Measurement and Modeling of Fuel Use and Exhaust Emissions from Idling Long-Haul Freight Truck and Auxiliary Power Unit Engines

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Objectives

• Collect real-world data from in-service long-haul sleeper cab trucks
• Categorize stop scenarios
• Analyze stop activity patterns
• Characterize real-world, in-use fuel use rates and emission factors for the base engine, auxiliary power units (APUs) and shore-power (SP) systems
• Quantify real-world fuel use and emissions from base engines and APUs
References


Long-Haul Sleeper Cab Trucks in the US

- 680,000 long-haul sleeper cab trucks
- Rest stops required by Federal Hours of Service (HOS) regulations
- Base engine idling to provide “hotel” services
- Idling is estimated at 1,460 to 1,800 hours annually
- Estimated to consume 960 million gallons of diesel fuel and emit 11 million tons of \( \text{CO}_2 \), 180 thousand tons of \( \text{NO}_x \) and 5,000 tons of PM
Auxiliary Power Units

- Auxiliary power units (APUs):
  - Small diesel engine-generator
  - Power for electrical air conditioning, heating, and auxiliary loads
Study Methodology

10 Fleet-A Trucks
With APU-A
With APU-B

Average In-service time: 11,300 hours (as of 2/29/07)

10 Fleet-B Trucks
With APU-A
With APU-B

Average In-service time: 8,500 hours (as of 2/29/07)

Data Acquisition System

VolvoLink System

Electronic Control Units (ECUs)

Data Logger

Additional Sensors
Results: Combined Multi-Monthly Route Map for 20 Field Trucks
Location and Duration of a Stop for an Example Truck

Example Truck: Truck No. 2

The driver of Truck No. 2 turned off the base engine and used the APU for 12 hours at a specific location.
Number of Stops versus Stop Duration for Fleet A (Single Drivers Predominately)

Note: On average, there are 520 stops (ranging from 329 to 748 stops) that have durations between 0.25 to 1 hour.
Number of Stops versus Stop Duration for Fleet B (Team Drivers Predominately)

Note: On average, there are 567 stops (ranging from 344 to 891 stops) that have durations between 0.25 to 1 hour.
Activity Pattern for An Example Truck (Single Driver)

Percentage of Time of Stop Scenarios versus Stop Duration
(Truck No. 3: 9/13/06-2/29/08)

Stop Duration (hour)

Percentage of Time

No Power
SP & Base Engine
Shore-Power (SP)
APU & Base Engine
APU
Base Engine (BE)
## Distribution of Powered Stop Time for Field Trucks

Through 2/29/2008 (for stops ≥ 0.25 hours)

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<th>Truck Number</th>
<th>Percentage of Time</th>
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</table>

*Legend:*
- SP & Base Engine
- Shore-Power (SP)
- APU & Base Engine
- APU
- Base Engine (BE)

*Fleet A (Single Drivers Predominately) → Fleet B (Team Drivers Predominately)*
Fuel or Energy Use Rates for the Base Engine, APUs and SP Systems

• For the base engine, average idle fuel use rates range from 0.46 to 0.65 gal/hr depending on ambient temperature.

• For the APUs, 99% of the electrical loads are below 3 kW.

• For the SP systems, average electrical loads are approximately only 0.1 kW.
## Emission Factors for the Base Engine, APUs and Shore Power Systems

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<th>Source</th>
<th>Load (kW)</th>
<th>Fuel or Energy Use Rate (gal eq./hr)</th>
<th>NO\textsubscript{x} (g/hr)</th>
<th>HC (g/hr)</th>
<th>CO (g/hr)</th>
<th>CO\textsubscript{2} (kg/hr)</th>
<th>PM (g/hr)</th>
<th>SO\textsubscript{2} (g/hr)</th>
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<td>4.7</td>
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<td>High</td>
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<td>0.33</td>
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<td>APU-B</td>
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<td>3</td>
<td>0.30</td>
<td>24.7</td>
<td>0.8</td>
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<td>0.0</td>
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<td>3.0</td>
<td>0.234</td>
<td>9.5</td>
<td>0.144</td>
<td>1.16</td>
<td>6.1</td>
<td>1.67</td>
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CO₂ Emissions During Stops

