - Likely to be implemented in 2014
  - EPA has established CO$_2$ as a “Public Health Threat”

Europe
- No current truck fuel economy standard, but CO$_2$ emissions considered when establishing NOx and particulate emissions limits in EURO 6
  - B7 biodiesel blends to reduce greenhouse gas emissions
Japan Fuel Economy Regulation

Japan Fuel Economy Regulations
2015 Targets for Heavy-Duty Vehicles (GVW>3.5 tons)

<table>
<thead>
<tr>
<th>Category</th>
<th>2015 Target</th>
<th>2002 Performance</th>
<th>Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trucks</td>
<td>7.09km/L</td>
<td>6.32km/L</td>
<td>12.2%</td>
</tr>
<tr>
<td></td>
<td>(369.6g-CO₂/km)</td>
<td>(414.6g-CO₂/km)</td>
<td></td>
</tr>
<tr>
<td>Buses</td>
<td>6.30km/L</td>
<td>5.62km/L</td>
<td>12.1%</td>
</tr>
<tr>
<td></td>
<td>(416.0g-CO₂/km)</td>
<td>(466.3g-CO₂/km)</td>
<td></td>
</tr>
</tbody>
</table>

Note: Fuel efficiency here is JE05 test cycle-measured, and targets (for average fuel efficiency) were established assuming the same respective shipment volume ratios by vehicle weight category for 2015 as those recorded in 2002.

Sources: Ministry of Economy, Trade and Industry (METI); Ministry of Land, Infrastructure, Transport and Tourism (MLIT)
Fuel Economy Legislation in Heavy Duty Diesel

- Standards have 26 categories by Vehicle types/weight (GVW).
- Fuel economy is simulated by 2 modes for City Driving/Highway Driving.

Rate of fuel consumption (quantity)

City Mode (Ave. 27km/h)

Highway Mode (Ave. 90km/h)

Source: HDDO WG in SAE Asia Steering Committee
Truck Fuel Economy Contribution by Area
Engine Oil Impact is Relatively Small

Maximum Fuel Economy Impact

Fuel Economy is Front Page News

Engine Oil Change Can Be Quickly Implemented and Has Immediate Impact on Entire Fleet
U.S. Heavy Duty Truck Fuel Economy Regulations
Model Year 2014 Introduction?!

- **NHTSA** - Regulates existing passenger car CAFÉ program
- **NAS** – National Academy of Science to conduct truck fuel economy study
- **DOT** – Regulates roads and transportation system
What is the Best Way to Measure Fuel Efficiency?

<table>
<thead>
<tr>
<th>Payload</th>
<th>Liters per 100 Kilometers</th>
<th>Ton-Liter per 100 Km</th>
<th>Cubic Meters</th>
<th>Kilometers per Liter</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 tons</td>
<td>36 ℓ/100 km</td>
<td>11 ℓ/100 km</td>
<td>2.7 m³</td>
<td>113.3 m³</td>
</tr>
<tr>
<td>30 tons</td>
<td>38,690</td>
<td>22</td>
<td>207.7 m³</td>
<td>44 ℓ/100 km</td>
</tr>
<tr>
<td>45 tons</td>
<td>38,690</td>
<td>239</td>
<td>207.7 m³</td>
<td>44 ℓ/100 km</td>
</tr>
</tbody>
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Fuel Economy Test Tools Have Improved

- Fuel Economy evaluations have been reported in the literature for decades
  - Engine test tools were not precise enough
  - Field testing was, and remains, inherently challenging for the evaluation of small differences

- With current instrumentation precision, fuel consumption can be measured more accurately
  - Only in steady state operation
  - Only in a well controlled testing environment
  - Only on a relative basis due to engine fluctuations

- The Volvo D12D FE test takes advantage of new instrumentation and operates within these limitations
Volvo D12D Fuel Economy Test

- Industry Standard Heavy Duty Fuel Economy Test
  - Test is also installed at Oronite’s Rotterdam Lab