Avoided CO₂ emissions:
For Fleet A: (Average: 22%; Range: 8 to 31%)
For Fleet B: (Average: 5%; Range: -1 to 22%)
Avoided NO\textsubscript{x} emissions:
For Fleet A: (Average: 47%; Range: 16 to 76%)
For Fleet B: (Average: 12%; Range: 1 to 45%)
Annual Avoided Fuel Use and Emissions

- Based on literature values for national idle base engine and APU fuel use rates, national average annual avoided fuel use could be as high as 480 to 770 million gallons per year.
- Based on results from Fleet A for single drivers, the estimated national annual avoided fuel use rate is 130 million gallons.
- Results are very sensitive to base engine and APU fuel use rates, which are variable among engines.

<table>
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<tr>
<th></th>
<th>Avoided Fuel Use (%)</th>
<th>Avoided NOx Emission (%)</th>
<th>Avoided HC Emission (%)</th>
<th>Avoided CO Emission (%)</th>
<th>Avoided CO2 Emission (%)</th>
<th>Avoided PM Emission (%)</th>
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<td>Average</td>
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<td>16 to 76</td>
<td>11 to 43</td>
<td>-30 to 32</td>
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<td>3 to 17</td>
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<td>Fleet B</td>
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<td>Average</td>
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<td>0 to 28</td>
<td>-14 to 14</td>
<td>-1 to 22</td>
<td>-11 to 12</td>
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</table>
Annual Avoided Fuel Use and Emissions (Continued)

- Avoided annual national NO$_x$ emissions:
  - 130,000 to 160,000 tons, based on literature emission factors
  - 42,000 tons based on Fleet A (single driver) results
  - 6,000 tons based on Fleet B (team driver) results

- Avoided annual national PM emissions:
  - An increase of 1,000 to a decrease of 4,800 tons, based on literature emission factors
  - 130 tons, based on Fleet A (single driver) results
  - 10 tons, based on Fleet B (team driver) results
**Simple Payback Period**

<table>
<thead>
<tr>
<th>Fleet</th>
<th>Truck No.</th>
<th>APU Capital Cost ($)</th>
<th>APU Annual O &amp; M Cost ($/yr)</th>
<th>APU Annual Fuel Saving (gallon/yr)</th>
<th>APU Annual Fuel Cost Saving&lt;sup&gt;a&lt;/sup&gt; ($/yr)</th>
<th>Simple Payback Period&lt;sup&gt;b&lt;/sup&gt; (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet A (Single Drivers)</td>
<td>1-10</td>
<td>8,500</td>
<td>460</td>
<td>70 to 420</td>
<td>340 to 1,960</td>
<td>6-10 yrs: 5 trucks, &gt; 10 yrs: 4 trucks, N/A: 1 trucks</td>
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<tr>
<td>Fleet B (Team Drivers)</td>
<td>11-20</td>
<td></td>
<td></td>
<td>-4 to 140</td>
<td>-20 to 650</td>
<td>6-10 yrs: 0 trucks, &gt; 10 yrs: 1 trucks, N/A: 9 trucks</td>
</tr>
</tbody>
</table>

<sup>a</sup>Weekly retail price for ultra low sulfur diesel on 6/9/2008 is $4.7/gallon (EIA, 2008)

<sup>b</sup>N/A means that there is no pay-back period for this truck because there is no net saving
Conclusions

• New methods have been developed for quantifying truck stop activity patterns and fuel use and emissions for long-haul trucks
• Single drivers have longer duration stops than team drivers
• APUs are used for both short and long duration stops
• Simultaneous use of the APU and base engine leads to higher fuel use and emissions, and was observed for several trucks
• The fuel use savings and emissions reductions projected from the field study results are lower than those from literature sources. The field trucks have relatively low base engine idle fuel consumption. APU engine fuel consumption is higher than assumed in most other studies, but takes into account actual electrical loads.
Recommendations

• APUs are promising for trucks operated by single drivers. The payback period for single drivers could be decreased by company policies that reward drivers for increased use of the APU instead of the base engine.

• “Double dipping” usage of both the base engine and APU occurs in the real world and incentives need to be developed to discourage this.

• The methodology developed here can be adapted to assess other idle reduction options, such as direct fire heater.
Acknowledgement/Disclaimer

• This project is sponsored by the U.S. Environmental Protection Agency’s SmartWay™ Mobile Idle Reduction Technology (MIRT) program
• The project partners include Volvo Technology of America, Volvo Trucks North America, the Department of Civil, Construction, and Environmental Engineering of North Carolina State University and the North Carolina Solar Center
• Anne Tazewell of the NC Solar Center is the overall project director. The authors are grateful to Skip Yeakel, George Bitar, Mike Siebert, Randy Peck, and Bill Klodaski of Volvo for their contributions to the APU prep kit and data acquisition tasks
• The authors are responsible for the facts and accuracy of the data presented herein
• The contents do not necessarily reflect the official views or policies of U.S. Environmental Protection Agency
Backup Slides
Categorization of Stop Scenarios

Start

Input the Original Data

Vehicle Stops? Yes

No

End (Truck is Moving)

Base Engine Idle? Yes

No

Shore-Power On? Yes

No

APU On? Yes

No

Scenario 1: Base Engine

Scenario 2: APU & Base Engine

Scenario 3: APU

Scenario 4: Shore-Power

Scenario 5: SP & Base Engine

Scenario 6: Off-Board

Scenario 7: No Power

At IdleAire Location?

Yes

No

IdleAire Use?

Yes

No
Analysis of Stop Activity Patterns

- Screen data for quality assurance
- Quantify number of stops within specific stop duration ranges
- Quantify activity during each stop
  - Estimate the duration for each stop event
  - Estimate the percentage of stop time for scenarios during each stop
- Quantify the time for different stop scenarios within specific stop duration ranges
- Quantify total amount of the time for different stop scenarios for each truck
Estimate Base Engine Fuel Use Rates

Using ECU data from field trucks, quantify fuel use rate versus ambient temperature

\[ y = 5 \times 10^{-5}x^2 + 0.001x + 0.4784 \]
\[ R^2 = 0.3842 \]

Fleet A Trucks at 600 RPM

\[ y = 7 \times 10^{-5}x^2 - 0.0021x + 0.4804 \]
\[ R^2 = 0.1481 \]

Fleet B Trucks at 690 RPM
Measure APU Engine Fuel Use Rates

\[ y = 5 \times 10^{-9} x^2 + 4 \times 10^{-5} x + 0.2804 \]
\[ R^2 = 0.9992 \]

\[ y = 9 \times 10^{-9} x^2 + 5 \times 10^{-5} x + 0.2224 \]
\[ R^2 = 0.9975 \]

Electrical Load (watt)
Fuel Use Rate (gal/hr)
APU-A
APU-B
Poly. (APU-A)
Poly. (APU-B)
Measure Emission Factors for Base and APU Engines

- NO, CO, HC and CO$_2$ emissions were measured using a portable emission measurement system (PEMS)
- Fuel-based emission factors based on carbon mass balance, exhaust emissions measurements, and fuel properties
- Mass per time emission factors: product of fuel use rates and fuel-based emission factors
- PM emission factors were estimated by averaging data from the literature

OEM-2100 Montana System, Clean Air Technologies International, Inc.
Shore-Power Energy Use Rate and Indirect Emissions