- Volvo Euro 3 Engine
  - 6-cylinder in-line configuration
  - 12.130 liter displacement
  - 338 kW at 1800 rpm
  - 2200 Nm at 1200 rpm

- Volvo D12D Fuel Economy Test Procedure
  - Laboratory engine test
  - 13-mode cycle at varying speeds/loads
  - SAE 15W-30 reference oil
  - Flush and run test procedure
The Volvo D12D FE Test Procedure

- Take Specific Fuel Consumption (SFC) measurements at each of the 13 ESC Modes
  - Repeat 5 times total
  - Calculate the average of measurements 2 through 5

- Bracket each candidate lubricant by a full SFC measurement on the 15W-30 Reference Oil

- Calculate the difference between Candidate SFC and the average of before and after Reference Oil SFC

- Multiply the differences for each mode with the Volvo proprietary weighting factors

- Add up the total for a Fuel Economy Improvement Percentage
The Volvo D12D FE Operating Conditions

ESC modes 7, 9, and 11 are the low load modes

![Graph showing engine speed and load percentage for different ESC modes.](image-url)
Fuel Consumption Improvements by ESC Mode

Some ESC modes magnify the impact, but the ranking of oils remains the same.
Different Sources of Friction

- Boundary Lubrication
- Mixed Lubrication
- Hydrodynamic Lubrication
- Solid Friction

The Volvo D12D FE Test Operates in This Regime

Coefficient of Friction vs Speed x Viscosity / Load
The Volvo D12D FE Operates Mostly in the Hydrodynamic Lubrication Regime

Candidate oils will be compared with this line for the 15W-30 reference oil

![Graph showing specific fuel consumption vs. quasi Stribeck number](image-url)
Fuel Consumption Effects are Magnified at Low Load / High Speed

![Graph showing the relationship between SFC improvement and Quasi Strubeck Number. The graph includes four groups (I, II, III, IV) with different linear equations and R^2 values.]

- Group I: $y = -0.15x + 0.05$, $R^2 = 0.70$
- Group II: $y = -0.25x - 0.21$, $R^2 = 0.93$
- Group III: $y = -0.31x + 0.04$, $R^2 = 0.92$
- Group IV: $y = -0.68x + 0.01$, $R^2 = 0.98$

**Quasi Strubeck Number (0.1*Speed/Load%)**

**SFC Improvement (Reference - Candidate), g/kWh**
The Impact of Viscosity Grade on Fuel Economy in Volvo D12D

<table>
<thead>
<tr>
<th>Test Oil Viscosity Grade</th>
<th>15W40</th>
<th>10W40</th>
<th>5W40</th>
<th>15W30 (REO)</th>
<th>10W30</th>
<th>5W30</th>
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<tbody>
<tr>
<td>Fresh Oil Viscosity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KV40, cSt</td>
<td>110</td>
<td>118</td>
<td>88</td>
<td>84</td>
<td>83</td>
<td>66</td>
</tr>
<tr>
<td>KV100, cSt</td>
<td>14.6</td>
<td>16</td>
<td>14.6</td>
<td>11.9</td>
<td>12</td>
<td>10.9</td>
</tr>
<tr>
<td>CCS, cP</td>
<td>6660</td>
<td>6180</td>
<td>6510</td>
<td>5695</td>
<td>6890</td>
<td>6100</td>
</tr>
<tr>
<td>HTHS, cP</td>
<td>4.16</td>
<td>4.28</td>
<td>4.09</td>
<td>3.55</td>
<td>3.62</td>
<td>3.35</td>
</tr>
<tr>
<td>Viscosity After 90 Cycles Shear in Bosch</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KV100, cSt</td>
<td>12.9</td>
<td>12.77</td>
<td>12.66</td>
<td>11.03</td>
<td>11.04</td>
<td>9.48</td>
</tr>
<tr>
<td>HTHS, cP</td>
<td>3.86</td>
<td>3.78</td>
<td>4.11</td>
<td>3.43</td>
<td>3.41</td>
<td>3.05</td>
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<tr>
<td>Volvo D12D FE Engine Test Result</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EFI On Highway Conditions, %</td>
<td>-0.76</td>
<td>-0.51</td>
<td>-0.31</td>
<td>0</td>
<td>0.17</td>
<td>0.44</td>
</tr>
<tr>
<td>EFI Hilly Conditions, %</td>
<td>-0.57</td>
<td>-0.38</td>
<td>-0.24</td>
<td>0</td>
<td>0.12</td>
<td>0.33</td>
</tr>
</tbody>
</table>