SP Energy Use Rate = \left( \frac{\text{Electricity Consumed per Hour}}{\text{Total Primary Energy Consumed to Generate Electricity in the U.S.}} \right) \times \frac{\text{Total Electricity Used by End User in the U.S.}}{\text{Total Pollutant Emission from Electricity Generation in the U.S.}}

SP Emission Factor = \left( \frac{\text{Total Pollutant Emission from Electricity Generation in the U.S.}}{\text{Total Electricity Used by End User in the U.S.}} \right)
Quantification of Avoided Fuel Use and Emissions

**Base Engine Scenario versus Actual Scenario**

- **Avoided Fuel Use**
  - Actual APU fuel use
  - Actual shorepower fuel use
  - Actual base engine fuel use

*The Base Engine Scenario assumes that the base engine is used for all power needs during each stop.*

*The Actual Scenario is based on the observed field data during each stop.*
Analyze Truck Stop Activity Patterns

Start

Screened Data

Estimate the duration for each stop event (A)

- Estimate APU duration (with overlapping) (B)
- Estimate APU & Base Engine duration (C)
- Estimate Base Engine duration (with overlap) (D)
- Estimate SP & Base Engine duration (E)
- Estimate APU duration (with overlapping) (B)
- Estimate potential IdleAire usage duration (G)

Scenario 3 duration (B-C)
Scenario 2 duration (C)
Scenario 1 duration (D-C-E)
Scenario 5 duration (E)
Scenario 4 duration (F-E)
Scenario 6 duration (G')
Scenario 7 duration (A-B+C-D+E-F-G)

Sort and categorize all stop events based on their stop duration ranges

- Calculate number of stops within specific stop duration ranges
- Calculate the percentage of time of utilization of base engine, APU, shore-power, off-board or no power within specific stop duration ranges
- Calculate the combination of time of utilization of base engine, APU, shore-power, and off-board within specific stop duration ranges
Per-Stop Location for an Example Truck

Example Truck: Truck No. 1
Per-Stop Location for an Example Truck

Example Truck: Truck No. 1
Activity Pattern for An Example Truck

Number of Stops versus Stop Duration

(Truck No. 1: 9/6/06-2/29/08)

Number of Stops

Stop Duration (hour)
Activity Pattern for An Example Truck

Number of Stops versus Stop Duration

(Truck No. 3: 9/13/06-2/29/08)

Number of Stops vs Stop Duration (hour)

804 stops in total.
Activity Pattern for Example Trucks

Number of Stops versus Stop Duration
(Truck No. 1: 9/6/06-2/29/08)

Stop Duration (hour)
Percentage of Time
No Power
SP & Base Engine
SP
APU & Base Engine
APU
Base Engine
# Avoided Fuel Use and Emissions from the Base and APU Engines

<table>
<thead>
<tr>
<th>Truck No.</th>
<th>Avoided Fuel Use (gal/yr)</th>
<th>Avoided NOx Emission (Ig/yr)</th>
<th>Avoided HC Emission (g/yr)</th>
<th>Avoided CO Emission (g/yr)</th>
<th>Avoided CO2 Emission (Ig/yr)</th>
<th>Avoided PM Emission (g/yr)</th>
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Through 2/29/2008
Quantification of Shore-Power Energy Use as Diesel Fuel Equivalent

1 kWh of end-use electricity = 0.0779 gallon of diesel equivalent

- 1 kWh of end-use electricity = 10,806 BTU of primary energy consumed to generate electricity
  - 1 kWh = 3,412 BTU
  - Primary energy consumed to generate electricity is 3.167 times of end-use electricity in 2006 in the US (EIA, 2007)
- 1 gallon of diesel fuel = 138,690 BTU
Extended Idling Estimates