VOLVO D12D FE TEST ON VISCOSITY GRADE

Fuel Economy Improvement (%)
Lowering the High Temperature Viscosity Has the Biggest Impact on Fuel Economy

SFC Improvement (Reference - Candidate), g/kWh

- y = 0.26x - 0.03
- y = 0.10x - 0.04
- y = -0.21x - 0.02
- y = -0.31x + 0.04
- y = -0.45x + 0.08

Quasi Stribeck Number (Speed/Load%/10)
Comparison of SAE 30 & 5W30 in FIELD TEST

Field Test Vehicle

- **Vehicle**: 10 ton lorry trucks x 4
- **Model Year**: 2000 MY x 2, 2002 MY x 2
- **Engine**: 10L (In-line 6)
- **Total mileage**: 100,000km

<table>
<thead>
<tr>
<th>Model Year</th>
<th>Vehicle</th>
<th>Engine</th>
<th>Total Mileage</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000 MY x 2</td>
<td>10 ton lorry trucks x 4</td>
<td>10L (In-line 6)</td>
<td>100,000km</td>
</tr>
<tr>
<td>2002 MY x 2</td>
<td>10 ton lorry trucks x 4</td>
<td>10L (In-line 6)</td>
<td>100,000km</td>
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</table>

<table>
<thead>
<tr>
<th>Oil Type</th>
<th>SAE 5W30</th>
<th>#30</th>
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<tbody>
<tr>
<td>KV100</td>
<td>9.95</td>
<td>11.08</td>
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<tr>
<td>KV40</td>
<td>58.09</td>
<td>94.24</td>
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4.7% FE
The Impact of FMs on Fuel Economy in D12D

<table>
<thead>
<tr>
<th>Test Oil Viscosity Grade</th>
<th>No FM</th>
<th>FM-A</th>
<th>FM-B</th>
<th>FM-C</th>
<th>FM-D</th>
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<tbody>
<tr>
<td>Fresh Oil Viscosity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KV40, cSt</td>
<td>69</td>
<td>72</td>
<td>71</td>
<td>71</td>
<td>72</td>
</tr>
<tr>
<td>KV100, cSt</td>
<td>12.1</td>
<td>12.2</td>
<td>12.3</td>
<td>12.3</td>
<td>12.2</td>
</tr>
<tr>
<td>CCS, cP</td>
<td>6170</td>
<td>6390</td>
<td>6460</td>
<td>6420</td>
<td>6470</td>
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<tr>
<td>HTHS, cP</td>
<td>3.63</td>
<td>3.66</td>
<td>3.67</td>
<td>3.68</td>
<td>3.69</td>
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<tr>
<td>Viscosity After 90 Cycles Shera in Bosch</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KV100, cSt</td>
<td>11.11</td>
<td>11.13</td>
<td>11.26</td>
<td>11.15</td>
<td>11.31</td>
</tr>
<tr>
<td>HTHS, cP</td>
<td>3.45</td>
<td>3.48</td>
<td>3.5</td>
<td>3.49</td>
<td>3.55</td>
</tr>
<tr>
<td>Volvo D12D FE Engine Test Result</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EFI On Highway Conditions, %</td>
<td>0.11</td>
<td>0.42</td>
<td>0.05</td>
<td>0.22</td>
<td>0.31</td>
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<tr>
<td>EFI Hilly Conditions, %</td>
<td>0.07</td>
<td>0.32</td>
<td>0.01</td>
<td>0.18</td>
<td>0.28</td>
</tr>
</tbody>
</table>

D12D FE TEST ON FRICTION MODIFIER

Fuel Economy Improvement (%)
Friction Modifiers Can Impact HD Fuel Economy

SFC Improvement (Reference - Candidate), g/kWh

- 5W-30 Baseline
- 5W-30 with FM A
- 5W-30 with FM B
- 5W-30 with FM C
- 5W-30 with FM D

Equations:
- \( y = 0.2464x - 0.0339 \)
- \( y = 0.1396x + 0.15 \)
- \( y = 0.1681x - 0.0714 \)
- \( y = 0.1112x - 0.1925 \)
- \( y = 0.0738x - 0.1763 \)

Quasi Strubeck Number (0.1*Speed/Load%)
Investigation Into HD Fuel Economy Retention

- Description of the experiment
  - Test on a charge of candidate oil with FM A
  - Test on candidate oil with FM A after pre-aging the oil in a different HD engine to roughly 1.75% Soot
  - Test on candidate oil with FM A after pre-aging the oil in a different HD engine to roughly 3.50% Soot

- Viscosity of the three oils was determined before the D12D FE test was run

- Results show FE deterioration caused by viscometric changes
Candidate Oils for Study of the Impact of Soot on FM Response in D12D Test (1)

<table>
<thead>
<tr>
<th>Test Oil Viscosity Grade</th>
<th>No FM</th>
<th>FM-A</th>
<th>FM-A with 1.75% Soot</th>
<th>FM-A with 3.50% Soot</th>
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<tr>
<td>KV40, cSt</td>
<td>69</td>
<td>72</td>
<td>71</td>
<td>71</td>
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<td>12.3</td>
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<td>6420</td>
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<td>3.63</td>
<td>3.66</td>
<td>3.67</td>
<td>3.68</td>
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</table>

<table>
<thead>
<tr>
<th>Fresh Oil Viscosity</th>
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<tbody>
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<td>KV100, cSt</td>
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<td>11.13</td>
<td>11.26</td>
<td>11.15</td>
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<tr>
<td>HTHS,cP</td>
<td>3.45</td>
<td>3.48</td>
<td>NA</td>
<td>NA</td>
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<td>0.22</td>
</tr>
<tr>
<td>EFI Hilly Conditions, %</td>
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</tr>
<tr>
<td></td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>0.03</td>
</tr>
</tbody>
</table>

D12D FE TEST ON FM AND SOOT

[Graph showing fuel economy improvement for different conditions and oils]
Diesel Soot Effect in D12D Test (2)

SFC Improvement (Reference - Candidate), g/kWh

- 5W-30 FM A Fresh Oil
- 5W-30 FM A with 1.75% Soot
- 5W-30 FM A with 3.5% Soot

Equations:
- $y = 0.2464x - 0.0339$
- $y = 0.0763x + 0.0309$
- $y = -0.0135x + 0.0922$
Field Test on with FM and without FM

- **Test Vehicle:** 18 Trucks
- **Model Year:** 2005~7 MY
- **Engine:** 10L, In-Line 6
- **Test Oil:** SAE 30 (Blank)
  - SAE 30 plus FM
- **Total Mileage:** 30,000km

Additives Effect on Friction Properties

Detergent Effect

ZnDTP Effect

Dispersant Effect

- Each additive is shown different friction properties.

Note: Use Gasoline Engine System in Test
Conclusion

- Heavy-Duty (HD) diesel fuel economy standards are in the process of being developed and implemented in many developed and developing countries.

- Fuel economy in HD Diesel Engines can be improved by lowering the viscosity of the engine lubricant.

- As known in passenger car engines, the friction modifiers and the additives formulations can improve fuel economy.

- Engine lubricant additives such as friction modifiers have also shown a response in HD diesel engines to fuel economy.

- The combination of lower friction coefficient additives with lower viscosity grade engine oils has the potential to reduce total friction of HD diesel engine oils and will also have further big potential benefit on fuel economy in HD diesel engines.

- Engine oil contaminated with diesel soot affected fuel economy performance and more work needs to be conducted on soot handling technology to further improve fuel economy in HD diesel engines.
Thank you!