• The average long-haul truck is estimated to idle from 1,460 to 1,800 hours annually for rest stops, varying from 500 to 4,000 hours annually (ATRI, 2004; Lutsey et al., 2004; Gaines et al., 2006)
• EPA estimated that 500,000 long-haul trucks in 2002 idle 1,500-2,400 hours per year per truck (Lim, 2002)
• The total amount of annual average extended idling duration for single driver-operated trucks is 1,450 to 1,630 hours for stop durations of greater than 7 and 5 hours, respectively.
• The total amount of annual average extended idling duration for team driver-operated trucks is 250 to 330 hours for stop durations of greater than 7 and 5 hours, respectively.
Avoided Fuel Use (another approach)

- It is estimated that each truck idle 1,500-2,400 hours per year and consume 0.94-1 gallon of fuel per hour (Lim, 2002)
- It is estimated that there were 500,000 long-haul trucks in 2002, which consume approximately 960 million gallons of fuel per year (Lim, 2002; EPA, 2008)
- Base on the data from Fleets A and B, idling of long-haul trucks uses 580 and 260 million gallons, respectively, of fuel per year (60 and 27% of the literature estimate)
- It is estimated that the APUs may reduce long-haul truck idle fuel use by from 50 to 80%, which are approximately 480 to 770 million gallons per year (Lim, 2002; EPA, 2008)
- Base on the data from Fleets A and B, avoided fuel use contributed by the APUs is 130 and 15 million gallons, respectively, per year (17-27 and 2-3% of the literature estimates)
Data

• Total diesel fuel consumption in the US is approximately 49 billion gallons
• It is estimated that there were 500,000 long-haul trucks in 2002, which consume approximately 960 million gallons of fuel per year (Lim, 2002; EPA, 2008)
• Idle fuel use for long-haul trucks is approximately 960 million gallons, which is 2% of total diesel fuel consumption in the US
• It is estimated that the APUs may reduce long-haul truck idle fuel use by from 50 to 80%, which are approximately 480 to 770 million gallons per year (Lim, 2002; EPA, 2008)
• An APU can achieve 50-80% reductions in fuel use and CO$_2$ and 70-90% reductions in NOx (Lim, 2002)
• An APU can achieve 50-97% reductions in NOx, CO and HC (???)(Storey, 2003)
• PM is seen to be generally reduced by using the APUs, but the reductions ranged from -20% to 95% (Storey, 2003)
## Simple Payback Period

### Fleet A (Single Drivers)

<table>
<thead>
<tr>
<th>Truck No.</th>
<th>APU Capital Cost ($)</th>
<th>APU Annual O &amp; M Cost ($/yr)</th>
<th>APU Annual Fuel Saving (gallon/yr)</th>
<th>APU Annual Fuel Cost Savinga ($/yr)</th>
<th>Simple Payback Periodb (yr)</th>
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</thead>
<tbody>
<tr>
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<td></td>
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<td>72</td>
<td>340</td>
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<td>283</td>
<td>1329</td>
<td>10 (12)</td>
</tr>
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<td>374</td>
<td>1759</td>
<td>7 (8)</td>
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<td>170</td>
<td>797</td>
<td>25 (31)</td>
</tr>
<tr>
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<td>306</td>
<td>1437</td>
<td>9 (11)</td>
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<td>1728</td>
<td>7 (8)</td>
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<td></td>
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<td>1957</td>
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<td>8</td>
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<td>197</td>
<td>927</td>
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<td>9</td>
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<td>106 (132)</td>
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<td>308</td>
<td>1450</td>
<td>9 (11)</td>
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<td>71</td>
<td>334</td>
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<td>N/A (N/A)</td>
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### Fleet B (Team Drivers)

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<th>Truck No.</th>
<th>APU Capital Cost ($)</th>
<th>APU Annual O &amp; M Cost ($/yr)</th>
<th>APU Annual Fuel Saving (gallon/yr)</th>
<th>APU Annual Fuel Cost Savinga ($/yr)</th>
<th>Simple Payback Periodb (yr)</th>
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### Notes:

- aWeekly retail price for ultra low sulfur diesel on 6/9/2008 is $4.7/gallon (EIA, 2008)
- bN/A means that there is no pay-back period for this truck because there is no net saving.